**Institute of
Hydrology**

Evaluation of Sulphur Hexafluoride as a Tracer for Groundwater

Contract Reference PECD7/7/206

Natural Environment Research Council

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This report was submitted to the Department of the Environment by the Institute of Hydrology (Natural Environment Research Council) presenting the results and conclusions of the above Contract.

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(i) Executive Summary

The Contract comprises four main topics:

a) build and commission equipment for the analysis of very low concentrations of sulphur hexafluoride (SF6) dissolved in water

b) conduct laboratory tests into the sorption or chemical interaction of sulphur hexafluoride with geological materials

c) examine the background levels of sulphur hexafluoride in air and water

d) conduct field trials using sulphur hexafluoride as a groundwater tracer

The measurement equipment was built by the Marine Biological Association, now part of the NERC Plymouth Marine Laboratory, and has performed well.

Laboratory tests were carried out to determine the extent of interaction between sulphur hexafluoride and a selection of aquifer materials. The results show some interaction but significant amounts of tracer remained in solution after five months.

The background levels of sulphur hexafluoride in the atmosphere were determined. Although background levels have risen some tenfold in the last ten years they do not pose a problem to the current use of sulphur hexafluoride as a groundwater tracer. Levels in surface water were found to be negligable.

Sulphur hexafluoride is an excellent groundwater tracer for sand and gravel aquifers containing clay. It is markedly superior to conventional dye and halide tracers and the successful evaluation indicates a major step forward in tracing technology.

Its advantages over other tracers include:-

a) a very conservative tracer with much less loss by sorption or chemical interaction with the aquifer matrix than either Rhodamine WT or Iodide.

b) very high sensitivity of detection (5×10^{-10}g/l) enabling large studies to be undertaken with small amounts of tracer. Inexpensive.

c) very low natural background. Air background is measurable and somewhat variable but the background in water is below the measurable limit.

d) non-toxic and inert

e) rapid and easy to measure by conventional chemical techniques although a dedicated analytical system is required. The system developed can determine 50 samples per day.

A disadvantage is that its use is limited to aquifers where flow is laminar. In turbulent flow in open channels, as in karstic limestone, it is lost by degassing. It would not be suitable for studies in the unsaturated zone.

(ii) Terms of reference

The objectives and proposed programme of work are taken from the contract between the Department of the Environment (DoE) and the Natural Environment Research Council's (NERC) Institute of Hydrology (IoH).

(ii)(i) MAIN OBJECTIVES

(a) to build a detection system for sulphur hexafluoride capable of measurements at extremely low concentrations

(b) to examine the effectiveness of sulphur hexafluoride as a groundwater tracer in a range of rock/soil types

(c) to develop techniques for field use of sulphur hexafluoride and apply them in one or more groundwater movement studies.

(ii)(ii) PROPOSED PROGRAMME OF WORK

(a) design and construct a portable measurement system capable of detecting sulphur hexafluoride in groundwater at levels of typically 10^{-14} v/v (10^{-11} g/litre).
(b) laboratory application of the measurement system for testing sulphur hexafluoride with various soils and geological materials to establish whether sulphur hexafluoride provides a reliable tracer for non-marine water. Use the measurement system to examine natural waters to determine the natural background and variation

(c) apply techniques to field trials in shallow and deep aquifers.

Evaluation of Sulphur Hexafluoride as a Tracer for Groundwater

1. Introduction

1.1 BACKGROUND

In 1986 the Marine Biological Association (MBA), now part of the NERC Plymouth Marine Laboratory, completed a DoE contract to prove the viability of certain perfluorinated compounds as economic and practical tracers for oceanic mixing studies (Watson 1986).

Among the compounds they investigated was sulphur hexafluoride (SF6). This gas, previously used in such applications as checking interconnections in mine workings (Herring et al 1983), showed promise as a marine tracer when dissolved in water especially as it could be detected at very low concentrations (Ledwell et al 1986), (Watson et al 1987). The present contract grew out of the MBA work from a suggestion that sulphur hexafluoride might form a useful groundwater tracer to augment those currently in use.

Tracers are used in groundwater studies to determine the rate and direction of flow in aquifers. Their applications are many and widespread; predicting the path of contaminants from proposed landfill sites, establishing leakage paths through earth dams and canal dykes, determination of aquifer characteristics including transmissivity and dispersivity and establishing interconnections between sources of supply and discharge points. Maximum and mean velocities can be determined directly and are relevant to most of the above studies.

With any tracer there are three main considerations to take into account:

- sensitivity of detection and its relation to natural 'background' levels
- conservation i.e. the ability of the tracer to remain in solution without loss by sorption or chemical reaction in the aquifer
- acceptability and health considerations

Detection: highly sensitive detection equipment is required to enable large scale studies to be undertaken with economic quantities of tracer. The ultimate limit is controlled by the natural 'background' concentrations of the tracer in the groundwater and by its natural variation.

Conservation: an ideal tracer should be conservative. Few tracers, except the isotopes of water (tritium, deuterium and oxygen-18) completely fulfil this criterion.

Acceptability: the tracer has to be inert and has to be medically acceptable. The toxic level should ideally be sufficiently low for the solution to be harmless at the concentration used for injection. The tracer should not be unsightly; this is relevant to the fluorescent dyes which before they become sufficiently diluted can temporarily discolour large volumes of water.

Historically a variety of tracers have been used in the groundwater regime including ionic compounds, fluorescent dyes and radioactive chemicals; to some extent biological agents have also been used. All these groups of tracers have disadvantages in terms of their conservation, the economics of use and their acceptability by Water Authorities and environmentalists. No widely used groundwater tracer has yet been discovered, in spite of extensive research. Growing concern particularly relating to groundwater pollution and prediction of contaminant movement provides the incentive for this investigation.

1.2 SULPHUR HEXAFLUORIDE

The properties of sulphur hexafluoride are given in Table 1.1. In summary sulphur hexafluoride exists as a gas at normal temperatures and is slightly soluble in water. There are no references to any toxic effect and it is described as chemically and physiologically inert.

Sulphur hexafluoride should pose little environmental threat. It is chemically inert except under conditions of red heat and even then does not react with hydrogen, ammonia or oxygen. It is not believed to pose any threat to stratospheric ozone; bonding is much stronger than in CFC's where in any case the chloride rather than fluoride is the destructive and worrying component. At this time sulphur hexafluoride appears to have a completely clean bill of health for environmental applications.

The chief use of sulphur hexafluoride is in the power supply industry where it is used as an arc quench in high voltage switch gear. The units are sealed for life, which in practice is about ten years, and the gas is only recovered from the larger switches. The CEGB have used sulphur hexafluoride to trace chimney plumes from some power stations. It has also been used in water mains for leak detection and in large scale gas flow measurements. These industrial uses cause a low but potentially variable background in the environment which has to be considered in the design of field investigations.

1.3 UNITS

Sulphur hexafluoride concentrations are given in nanograms per litre (ng/l) unless stated otherwise. One nanogram is equivalent to 10^{-9} grams.

Exponential notation is used for concentration values in some of the graphs. This is in the form E-9 which means multiply by 10^{-9}.

Table 1.1 Properties of Sulphur Hexafluoride SF_6

molecular weight : 146.05
melting point : -50.5°C
boiling point : -63.8°C (sublimes)
density gas : 6.602 g/l (dry air: 1.19 g/l)
liquid : 1.88 g/l @ -50.5°C
solubility water : 0.04 g/l

Toxicity :
Dangerous Properties of Industrial Materials (N Irving Sax)
toxicity level value (TLV) = 1000 mg/l in air
Registry of Toxic Effects of Chemical Substances (National Institute for Occupational Safety and Health)
not listed as carcinogenic
Asphyxiant at high concentrations

WHO Drinking Water Standards : not listed
EEC Drinking Water Standards : not listed

2. Analysis techniques and tracer preparation

2.1 ANALYTICAL SYSTEM

The groundwater analytical system is a modified version of the equipment developed by MBA for marine samples. The principle of sulphur hexafluoride determination is to remove the gas from solution and separate it out using a combination of freezing and gas chromatography techniques. The quantity of sulphur hexafluoride is then measured by means of an electron capture detector (ECD).

The apparatus, constructed by MBA, has three elements:

(a) the sparging system
(b) the measurement system
(c) the control system.

The first two elements reflect the main activities of the analysis cycle and are shown diagrammatically in Figure 2.1. The valves V1, V2 and V3 are pneumatically operated and valve V4 is electromechanical.

2.1.1 The sparging system

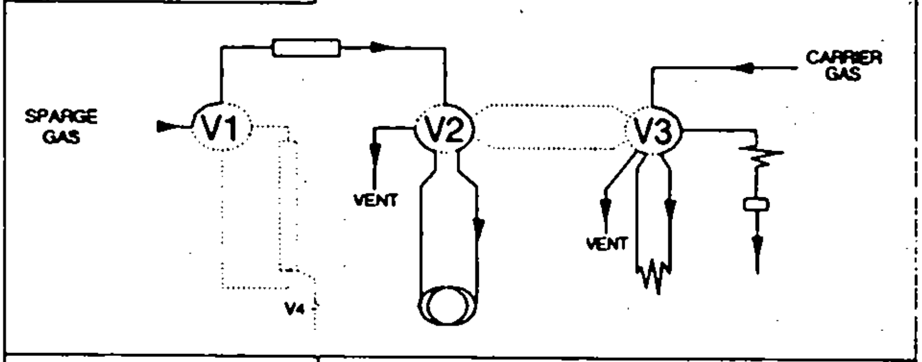
While the system is in the standby mode (Figure 2.1A) the water or air sample is introduced into the apparatus by means of a large capacity syringe. For a water sample the sample column is filled to a fixed mark so that the same sample volume is used for each analysis; in the case of an air sample the volume introduced is measured by means of the graduations on the syringe. An injection port with a self sealing septum has been incorporated into the equipment so that calibration gases may be introduced from a gas tight microsyringe.

The sparge cycle (Figure 2.1B) passes compressed gas (oxygen free nitrogen) through a sintered stainless steel bubble stone to strip out or displace any sulphur hexafluoride present in the sample. The sparge gas, together with any sulphur hexafluoride from the sample, is dried before passing through a cold trap. The trap is a metre of coiled stainless steel tube packed with a graded gas chromatograph solid support which restricts the gas flow. The trap is immersed in a coolant so that the temperature is a maximum of -55°C. Any sulphur hexafluoride present is retained in the trap.

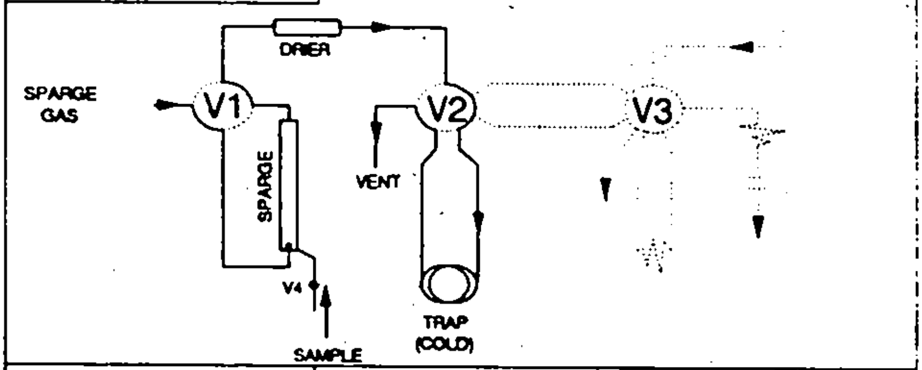
At the conclusion of the sparging mode the valve V2 isolates the trap which is removed from the coolant. The trap is then electrically heated to a minimum temperature of +90°C. This causes the sulphur hexafluoride to vaporise.

ANALYTICAL EQUIPMENT

(a)Standby Mode



(b)Sparge Mode



(c)Analysis Mode

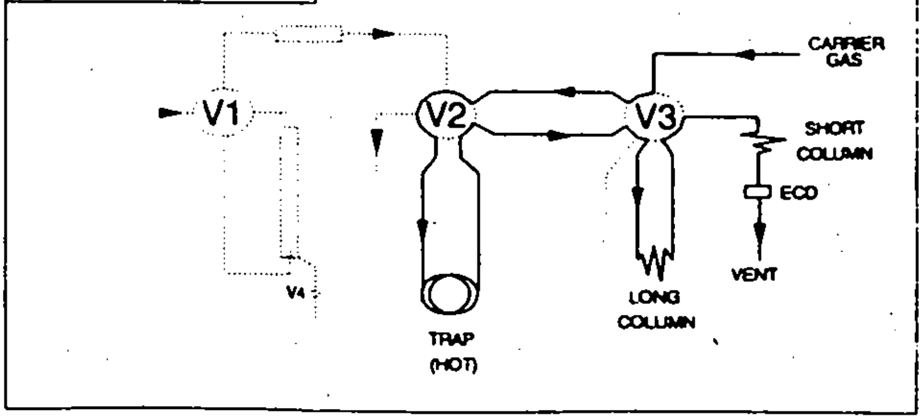


Figure 2.1

2.1.2 The measurement system

This is based on a standard gas chromatograph with two columns. A carrier gas (oxygen free nitrogen) is used to maintain uniform conditions within the columns and detector.

After the trap has been heated, the carrier gas is switched by valve V3 to flow through the trap and flush out any sulphur hexafluoride (Figure 2.1C). The mixture of gases pass through the two columns both of which are packed with graded molecular sieve which acts as a retardant. The degree of retardation is different for each gas and results in the gaseous mixture being separated into the individual components. As sulphur hexafluoride is particularly difficult to retard, the column filler has been selected to hold back any other gases likely to be present.

The gases then pass through the electron capture detector. This type of detector is especially sensitive to the presence of halogens. It contains a small radioactive source which ionises the gas. The ionised nitrogen carrier gas provides a steady base line current. As halogens are good electron acceptors, any halogen present will remove some of the nitrogen generated electrons which results in a decrease in the baseline current. An integrator is used to produce a graph of the electron capture detector's output. Coupled with the graph is a printout of the area beneath any resulting peak (Figure 2.2).

2.1.3 The control system

The automatic operation of the analytical equipment is controlled by a real time programmable controller. This controller is used to operate the three pneumatic multiport valves, the sample valve, the position of the trap and the trap heater. The ability to control the valves permits the system to automatically time the various operations, such as sparging, in the analytical sequence. Once a sample has been introduced into the sample column and the controller started the operation is automatic until the results of the analysis have been printed out.

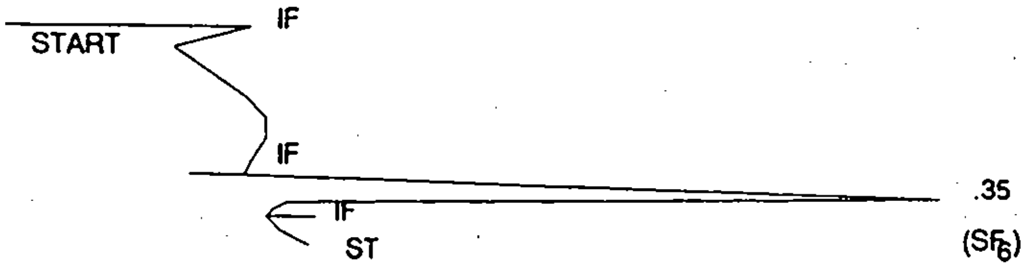
The control program is contained in an EPROM solid state store which allows the instructions to be modified. The control panel which houses the controller allows the operator to monitor the progress of the cycle. Provision is included to allow the operator to over-ride the controller and it is possible to manually control the analysis of samples.

The analytical cycle takes about five and a half minutes. The sparging and trap heating take some two and three quarter minutes while the equipment is flushed with nitrogen for two and a quarter minutes. The analysis takes thirty seconds plus time to print the result.

2.1.4 Modifications to the analytical equipment

Some modifications to the original equipment supplied by MBA have been

ANALYTICAL EQUIPMENT ; OUTPUT



```
RUN  498                    JUN 08/89            16:35
WORKFILE ID: B
WORKFILE NAME:
AREA%
   RT        AREA      TYPE      AR/HT      AREA%
  0.35      169990      BB       0.034      100.00
TOTAL AREA=          169990
MUL FACTOR=          1.000E+00
```

Figure 2.2

necessary. In the original form there was a sample loop, which when filled, provided a fixed volume sample. The sample was then automatically transferred to the sparge column at the beginning of the analytical cycle. The sample loop caused two problems.

Firstly the volume of the loop was such that an excess of water could be carried over from the sparge column. The drier was unable to cope with the water and this resulted in the contents of the trap becoming wetted. Unfortunately it is not possible to refurbish the contents which had to be replaced.

Secondly, and more seriously, during transfer the sample was forced through the bubble stone which acted as a very fine filter. This caused the stone to become blocked especially if the sample contained any suspended solids. It was shown that vacuum filtration before introducing the sample, could cause loss of sulphur hexafluoride.

To overcome these related problems the sample loop was removed and the analytical protocol modified to ensure that any air entering the apparatus was flushed out of the equipment between each analysis.

2.2 CALIBRATION AND SENSITIVITY

Calibrations were carried out using a standard mixture of sulphur hexafluoride and nitrogen at a concentration of 5.4 parts per billion of sulphur hexafluoride. The equipment was calibrated by using a gas tight syringe to inject various quantities of the standard mixture. The calibration was linear and checks showed it to be stable and reproducible.

The equipment determines the actual amount of sulphur hexafluoride present in a sample and not the concentration. This means that while the equipment is capable of detecting a minimum mass of sulphur hexafluoride the volume of the sample determines the actual minimum concentration detectable.

2.3 PREPARATION OF SULPHUR HEXAFLUORIDE SOLUTIONS

In order to use sulphur hexafluoride as a groundwater tracer it is necessary to dissolve it in water and use the solution for injection.

The solubility of sulphur hexafluoride is only 0.04g/l and the pure gas has to be circulated, via a bubble stone, to dissolve sufficient tracer to prepare a solution suitable for injection. An airpump was used to circulate the gas in a closed system suitable for preparing up to ten litres of solution. The solution can be withdrawn and replaced several times by clean water to produce further injection solutions.

Solutions for laboratory use were prepared at a lower concentration from sulphur hexafluoride gas diluted with nitrogen to give tracer concentrations between 20ng/l and 60ng/l.

3. Laboratory experiments

3.1 INTRODUCTION

A series of tests were carried out to determine the effects of different geological material on sulphur hexafluoride. The degassing of sulphur hexafluoride from a free water surface was also investigated.

3.2 DEGASSING

Two different types of open topped glass containers were used. Type A was a straightsided glass beaker with a free surface area of 95 cm^2. Type B, a narrow necked glass bottle had a surface area of 45 cm^2. Both types contained similar volumes and depths of tracer. Apart from slight agitation during sampling the solutions were not disturbed. The initial concentration was approximately 100 ng/l.

Figure 3.1 shows the results expressed as the percentage of tracer remaining in solution. As can be seen the rate that sulphur hexafluoride leaves solution depends exponentially on the concentration. The rate also depends, to a much lesser extent, on the surface area exposed. The concentration of sulphur hexafluoride in the straight sided vessel had fallen to fifty percent of the original after eleven and a half hours, while the concentration in the other vessel took sixteen and a half hours to fall by the same percentage.

3.3 INTERACTION WITH AQUIFER MATERIALS

As a preliminary to field tracing laboratory tests were carried out to establish the extent of the interaction between sulphur hexafluoride and a selection of geological materials characteristic of major aquifers.

The materials were:

siliceous sand
calcareous sand
Chalk (powdered)
Fullers Earth
peat

The first three of these materials were selected as representing material typical of the major aquifers in Britain. Fullers Earth, a montmorillonite clay, was included since it is the clay fraction which is most likely to remove any inorganic or organic tracer. Peat was partially tested to establish whether highly organic material reacted with the tracer.

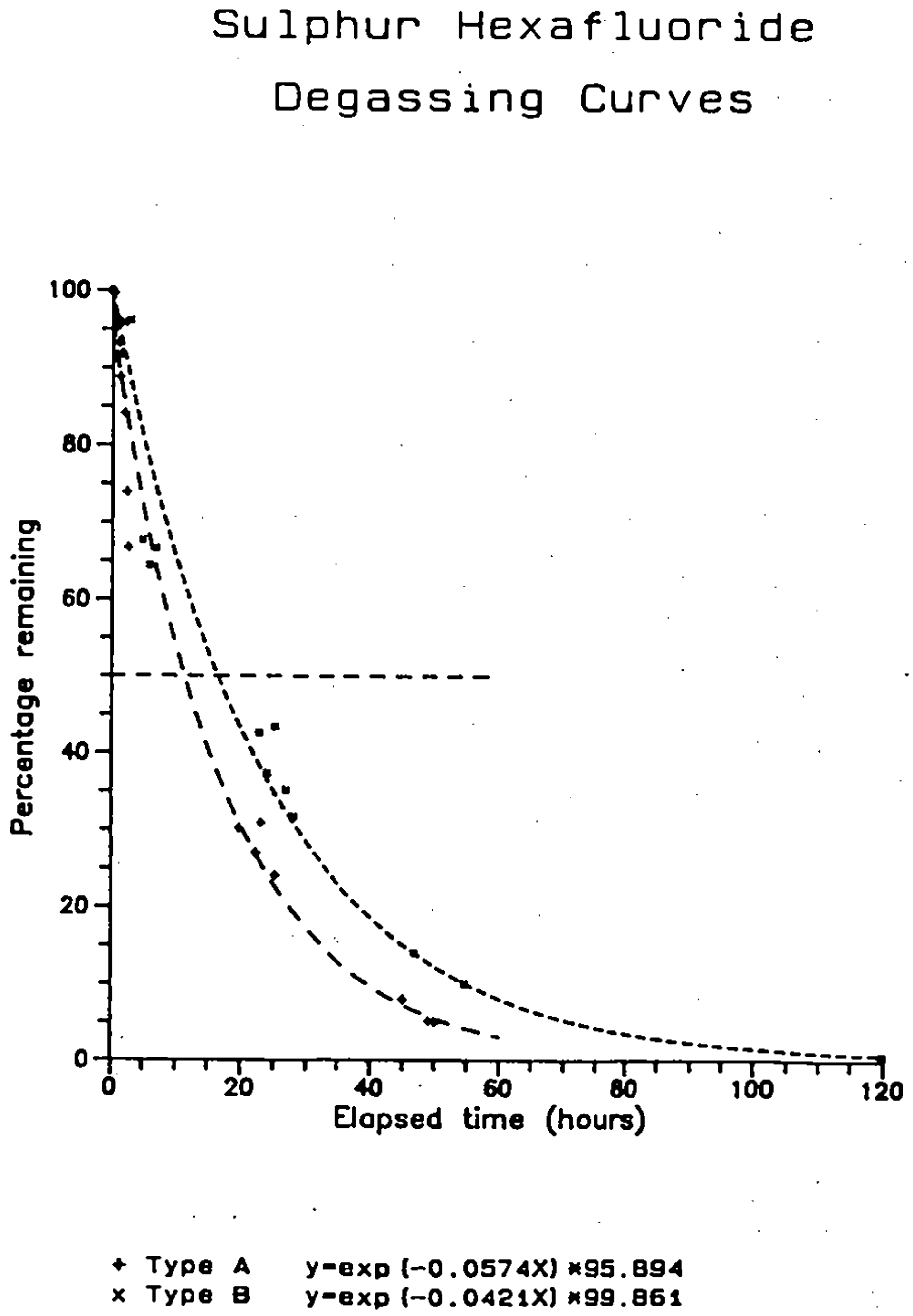

Sulphur Hexafluoride
Degassing Curves
Percentage remaining
0
20
40
60
80
100
Elapsed time (hours)
0
20
40
60
80
100
120
+ Type A y=exp (-0.0574X) *95.894
× Type B y=exp (-0.0421X) *99.861

Figure 3.1

A series of 320 ml plastic capped glass bottles was first prepared with weighed amounts of materials such that they were about half filled with the solids. Water was added and, after settling, the clear liquid was decanted. The remaining water in the sample was then determined by weighing and oven drying. From these figures the dilution of the tracer to be added during the tests could be determined.

Fifteen bottles were then prepared for each test material. The tracer, sulphur hexafluoride solution, had a concentration of between 13 and 22ng/l and the bottles were completely filled to exclude air. The bottles were periodically agitated. Fifteen empty bottles were completely filled with tracer solution to act as controls. Table 3.1 gives details of the sample preparation.

Three samples were taken from each of three bottles of each material for measurement. The sampled bottles were then discarded. Sampling was carried out after 20, 35 and 152 days with a partial test on peat at 24 days. The results are shown in Table 3.2 as a percentage loss of the tracer. The results do not show the pattern which would be expected from the normal mechanisms of tracer loss. There is no clear relation between either the chemical composition of the samples or the surface area. Fullers Earth would have removed many otherwise acceptable tracers and the large surface area of this and powdered Chalk would also be expected to result in the highest tracer loss. The loss in the water sample is unexpectedly large but shows a steady increase with time.

One explanation, which can only be checked by further work, is that there is either interaction with the plastic cap or that sulphur hexafluoride is capable of passing through the plastic. If the cap has a limited number of interaction, or sorption, sites then the loss from the water sample which contained more sulphur hexafluoride than the aquifer samples would, expressed as a percentage, be less. The mass of sulphur hexafluoride in the water sample is about 1.8 times the average mass in the aquifer samples. The relative loss from the water then becomes very similar to that from the aquifer samples.

The explanation of tracer loss at these extremely low concentrations is likely to be complex. The interaction of materials at the concentration of nanograms per litre is not predictable. The total number of molecules of sulphur hexafluoride in the aquifer samples is approximately 10^{13} and if these formed a monomolecular layer on the cap, or glass at sample, they would require a surface area of approximately 0.01 cm^2.

A further set of samples were prepared using tracer at 1.6 times higher concentration. These were sampled after 165 days and showed an average loss of only 0.7 that found in the main investigation for calcareous sand, Chalk and Fullers Earth. The loss for siliceous sand was negligible and assumed to be an anomalous result.

Without further experimentation, which would be based on the results obtained in these tests, no unique explanation of the results can be given. However, it is clear that there is no major interaction with the aquifer materials and even the montmorillonite clay fails to remove all the tracer in 150 days. This result is taken to support the value of sulphur hexafluoride as a ground water tracer and was sufficiently encouraging to proceed with the planning of the

Table 3.1 Interaction Sample Preparation

Material	Dry weight (g)	Volume of SF6 solution added (ml)	Dilution of tracer solution
Siliceous sand	200	202	0.74
Calcareous sand	200	197	0.73
Chalk (powdered)	150	184	0.59
Fullers Earth	100	130	0.70
Peat	60	220	0.77

Table 3.2 Interaction Sample Results

		PERCENTAGE LOST				
Time elapsed (days)	Water	Siliceous sand	Calcareous sand	Powdered chalk	Fuller's Earth	Peat
20	7	33	38	23	47	-
24	15	-	-	-	-	46
35	23	55	56	50	63	-
152	33	96	43	87	71	-

field investigations.

An alternative method of observing loss by interaction with aquifer materials is by passing tracer through columns packed with the material under test.

A column was packed with aquifer material from Brown's Pit, Stanton Harcourt which was one of the selected field sites. The column was one metre long and 15 cm in diameter and the packing material was small gravel and sand including a clay fraction. Water was introduced at the base of the column and samples taken at one third, two thirds height and at the overflow. The tracer was injected in 100ml as a pulse. The column flow rate was about 70 ml/minute and sampling over a six hour period gave a throughput of about four times the water capacity of the column.

Four tests were undertaken and all showed similar features. A short cut route gave a peak within 30 minutes of the injection with a secondary peak between 100 and 150 minutes. A smaller and erratic peak occurred at about 280 minutes. The column material had not consolidated to produce intergranular flow so that fissure movement predominated.

3.4 WATER CHEMISTRY

The effects of pH and conductivity, a measure of the dissolved solids present, were examined.

Normal tap water at Wallingford has a pH of about 7.8. Solutions of sulphur hexafluoride were made and the pH altered. The pH was lowered using sulphuric acid and raised using sodium hydroxide. One normal solutions were used so that the quantity of acid or alkali added was very small making a dilution correction unnecessary. After the pH adjustment the solutions were analysed for sulphur hexafluoride and the pH determined. There was no significant lowering of the sulphur hexafluoride concentrations with altered pH.

A series of solutions were prepared by adding a known quantity of stock sulphur hexafluoride solution to waters having different electrical conductivities. The conductivity was adjusted using a solution of an ammonium sulphate. The resulting solution was analysed for sulphur hexafluoride and the conductivity measured. No significant alteration of the sulphur hexafluoride concentrations was detected.

The pH and conductivity of the water caused no significant lowering of the solubility of sulphur hexafluoride gas. This means that there is no tendency for the gas to leave solution because of the pH in the range of 2.8 to 9.8 or in conductivities up to 11000 microsiemens.

4. Natural Background Levels

4.1 INTRODUCTION

Sulphur hexafluoride does not occur naturally. A survey carried out in the late seventies reported that there was an almost uniform global distribution of atmospheric sulphur hexafluoride of about 0.3×10^{-12} v/v; levels were slightly lower in the southern hemisphere (Singh et al 1979). Atmospheric background levels had reached 1.5×10^{-12} v/v by the mid-eighties (Watson and Liddicoat 1985).

4.2 WATER SAMPLES

Samples of both surface and ground waters were collected and analysed for sulphur hexafluoride. The present sample size gives a detection limit of approximately 4.5×10^{-18} v/v (4.5×10^{-10} g/l).

A series of samples were taken over a two month period from the River Thames at Wallingford. The sampling point was downstream of Didcot power station a possible potential source of sulphur hexafluoride. The triplicate samples were collected at least twice a week, often more frequently, covering a period with both high and low flow regimes. None of the samples showed detectable levels of sulphur hexafluoride.

Samples were also collected from the River Thames to the west of Oxford at University Farm. None of the river samples gave detectable levels of sulphur hexafluoride. Other samples taken from surface water sources have all had no detectable levels.

Groundwater samples have also been taken to establish background levels. Samples were collected from the springs in Cheddar village and from the Thames Valley floodplain. In all cases no sulphur hexafluoride was detected.

4.3 AIR SAMPLES

Atmospheric samples have been taken during the study. The method of sampling was to fill the sample bottles with water. At the sampling site the bottles were emptied ensuring that the air sample was collected at the desired location.

4.3.1 IoH

To determine the variability of atmospheric sulphur hexafluoride samples of air were taken on thirty separate days over a two year period from outside the Institute building. On several days samples were taken throughout the day to test for any diurnal variations in sulphur hexafluoride concentrations.

Samples taken during a single day showed fluctuations of a random nature. The range of variation mainly fell within ten percent of the mean value. However on one day a large variation in the sulphur hexafluoride concentrations was found. Over a half hour period five samples showed a steady fall from over 9.8 ng/l to less than 4.4 ng/l. During the following two hours there were only the usual random fluctuations. This may have been part of the falling limb of an atmospheric pollution plume of sulphur hexafluoride.

Daily means were more variable. The data show no seasonal trends although the distribution of sampling was not regular throughout the year. These daily means ranged from 2.28 ng/l to 12.0 ng/l with the mean value of 6.4±2.4 ng/l.

4.3.2 Didcot Power Station

The CEGB have a large coal fired power station at Didcot, about ten kilometres west of Wallingford. As the CEGB are one of the main users of sulphur hexafluoride a sampling exercise was undertaken to determine any detectable increase in sulphur hexafluoride associated with the power station.

Samples were collected over a two hour period, from thirteen sites around the power station and one at IoH. Three sites were upwind varying from five kilometres to about two hundred metres from the power station. The remaining ten sites were between three and twelve kilometres downwind and over a spread of ten kilometres east to west.

The samples showed the usual background variation about a concentration of 6.1±1.4 ng/l. There were two samples outside this band, one higher and one lower. The high sample was downwind of the power station but the distribution of concentrations gave no clear pattern to indicate a significant contribution from the power station.

4.3.3 Samples adjacent to London; M25 Motorway

As part of the sampling programme the impact of a large city on background levels was investigated.

Samples were taken at fourteen points around the M25 motorway at interchange roundabouts. The exceptions to this were at South Mimms where the samples were taken in the service area close to junction 23 and at junction 5 where the sampling took place about half a kilometre south of the motorway.

Samples were taken at IoH and at junction 14 near Heathrow before and after the main sampling. At each site triplicate samples were taken. Both the repeat sample sites showed good agreement between the before and after samples taken five hours apart at Wallingford and three and a quarter hours apart at junction 14. The wind was light to moderate from the south to south-west when the samples were collected.

The western half of the motorway showed concentration varying from 2.7 to 4.1 ng/l. A distinct area of high concentrations appear in the eastern side (Figure 4.1). A maximum value of 9.8 ng/l was recorded at junction 28 downwind of the industrial areas of Dagenham and Purfleet. There was also a high value at junction 2, with the A2 road, south of the river. In general there was a definite pattern with higher concentrations of sulphur hexafluoride in the south-east and north-east quadrants of the motorway.

The two sampling exercises at Didcot and the M25 give instantaneous pictures of the spatial variability of sulphur hexafluoride concentrations in the atmosphere.

These levels of sulphur hexafluoride in the atmosphere do not present a problem in terms of background levels in water as the solubility coefficient means that water levels are about two hundred times lower than the air levels.

SULPHUR HEXAFLUORIDE AIR BACKGROUND ; M25 MOTORWAY

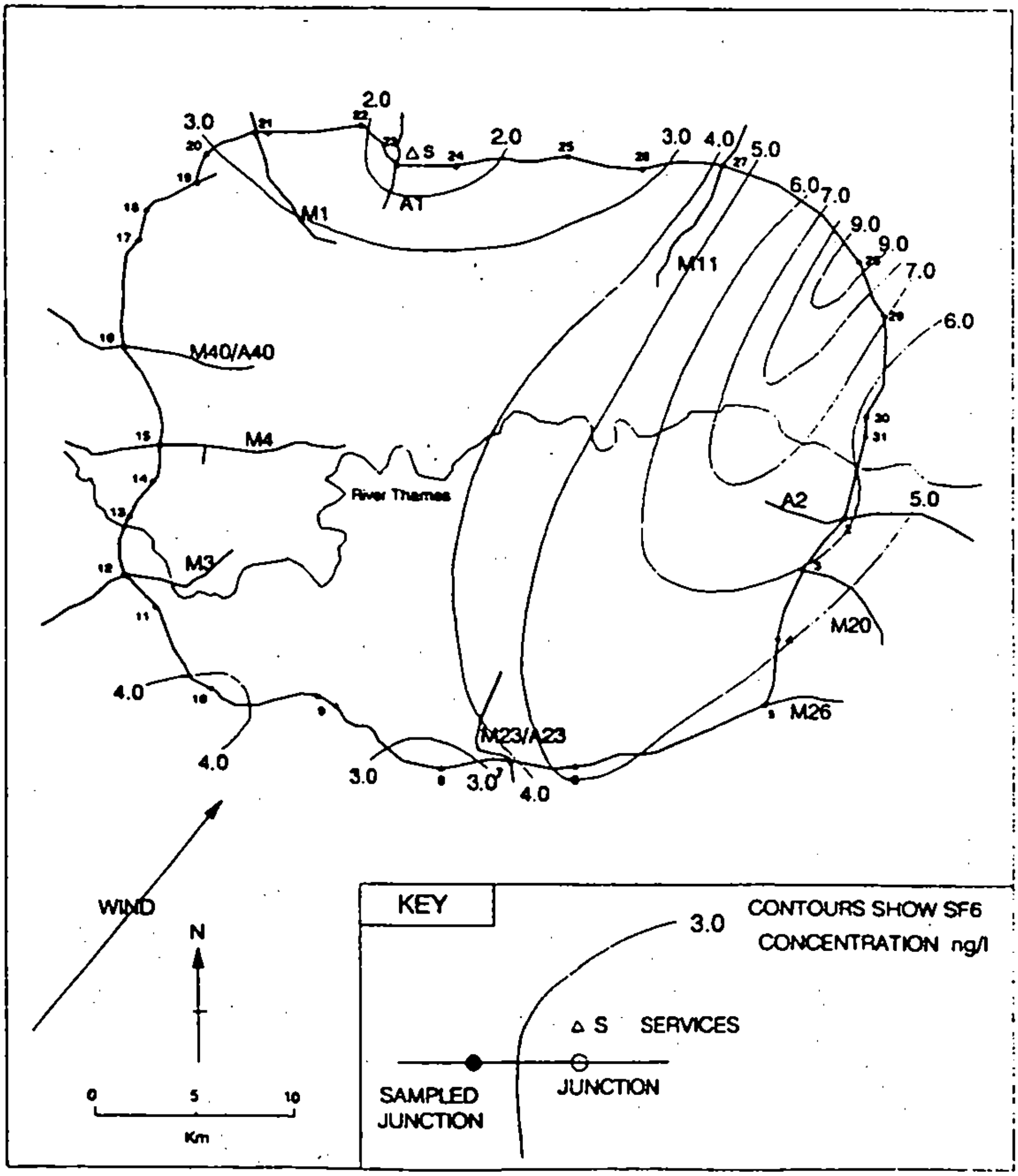


Figure 4.1

5. Field trials

5.1 INTRODUCTION

Field trials were planned in the three major aquifer groups found in Britain which are:

sands and gravels - intergranular flow
sandstones and chalk - intergranular and fissure flow
karstic limestone - fissure flow

A local site in sands and gravels formed an ideal area for testing methodology in an initial field trial of sulphur hexafluoride. Further field testing would then investigate shallow and deeper aquifers with an additional trial in karst formations.

The field programme adopted was:

unconfined gravel at Stanton Harcourt (test of methodology)
unconfined gravel at Wallingford, Oxon
confined chalk at Stoke Newington, London
karstic flow at Mendip Hills, Somerset
karstic flow at Tawe Valley, South Wales (provided the Mendip trial was successful)

The planned chalk site was a pumping test to be carried out by Thames Water at Stoke Newington in North London. However the test was indefinitely postponed and it proved to be impossible to find a suitable alternative site at a time when the water industry was preoccupied with the transition to privatisation.

The modified field programme carried out was:

unconfined gravel at Stanton Harcourt
unconfined gravel at Wallingford
confined gravel at Oxford
karstic flow at Mendip Hills

5.2 METHODOLOGY

In each trial at least one other tracer was used in addition to sulphur hexafluoride for purposes of comparison. The comparative tracers used were:

Stanton Harcourt - Rhodamine WT, chloride
Wallingford - Rhodamine WT, iodide, bacteriophage
Oxford - Rhodamine WT
Mendip Hills - Rhodamine WT

Table 5.1 gives the quantities of each tracer used in the trials.

Rhodamine WT is one of a group of fluorescent chemicals extensively used in groundwater tracing. They are relatively cheap and can be detected quickly and easily using a fluorometer. Rhodamine analysis was carried out by IoH and the Geography Department at Bristol University using Turner fluorometers as described by Wilson et al (1984).

Inorganic salts can be used for tracing as they are readily available and are relatively easy to detect. Samples containing the inorganic salts, (sodium) chloride and (potassium) iodide, were analysed by IoH, both ions were detected using colourimetric procedures. Chloride was determined by the standard mercuric thiocyanate/ferric nitrate method, while the iodide method involved the catalytic reduction of cerricions by arsenate (Truesdale and Smith 1975). Both these anions are known to be satisfactory tracers in sand and gravel aquifers.

The use of micro-organisms for tracing has tended to be restricted to contaminate modelling studies. However the use of bacteriophages, which are non-pathogenic to man and domestic animals, in groundwater movement studies is becoming more common. As IoH has no expertise in the specialised skills for handling and detecting biological agents the Robens Institute of the University of Surrey at Guildford undertook the bacteriophage tracer injection and sample assays. The techniques used are fully described by Skilton and Wheeler (1988).

For the trial at Wallingford deuterium, a stable isotope of hydrogen, was considered as an additional comparative tracer but calculations showed that it would have been much too expensive to use.

For all field trials a solution, using undiluted sulphur hexafluoride, was made up at IoH as described in Section 2.4. A quantity of the solution was decanted into a sealed container and taken to the test site. The predetermined quantity was then injected and a small sample of the solution was taken to determine the injected concentration.

The method of injection was to tremie the tracers into the borehole below the water surface. Injections were made by placing a pipe from the surface down to the centre of the saturated screened section and pouring in the tracers; water was then added to ensure the tracers had been flushed into the borehole. The tube was withdrawn until the end was located at or just below the water surface. Water was then slowly added to the borehole for some time so that a slight positive head was maintained. This encourages the migration of the tracers out of the borehole and into the aquifer.

Water samples were obtained by means of a simple hand vacuum pump. The sample was then quickly sealed in a McCartney bottle, a glass bottle with a screw cap having a rubber insert. Tests were carried out to make sure that the reduced pressure did not cause degassing. Care was taken to avoid cross contamination of boreholes by either using separate equipment for each borehole or carefully cleaning the equipment between samples. In addition at least one flask full of water was taken and discarded before the actual sample was taken.

Table 5.1 Quantities of Tracer Used

		Stanton Harcourt	Wallingford	Oxford	Mendip 1	Mendip 2
Sulphur hexafluoride	conc(g/l)	0.0108	0.0367	0.0162	~0.03	~0.025
	mass(g)	5.08×10^{-2}	5.14×10^{-3}	2.92×10^{-4}	0.06	0.27
	volume(l)	4.70	0.14	0.014	1.85	10.8
Rhodamine WT	conc(g/l)	238	238	238	238	238
	mass(g)	11.9	3.33	0.71	71.4	59.5
	volume(l)	0.05	0.014	0.003	0.30	0.25
Chloride Cl'	conc(g/l)	100				
	mass(g)	1950 (1)				
	volume(l)	19.50 (1)				
Iodide I'	conc(g/l)		680			
	mass(g)		692 (2)			
	volume(l)		1.018 (2)			
Bacteriophage	conc(pharge/ml)		9.8×10^{11}			
	volume(l)		10.0			

(1) calculated quantities from concentration and mass of 3000g of NaCl

(2) calculated quantities from concentration and mass of 1000g of KI

Ideal minimum concentrations:

Sulphur hexafluoride	1.0×10^{-8} g/l
Rhodamine WT	5×10^{-7} g/l
Chloride	0.1 g/l
Iodide	4×10^{-5} g/l

LOCATION OF GRAVEL TRACING SITES

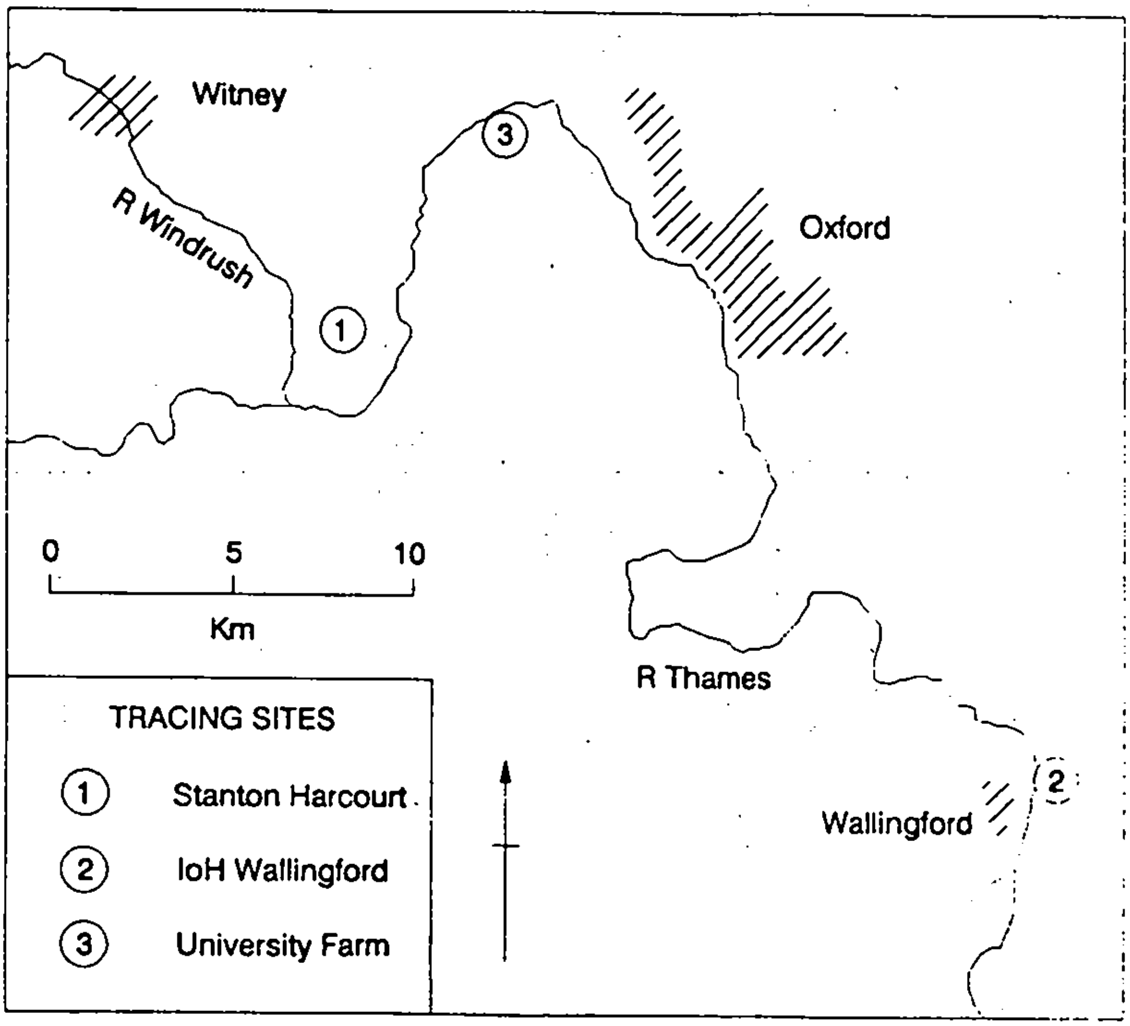


Figure 5.1

Sampling tests revealed a tendency for uptake of sulphur hexafluoride by the rubber seals in the sample containers particularly at high concentrations. In using sulphur hexafluoride as a tracer any sealing caps must be new and discarded after use.

5.3 INTERPRETATION OF RESULTS

The conventional method of presenting tracing results is graphical using breakthrough curves showing time since the injection on the horizontal axis. The vertical axis can be either the concentration of the tracer or the ratio, C/Co, which is the sample concentration corrected for any background present, C, divided by the original concentration Co.

Three criteria are used in the analysis of tracer breakthrough curves (Davis *et al*, 1985):-

a) The time of first arrival of the tracer. This represents movement through the easiest and fastest route in the aquifer.

b) The shape of the curve. This is the most important criterion in demonstrating a good tracer. A sharp main peak followed by a rapid fall is indicative of a good tracer with the shape indicating that there is little delay or interaction of the tracer with the aquifer material. An extended peak and high tail shows that the tracer is held back by interaction and is slowly flushed through by the moving water. Such a tracer is not likely to be conservative and could be subsequently lost by sorption.

c) The area under the curve. A high area indicates a high recovery. However, with periodic spot sampling, this is difficult to determine in a tracer where the peak is very sharp. Related to the area is the centroid time which is the time taken for half the mass of the tracer to be recovered and indicative of the mean speed of the water molecules.

The flow paths of water in an aquifer are complex. There are different paths with different velocities so that in an inhomogeneous system, particularly where there is a fissure component, the distribution of a perfect tracer is not necessarily shown as a single sharp peak. This complicates the interpretation of the breakthrough curves but in multiple investigations it should affect all the tracers in a similar way.

5.4 INTERGRANULAR FLOW

5.4.1 The gravel aquifers

The three intergranular flow trial sites lie on the First or Floodplain Terrace of the River Thames (Figure 5.1) and comprise mainly Devensian braided river deposits. These have been described for Brown's Pit at Stanton Harcourt (Briggs et al, 1985) and for Cassington Pit, located half a kilometre north of the University Farm site at Oxford, (Dixon, in press).

The bulk grading characteristics allow all three sites to be classified as 'very sandy gravels' according to BS5930 (1981). The gravels in the vicinity of Brown's Pit are finer with less than four millimetre dominant than those in the Cassington area (>4mm dominant). The gravels at the Wallingford site are 'muddy very sandy gravel' and contain a clay fraction.

The gravels at all three sites are described as rounded oolitic limestone gravels with a quartz sand matrix. The limestone pebbles tend to be elongated or flaky and lie with the long axes horizontal but often display imbricate structure (the long axes at an angle and parallel to each other). While the gravels at Brown's Pit are predominantly limestone those at Cassington have an additional ironstone and quartzite input. The gravels at Wallingford have an angular flint input from the tributaries of the Ock and Thame to give a composition of about twenty per cent flint.

5.4.2 Stanton Harcourt

The first field trial was carried out near the village of Stanton Harcourt in Oxfordshire. The object of the trial was to ascertain that it was possible to inject a solution of sulphur hexafluoride in one borehole and recover a sample containing sulphur hexafluoride from one or more adjacent boreholes. The trial would be regarded as an experiment to ensure that the methodology would apply to field conditions and, if necessary, modify it.

The site, located about ten kilometres west of Oxford, is an actively worked gravel pit, Brown's Pit, owned by ARC Ltd. The pit is being worked dry and had been in operation for at least five years. Continuous pumping has generated steep groundwater gradients adjacent to the pit. First trials were designed to benefit from this artificial but fast moving groundwater flow.

Brown's Pit is located on the Floodplain Terrace of the River Thames near the confluence with the River Windrush (Figure 5.2). The geology comprises less than a metre of soil and subsoil and this is underlain by about four metres of floodplain gravels. The whole area is underlain by Jurassic Oxford Clay forming an impermeable base of the aquifer. At the foot of the pit face at the contact between the gravels and the clay a seepage line has formed. In some places there are distinct points of discharge. The top and subsoil have been removed in a strip about forty metres wide back from the face prior to extraction. The structure of the gravels is one dominated by massive and horizontally bedded gravels with thin but persistent mud drape layers.

An array of eight boreholes was drilled back from the pit face. The boreholes were arranged in two lines of three parallel to the face with the two other boreholes extending the centreline away from the face (Figure 5.2). The most distant hole was 20 m from the face and was used for tracer injection. Each borehole was constructed so that the casing was perforated from above the water table to the base of the aquifer. At the foot of the

STANTON HARCOURT TRIAL SITE

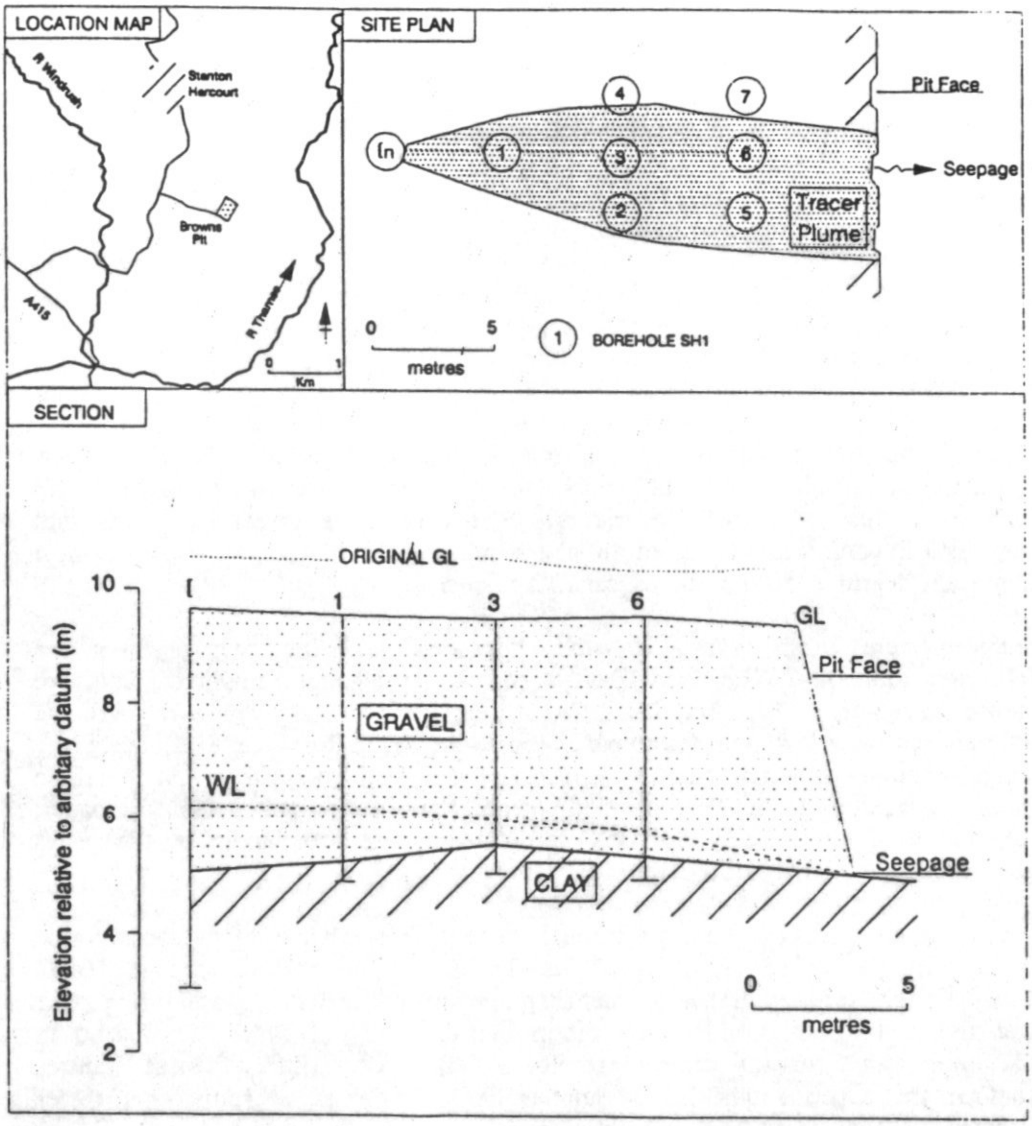


Figure 5.2

face on the centreline was a discharge point. The saturated thickness of the aquifer was approximately one metre at the injection point reducing to almost zero at the seepage face. This relatively thin zone meant that the free surface area to total water volume was high providing a test as to whether sulphur hexafluoride readily degasses from the surface under laminar flow conditions.

Tests to confirm hydraulic continuity between borehole and aquifer were conducted prior to the sulphur hexafluoride tracing by means of a short initial trial using (sodium) chloride. The chloride was detected in several of the boreholes confirming hydraulic connection.

Three tracers, sulphur hexafluoride, Rhodamine WT and (sodium) chloride, were introduced into the injection borehole (Table 5.1). A slight positive head was maintained for several hours to encourage movement of the tracers into the aquifer. Sufficient Rhodamine WT was used to allow for some tracer loss relative to sulphur hexafluoride. The amount of chloride used was limited since to provide sufficient tracer to equal the sensitivity of the other two tracers would induce distortion in the water flow due to density currents.

Plotting the curves with a vertical axis of [C/mass injected] shows very low levels of Rhodamine WT and chloride relative to sulphur hexafluoride. This indicates a loss of those two tracers. The curves are therefore shown with the vertical [C/C_0] axis adjusted to give similar peaks heights so that the most important features of the curves can be compared.

Samples were taken from the other boreholes and the seepage over the following four days. The breakthrough curves for all the sampling points are shown in Figures 5.3A and 5.3B. The tracers were detected in each borehole although in very low concentrations in borehole SH7. Borehole SH1, being the closest, shows all three tracers with clear well defined peaks. At borehole SH6, 15 metres from the injection point, the peaks had become broader, sulphur hexafluoride being the clearest defined. The broadening of the peaks had increased further at the seepage.

Visual examination of the breakthrough curves show that sulphur hexafluoride is the first tracer to arrive at all the boreholes and at the seepage (Table 5.2). Of greater significance is the sharpness of the sulphur hexafluoride peak and the rapid decrease in concentration in the peak tail which is reflected in the lower value for the centroid results in Table 5.2. Both of these features confirm the superior qualities of sulphur hexafluoride as a groundwater tracer relative to Rhodamine WT and chloride.

The Stanton Harcourt test, carried out over a period of 95 hours, and a distance of 20 m, showed that, even in a thin saturated zone where degassing could be a problem, sulphur hexafluoride was an excellent tracer. The results lead to the design of a more protracted field test at a Wallingford site using a longer distance and less tracer to simulate larger scale investigations.

5.4.3 Wallingford

The first rigorous tracer test was at Wallingford in an unconfined gravel site.

Stanton Harcourt Breakthrough Curves

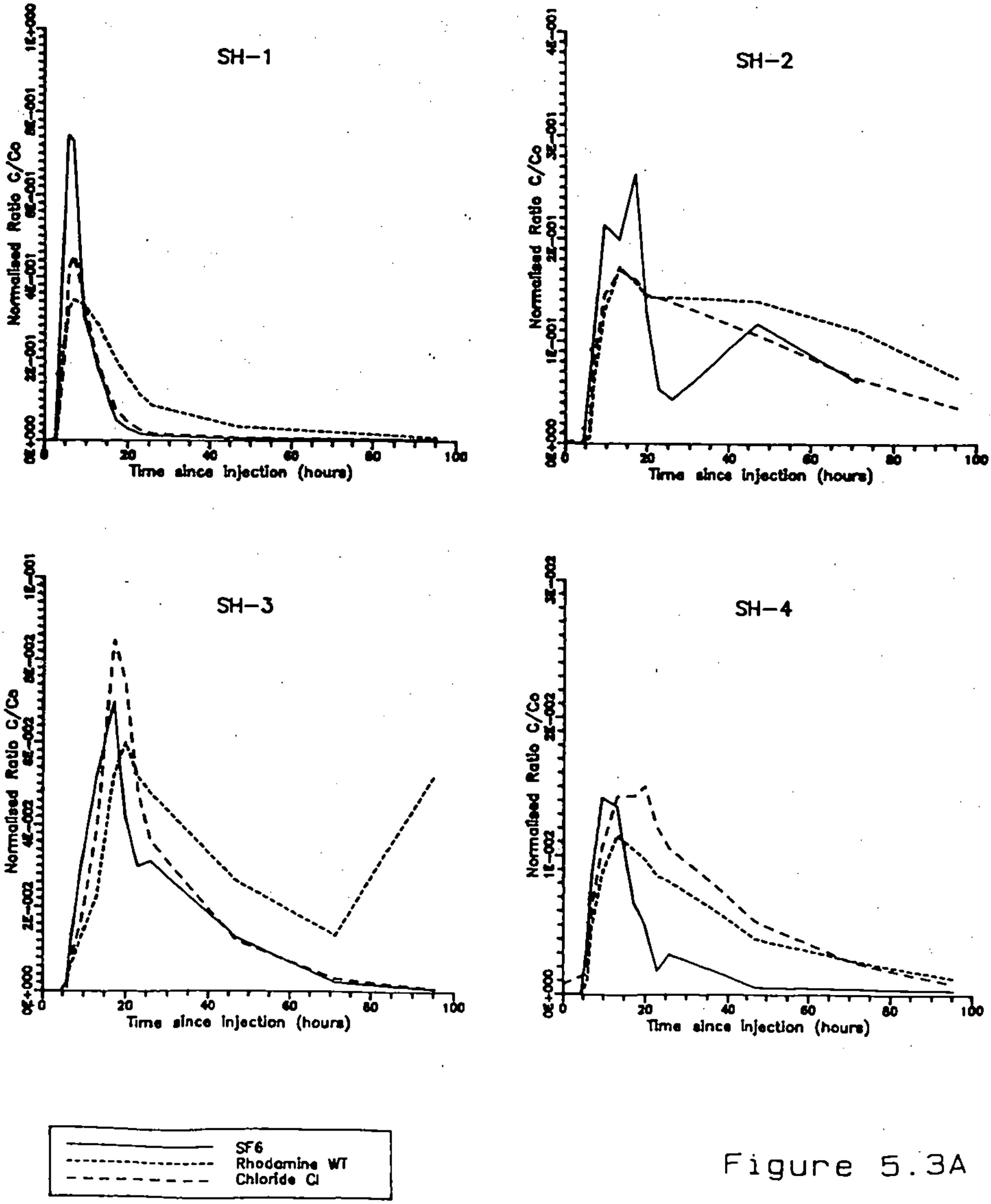


Figure 5.3A

Stanton Harcourt Breakthrough Curves

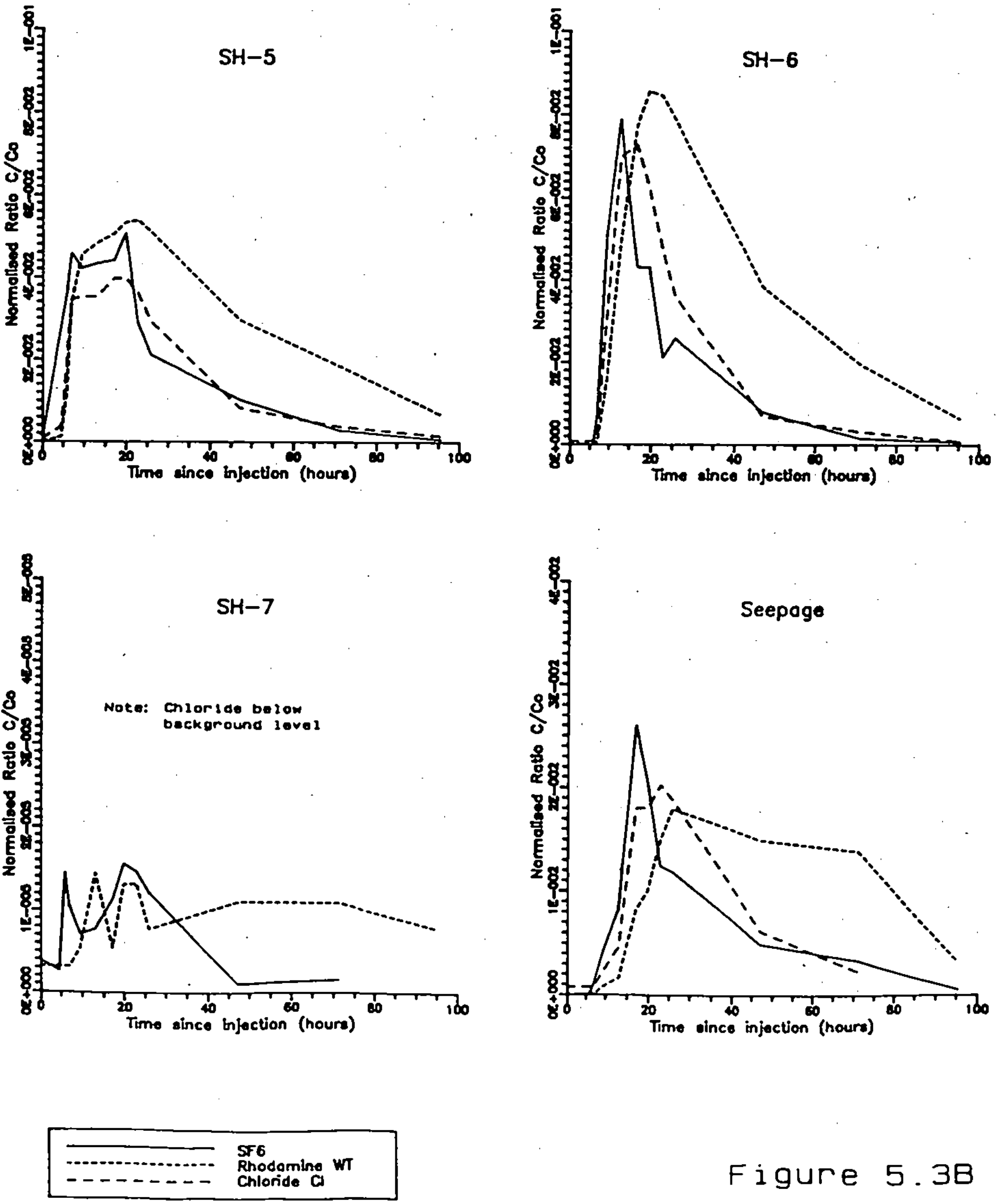


Figure 5.3B

Table 5.2 Stanton Harcourt, Field Trial Results

Well	Distance from injection (m)	Tracer	First Arrival (days)	Centroid (days)	Velocity (m/d)	
					First Arrival	Centroid
SH1	5.1	SF6	0.08	0.27	63.7	18.9
		Cl	0.15	0.42	34.0	12.1
		RhodWT	0.15	0.59	34.0	8.6
SH2	10.6	SF6	0.22	1.18	48.2	9.0
		Cl	0.27	1.93	39.3	5.5
		RhodWT	0.22	1.30	48.2	8.2
SH3	10.3	SF6	0.15	0.78	68.7	13.2
		Cl	0.27	1.02	38.1	10.1
		RhodWT	0.22	1.04	46.8	9.9
SH4	10.6	SF6	0.15	0.52	70.7	20.4
		Cl	0.27	1.16	39.3	9.1
		RhodWT	0.22	1.00	48.2	10.6
SH5	17.0	SF6	0.15	0.80	113.3	21.2
		Cl	0.22	1.03	77.3	16.5
		RhodWT	0.22	1.04	77.3	16.3
SH6	17.2	SF6	0.22	0.76	78.2	22.6
		Cl	0.27	1.00	63.7	17.2
		RhodWT	0.27	1.04	63.7	16.5
Seepage	20.0	SF6	0.25	1.89	80.0	10.6
		Cl	0.4	1.94	51.3	10.3
		RhodWT	0.4	2.46	51.3	8.1

The site was located in a field between the IoH site and the River Thames (Figure 5.4). Aquifer properties, aquifer configuration and ground water flow at the site are well known having been used for research over many years. An existing well was equipped with a pump and five observation boreholes constructed along a known flow line extending a distance of one hundred and twenty metres. An 80 day pumping test was planned to test the long term performance of sulphur hexafluoride in a water table situation where degassing of the tracer was possible.

The broad lithology of the Thames floodplain at Wallingford is about a metre of silt overlain by soil and subsoil. Below the silt are the sands and gravels of the floodplain which at the test site are about two to two and a half metres thick. These are underlain by a clayey sandy silt which is the weathered surface of the Cretaceous Greensand. Over the test site the water surface lies wholly within the sands and gravels. The structure of the aquifer is not known. Borehole logs, however, suggest a considerable variability in texture implying a high degree of heterogeneity. This variability is substantiated by a resistivity survey of the field. The boreholes were drilled to the top of the Greensand with the casing perforated below the water table. The thickness of the saturated zone was between one and two metres thus reducing any tendency for sulphur hexafluoride to degas.

An electric submersible pump was installed in the pump well. The discharge was monitored by means of an orifice plate with a totalising meter installed in the discharge pipe. The waste water was piped to the Thames about one hundred and fifty meters away. The well was pumped at 152 m^3/day.

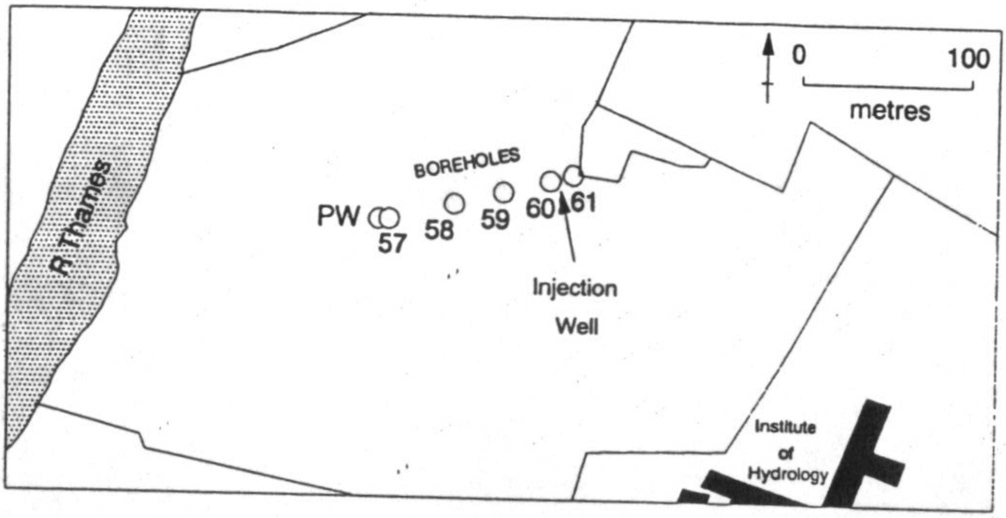
Borehole Wall-60 was selected as the site of the tracer injection as the unusual very shallow gradient existing at the start of the trial would have greatly extended the trial time. After the pump had been running for twenty four hours to establish the cone of depression a mixture of sulphur hexafluoride and three comparative tracers was injected in the observation well one hundred metres from the pump well. The comparative tracers used were Rhodamine WT, (potassium) iodide and a bacteriophage (*Serratia marcescens*). Details are given in Table 5.1. Relative to sulphur hexafluoride an excess of Iodide and Rhodamine WT were added to try and ensure that, in the event of tracer loss, sufficient remained to compare with sulphur hexafluoride.

Sampling from the pump well and the observation wells took place over the following eighty days. Samples for biological assay were collected during the first thirty nine days. Sterile bottles were used for the bacteriophage samples which were kept refrigerated until being sent in batches to the Robens Institute for assay. The pump well was sampled for all the tracers using a vacuum line located about half a metre from the base of the aquifer. The pump discharge was also sampled for sulphur hexafluoride. The trial period coincided with a dry period when only 84.3 mm of rain fell in the entire eighty days of the trial (70% falling in the last quarter of the test).

The breakthrough curves are shown in Figure 5.5. The breakthrough curves for Wall-59 display a clear well defined peak of sulphur hexafluoride which has been truncated to allow the lower concentrations to be shown more clearly. However the results for Wall-58 and Wall-57 show that the Rhodamine WT has nearly all been lost while the curves for sulphur hexafluoride and iodide are greatly attenuated.

WALLINGFORD TRIAL SITE

SITE PLAN



SECTION

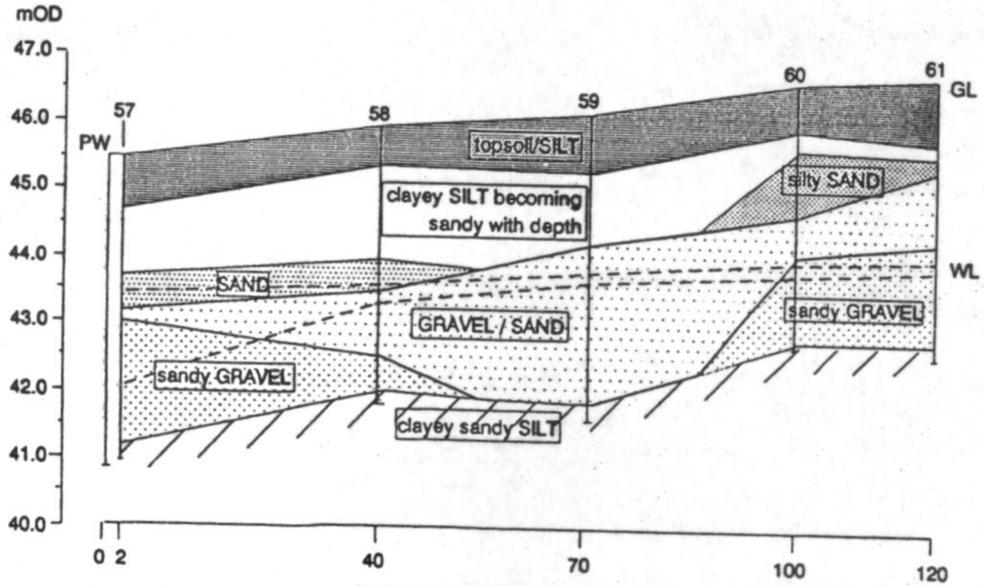


Figure 5.4

Wallingford Breakthrough Curves

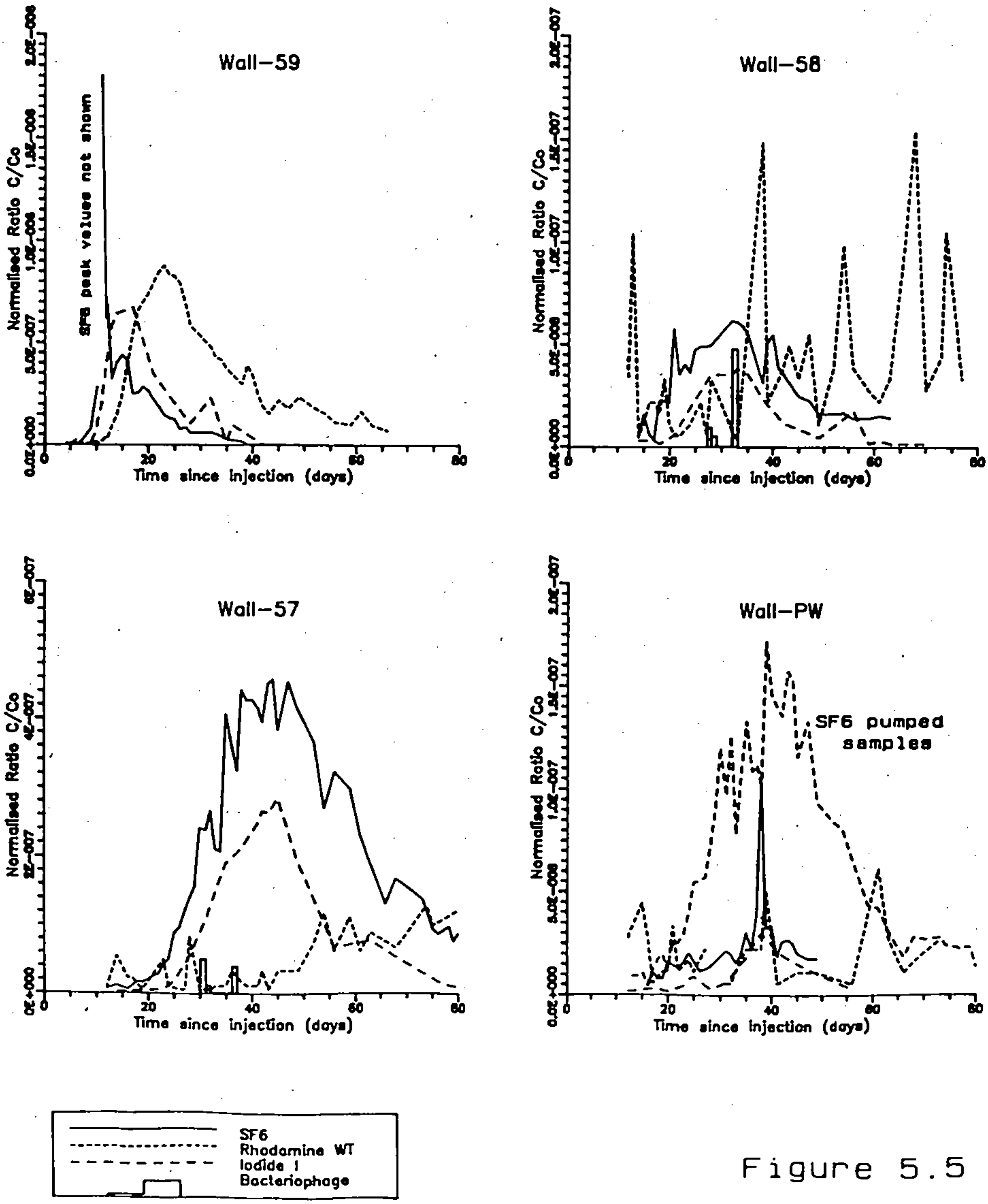


Figure 5.5

The pump well breakthrough curves indicate very low levels for the vacuum taken samples while the sulphur hexafluoride curve for the pump discharge is at higher concentrations and better defined. The probable explanation is that the tracer entered the borehole through one or more paths of preferential flow and was swept into the pump and discharged before it had an opportunity to mix with the other water in the well. It is unfortunate that the pump discharge was not sampled for all the tracers but the difference between the vacuum and discharge samples was not found until it was too late.

The bacteriophage was recorded only in a limited number of samples from Wall-57 and Wall-58 having apparently by-passed Wall-59. This may have been due to the filtering effect of the sand content in the aquifer.

The results of the velocity calculations are given in Table 5.3. As with Stanton Harcourt sulphur hexafluoride gave higher first arrival velocities than the other tracers. But, apart from Wall-59, the centroid velocities for all the tracers, except the bacteriophage, were similar. Wall-58 showed low concentrations of tracers and was probably not on the main flow path. The extended and complex peaks, which have similar shapes in Wall-57 and the pump discharge reflect the complex flow paths which become evident over a distance of 100 m. The ratios of the peak values of the three tracers in Wall-57, related to the mass of tracer injected show values for sulphur, Rhodamine and Iodide of 1.0, 0.006 and 0.01 respectively. This indicates the extent of loss of the conventional tracers, particularly Rhodamine, relative to sulphur hexafluoride.

Using the formula:

$$v = \frac{T\Delta h}{m.S}$$

where:

v = groundwater velocity (m/day)
T = transmissivity (m^2/day)
Δh = groundwater gradient
m = saturated thickness of the aquifer (m)
S = storage coefficient

it is possible to calculate the storage from the tracer velocities provided that the transmissivity, gradient and saturated thickness are known. The aquifer characteristics were determined from a conventional pump test which subsequently took place and gave a transmissivity of 100 m^2/d. The results of the storage calculations are given in Table 5.4 together with the storage determined from the pump test and column drainage experiments.

Both the pump test and tracers give high values of storage for Wall-57; however the mean storage values are in excellent agreement. The storage calculated from the pump test for Wall-58 is about half the mean tracer value but close to the sulphur hexafluoride value. The storage values given for Wall-59 are similar for the mean pump test values if Wall-57 is discounted. A core taken from a borehole drilled about two metres from the pump well gave a storage close to the mean which would perhaps indicate the high values from Wall-57 may be due to the small saturated thickness or the close

Table 5.3 Wallingford, Field Trial Results

Well	Distance from injection (m)	Tracer	First Arrival (days)	Centroid (days)	Velocity (m/d)	
					First Arrival	Centroid
Wall-59	29.9	SF6	5.2	11.1	5.7	2.7
		I	8.0	16.8	3.7	1.8
		RhodWT	10.7	18.5	2.8	1.6
		Bact.	-	-	-	-
Wall-58	59.1	SF6	14.0	33.4	4.2	1.8
		I	19.5	34.2	3.0	1.7
		RhodWT	(23.4)	52.2	2.5	1.1
		Bact.	26.6	-	2.2	-
Wall-57	97.1	SF6	12.1	46.2	8.0	2.1
		I	20.5	44.7	4.7	2.2
		RhodWT	(22.4)	55.7	4.3	1.7
		Bact.	29.5	-	3.3	-
PW (vacuum)	98.9	SF6	14.1	37.1	7.0	2.7
		I	21.4	38.8	4.6	2.5
		RhodWT	-	36.8	-	2.7
		Bact.	-	-	-	-
PW (discharge)	98.9	SF6	13.0	42.0	7.6	2.4

Table 5.4 Wallingford, Aquifer Storage - Wallingford

PUMP TEST RESULTS

WELL	Theis		Jacobs		Mean
	T m^2/d	S %	T m^2/d	S %	S %
Wall-57	99	42.0	98	46.0	44.0
Wall-58	106	16.7	100	15.3	16.0

TRACER RESULTS

First arrival (assuming T = 100 m^2/d)

Well	SF6 %	Iodide %	RhodWT %	Bact. %	Mean %
Wall-57	25.5	43.4	47.4	61.8	44.5
Wall-58	19.5	27.2	32.7	37.1	29.1
Wall-59	6.7	10.4	13.7	-	10.2

COLUMN DRAINAGE RESULT

Core taken between 2-3m at 2m from Pump Well equivalent to Wall-57 13%

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proximity of the pump well. In all the boreholes the storage calculated from the sulphur hexafluoride velocity was about sixty percent of the value calculated from the iodide which was the most reliable comparative tracer.

As there was pumping being carried out it is possible to calculate the percentage of the sulphur hexafluoride recovered which totalled 44% of the injected mass.

The trial at Wallingford was a success. The sulphur hexafluoride was being detected in the groundwater samples eighty days after injection. This indicates that degassing in laminar (non-turbulent) flow conditions is not a serious problem. The peak concentrations of sulphur hexafluoride in Wall-59 show that it is a much more conservative and successful tracer than Iodide or Rhodamine WT, which was very poor, in a sand and gravel aquifer. The storage calculated from the sulphur hexafluoride arrival times is in good agreement with that calculated by traditional pump test; and is much better than the results using the conventional tracers.

5.4.4 University Farm, Oxford

A confined situation is similar to many deep aquifers and as the water is not in free connection to the surface there is less likelihood of degassing. After the cancellation of the chalk pumping test an investigation was undertaken in a confined gravel aquifer which would give the best simulation of a deep aquifer.

A suitable confined site was located on the University Farm and Field Station (UFS) belonging to Oxford University (Figure 5.6). The broad lithology of the site is about half a metre of top soil and clay overlying between one point four and two metres of very soft mud (Figure 5.7). The junction of the mud and aquifer is complicated by discontinuous layers of muddy sands, muddy gravels and extending across part of the site a layer of organic material varying from peat through peaty sand to peaty silt. The aquifer, between one point eight and four metres thick is a muddy sandy gravel. The aquifer is underlain by the Oxford Clay. The mud acts as a confining layer with the piezometric surface lying within it over the entire site.

The gravels in the Cassington area have been subdivided into three elements. Element A is an upper muddy sandy layer overlying the clean Element B gravels. The lowest element, C, is a muddy gravel probably not present at the tracing site. The Element B gravels in the Cassington Pit are characterised by massive horizontally bedded 'bar gravels' with thin openwork gravel and coarse sand layer. These generally overly channel and bar facies with thicker openwork gravel layers.

The approximate groundwater configuration was determined by hand auger and an array of nine boreholes planned. After the boreholes had been installed and levelled the piezometry configuration was found to be incorrect, and a further two boreholes, UFS79 and UFS80, were added to the array (Figure 5.6). The hydraulic gradient was away from the river and UFS80 was used for injection.

A mixture of sulphur hexafluoride and Rhodamine WT was injected in

UNIVERSITY FARM TRIAL SITE AND PIEZOMETRIC SURFACE

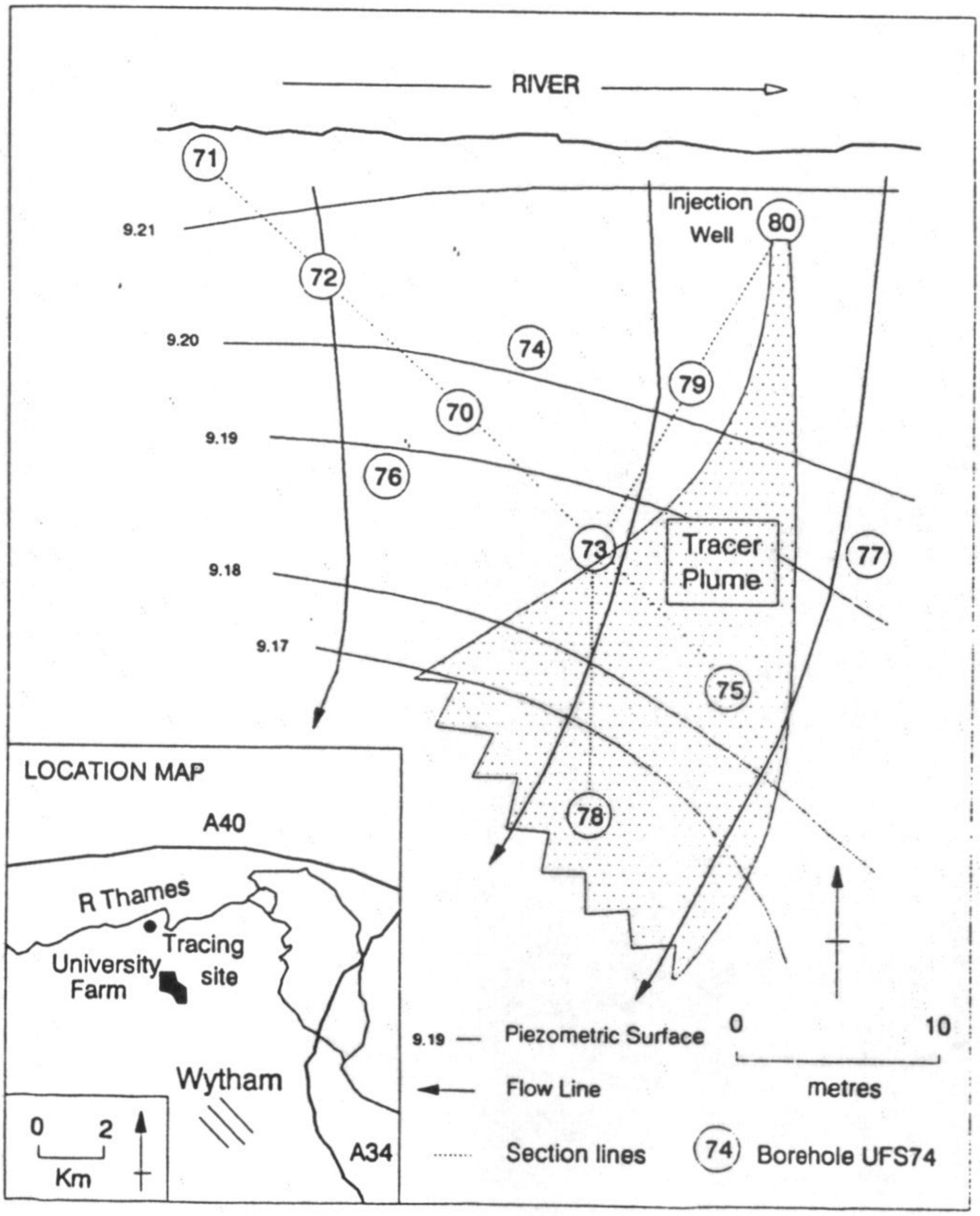
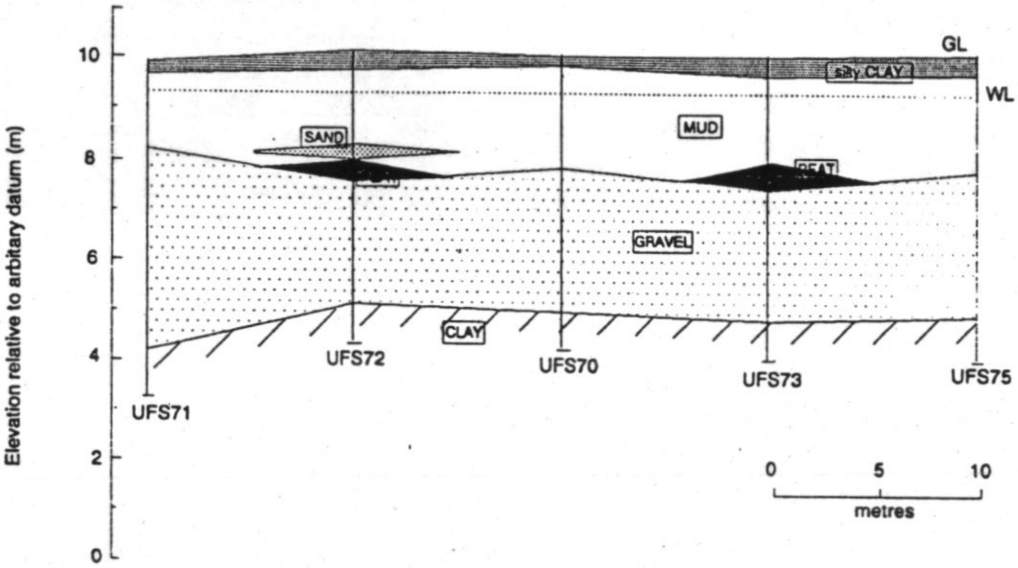


Figure 5.6

UNIVERSITY FARM SECTIONS

UFS 71 - 75



UFS 80 - 78

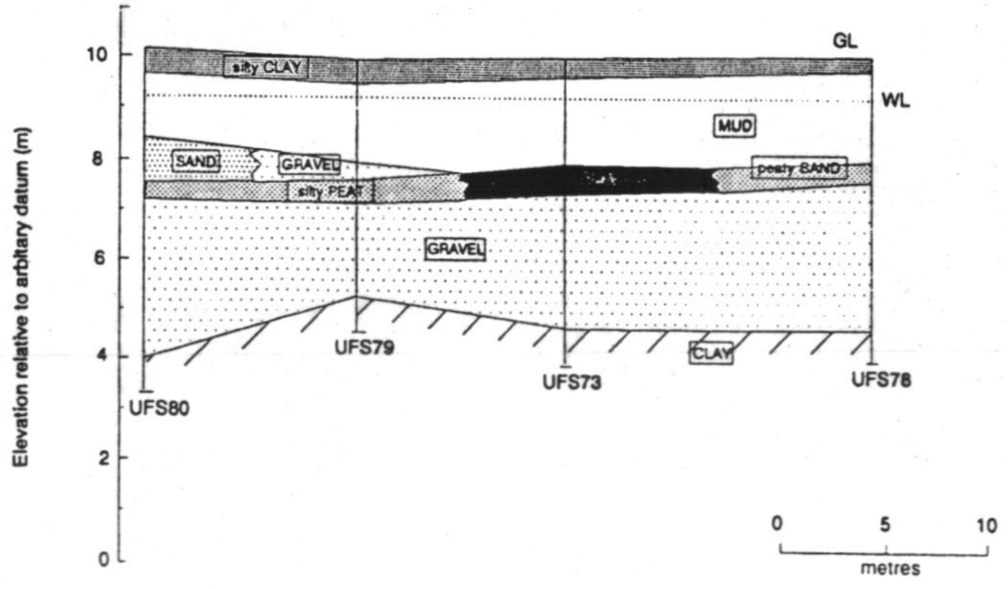


Figure 5.7

borehole UFS80 (Table 5.1). The other boreholes were sampled for the following forty eight days. Tracer was detected only in boreholes UFS73, 75 and 78 (Figure 5.8).

The breakthrough curves show that UFS78 is on the main flow path while UFS73 is peripheral. The maximum and mean velocities are based on the first arrival time and the time to the centroid (Table 5.5). Sulphur hexafluoride showed more rapid breakthrough than Rhodamine WT with a much more pronounced peak with a lower tail. The maximum tracer concentration at the peak for UFS78 related to the mass of tracer used shows that the sulphur hexafluoride to Rhodamine ratio is 1:0.014 showing a loss of Rhodamine tracer.

As in the other intergranular low flow tests sulphur hexafluoride proved to be a superior tracer to Rhodamine. This is based on more rapid breakthrough, a sharper peak with low tail and much higher peak concentration than Rhodamine.

5.5 KARSTIC FLOW

5.5.1 Introduction

As one of the uses of groundwater tracers is to determine interconnections and transit times in karstic fissure systems two sites in karstic areas were selected for trials. These were in the Mendip Hills near Cheddar in Somerset and in the River Tawe valley near Penwyllt, about forty kilometres north east of Swansea in South Wales.

The Penwyllt site contrasts with the Mendip site in that only approximately ten percent of the flow channel is water filled compared to over eighty percent at the Mendip site. As turbulent flow occurs at both sites there would be a much greater opportunity for the sulphur hexafluoride to leave solution at Penwyllt. Both sites have been traced on previous occasions.

5.5.2 Mendip Hills

The cave system selected for the first karstic experiment was the Longwood to Cheddar rising system. The distance between the sinks at Longwood and the resurgence at Cheddar is some 2.7 km. The system can be followed below ground for about 360 m before becoming impossible to follow; the course is then unknown. It is estimated that between 85% to 90% of the system is water filled (Smart and Hodge 1981) thus allowing less opportunity for the sulphur hexafluoride to be lost from solution.

This system was chosen as a large number of fluorescent dye tracings have been carried out on it. As a result the connection between sink and resurgence is well documented as is the relationship between stream discharge and travel time (Smart 1981) which helped in planning the sampling

University Farm Breakthrough Curves

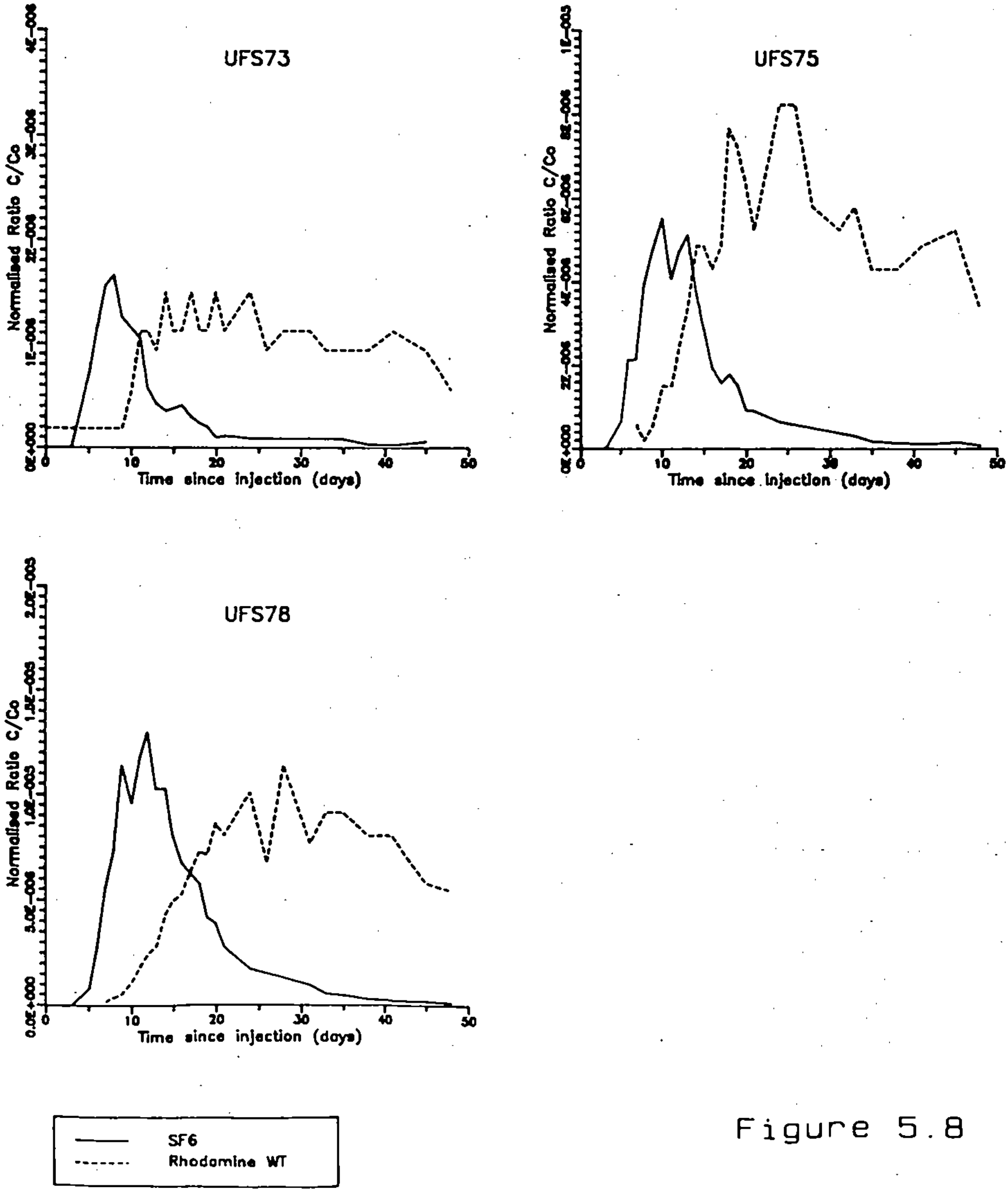


Figure 5.8

Table 5.5 Oxford, Field Trial Results

Well	Distance from injection (m)	Tracer	First Arrival (days)	Centroid (days)	Velocity (m/d)	
					First Arrival	Centroid
UFS73	20.0	SF6	4.0	8.86	5.0	2.3
		RhodWT	9.5	31.25	2.1	0.6
UFS75	24.5	SF6	4.0	11.68	6.1	2.1
		RhodWT	6.5	32.28	3.8	0.8
UFS78	33.0	SF6	4.0	12.41	8.2	2.7
		RhodWT	8.4	34.60	3.9	1.0

SF6 arrival between 3.04 days and 5.06 days

Well	Velocity (m/d)			
	Min (5.06d)	Max (3.04d)	Mean (Max/Min)	Mean (4.0d)
UFS73	4.0	6.6	5.3	5.0
UFS75	4.8	8.1	6.4	6.1
UFS78	6.5	10.9	8.7	8.2
Mean	5.1	8.5	6.8	6.4

programme.

The Longwood swallet lies on the southern flank of the Black Down (Old Red Sandstone) at the junction of the relatively impermeable Lower Limestone Shales and the purer Black Rock Limestone of the Carboniferous Limestone Series. There are several swallets along the floor of the Longwood Valley into which the surface stream sinks. The valley continues dry beyond the final sink and joins the head of Cheddar Gorge at Black Rock Gate (Figure 5.9).

The water emerges in a series of springs at the foot of the Gorge at the junction of the Hotwells Limestone with the underlying mudstones of the Clifton Down Limestones (Green and Welch 1965). The resurgence consists of two main springs known as First and Second Feeder and a series of springs which emerge in the small artificial lake owned by the Bristol Water Company. The spring sampled was First Feeder and is the one highest up the Gorge located close to one of the show caves. During the tracing discharges were measured by current meter.

5.5.2.1 Mendip 1 trace (high flow)

In March 1989 an injection of saturated sulphur hexafluoride solution and Rhodamine WT was made at Longwood (Table 5.1). The discharge of the stream at Longwood was measured and found to be 57 l/s. An estimated first arrival time of about 20 hours was determined from graphs given in Smart, (1981).

The First Feeder spring was sampled at intervals of 2 to 4 hours from 14 hours after injection until 71 hours after injection. A frequent sampling period was maintained as previous work indicated a relatively short well defined peak. At each sampling duplicate samples were collected for sulphur hexafluoride and Rhodamine WT analysis. Discharge measurements of the Longwood stream varied from about 60 l/s to a flood of 470 l/s which occurred about 41 hours after injection.

The samples were analysed for sulphur hexafluoride and Rhodamine WT. Sulphur hexafluoride was detected at low concentrations in only two samples taken at 22 hours (0.9 ng/l) and 27 hours (0.7 ng/l) after injection. The Rhodamine WT appeared as a double peak (Figure 5.10). The reason for the shape of the graph, which only occurs at high discharges, is thought to be two separate stream pathways having different travel times. This effect is not seen at low flows when the graph is of a much more attenuated form so that different travel times merge into a single peak.

As the Rhodamine appeared in the samples and not the sulphur hexafluoride it was concluded that either the gas had left solution, possibly because of the high discharges occurring at the time, or that insufficient tracer had been used.

5.5.2.2 Mendip 2 trace (low flow)

In June 1989 the Mendip tracing was repeated using a greater volume of saturated solution (Table 5.1). The injection of Rhodamine WT and 10 litres

MENDIPS TRIAL SITE

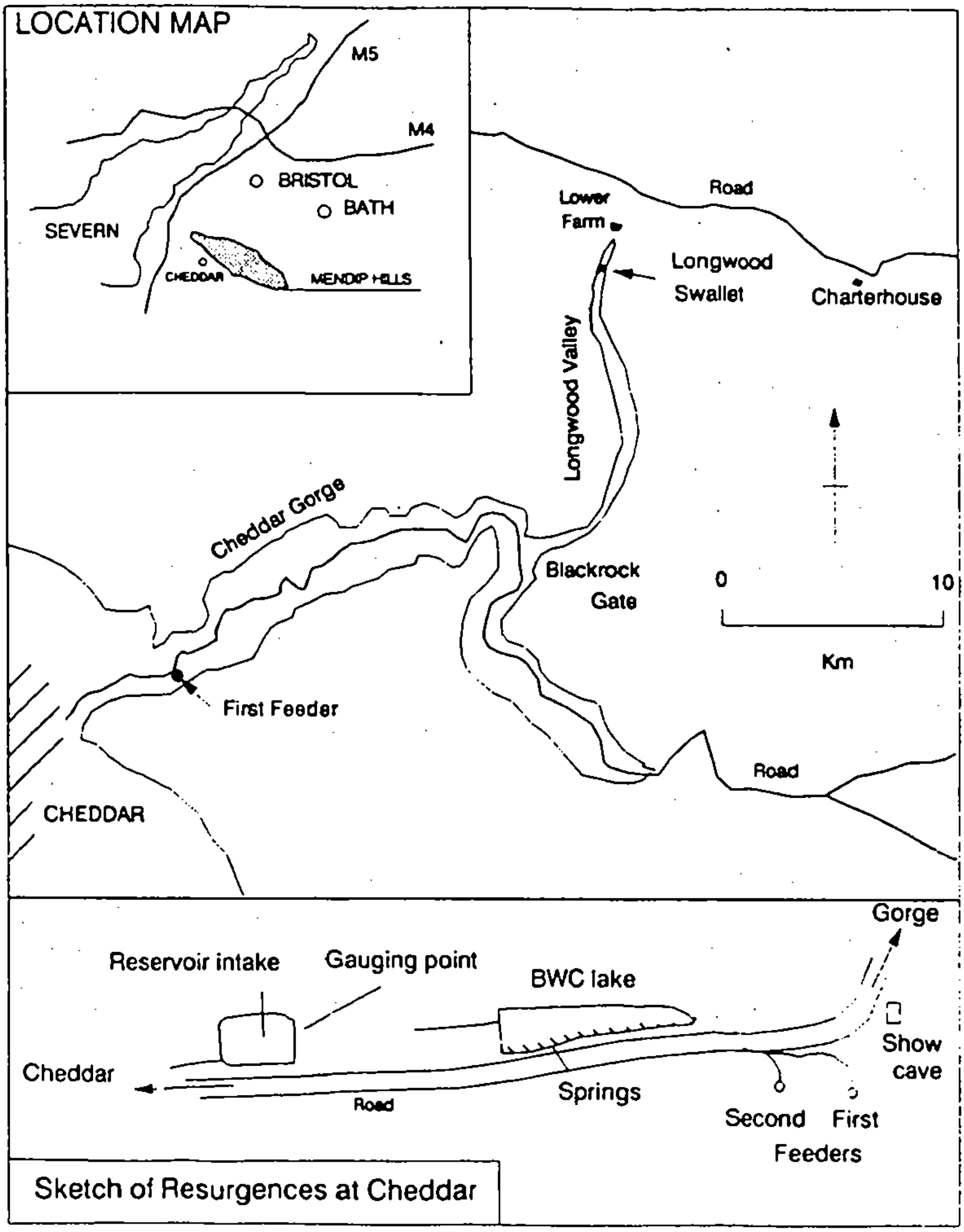


Figure 5.9

Mendips Breakthrough Curves

(Rhodamine WT)

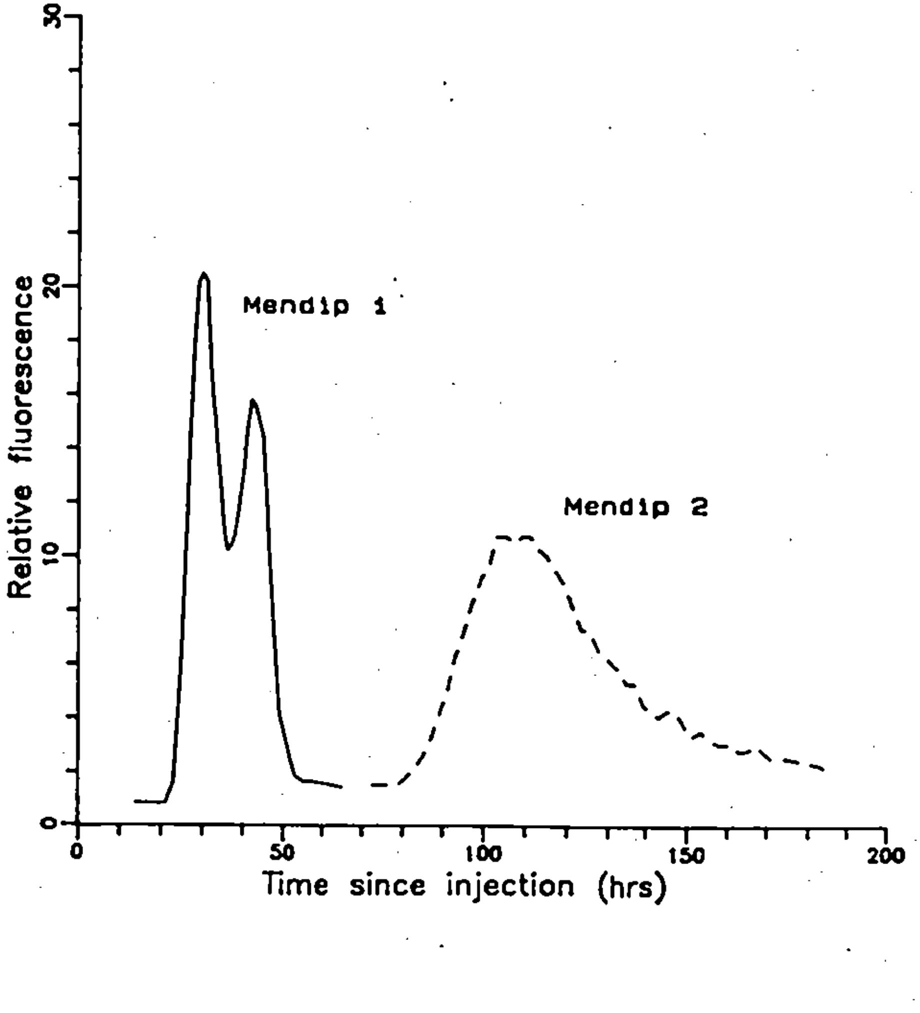


Figure 5.10

of sulphur hexafluoride solution compared with the previous value of 1.8 litres took place at Longwood.

The First Feeder spring was again sampled. The sampling interval was approximately every 4 hours from 24 hours to 186 hours (7.8 days) after injection. The discharge of the resurgence was measured at the Cheddar reservoir intake downstream of the artificial lake. The discharges measured during the tracing showed a recession, with the flow falling from 390 l/s at the time of injection to 270 l/s at the conclusion of the trial. The discharge of the Longwood stream was too low to gauge accurately.

The Rhodamine analysis showed a very much attenuated peak of the expected low flow form. Again there was no significant sulphur hexafluoride in the samples collected.

As the two tracing experiments, which were carried out in contrasting flow regimes, did not have any significant levels of sulphur hexafluoride no further trials in karstic conditions were undertaken. Therefore the plans for trials at Penwyllt in South Wales were abandoned.

It must be stressed that many of karstic systems have turbulent flow conditions and reaches with open air surfaces comparable with upland surface streams with waterfalls and rapids. As such they represent the opposite extreme to the laminar flow conditions encountered in most aquifers, such as the gravels. In the vicinity of pumping wells turbulent flow may exist.

6. Conclusions and Recommendations

6.1 CONCLUSIONS

Sulphur hexafluoride is an excellent groundwater tracer for sand and gravel aquifers containing clay. It is markedly superior to conventional dye and halide tracers and the successful evaluation indicates a major step forward in tracing technology.

Its advantages over other tracers include:-

a) a very conservative tracer with much less loss by sorption or chemical interaction with the aquifer matrix than either Rhodamine WT or Iodide.

b) very high sensitivity of detection (5×10^{-10}g/l) enabling large studies to be undertaken with small amounts of tracer. Inexpensive.

c) very low natural background. Air background is measurable and somewhat variable but the background in water is below the measurable limit.

d) non-toxic and inert

e) rapid and easy to measure by conventional chemical techniques although a dedicated analytical system is required. The system developed can determine 50 samples per day.

A disadvantage is that its use is limited to aquifers where flow is laminar. In turbulent flow in open channels, as in karstic limestone, it is lost by degassing. It would not be suitable for studies in the unsaturated zone.

6.2 RECOMMENDATIONS

The results of the trials clearly indicate that sulphur hexafluoride should be exploited further as a new tracer.

The programme should include:-

a) Field trials in the chalk. Preliminary laboratory results indicate that sulphur hexafluoride should be as conservative in this aquifer as it is in sand/gravel but this can only be demonstrated by an extensive field programme. A major test pumping application to replace the Stoke Newington trial is strongly recommended.

b) laboratory and field tests with land fill material. An examination of any interaction between plastics and sulphur hexafluoride is particularly relevant to the application of this tracer to flow pathway studies and site evaluation testing.

c) testing in joint and fracture flow situations. Despite failure in the turbulent flow conditions of massive karst the possibility exists of using sulphur hexafluoride in less turbulent fracture flow situations.

d) development of the existing measurement system. A simple modification to duplicate the input sparge system could almost double sample throughput.

7. Acknowledgements

Acknowledgement is given to the Farm Manager of the University Farm and to the company and staff of ARC Ltd and the Bristol Water Company for their permissions and co-operation in the various field trials. Thanks are also due to Dr PL Smart of the Geography Dept. at Bristol University for invaluable advice and for his assistance in the Rhodamine analysis. Finally thanks to colleagues at IoH for their advice and assistance.

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APPENDIX A

DETAILS OF ANALYTICAL APPARATUS AND RUNNING COSTS

Water sample volume size : 46ml
Sparging gas : oxygen free nitrogen
Carrier gas : oxygen free nitrogen

Column filler : molecular sieve Type 5A mesh 80-100
Trap filler : Porapak Type QS mesh 80-100
Trap coolant : Propan-2-ol and solid carbon dioxide (-55 to -76°C)
Gas drier : semi-permeable membrane and Type 13X ungraded, molecular sieve
Bubble stone : type 316 stainless steel solvent filter
(2um pore size)

Detector : Shimadzu GC-8AIE gas chromatograph
Integrator : Hewlett Packard 3390A reporting integrator
Controller : Mitsubishi Melsec F1-20P programmable controller

Molecular sieve supplier : Phase Separation Ltd

Costs as at January 1990:

One gross of McCartney bottles with caps : £40
One gross of McCartney bottle caps : £15

Gas	Cylinder size	Replacement Cost (£)	Monthly cylinder rental (£)
SF6	J	47	4
OFN	K	10	3
Liquid CO2	K	6	3

Appendix B

ANALYTICAL RESULTS

AQUIFER MATERIAL INTERACTION TESTS

concentrations (g/l)

Initial SF6 Solutions

	Sol A	Sol B	Sol C
	2.23E-08	3.79E-08	2.43E-08
	2.24E-08	3.79E-08	2.27E-08
	2.32E-08	3.97E-08	2.48E-08
	2.27E-08	3.38E-08	2.43E-08
	-	3.30E-08	-
	------	------	------
mean	2.26E-08	3.65E-08	2.40E-08

DAY 20 (Sol A)

	Blank	Silic	Calcar	Chalk	Clay	Peat
	2.10E-08	1.12E-08	1.07E-08	1.02E-08	8.47E-09	-
	2.07E-08	1.27E-08	9.83E-09	1.07E-08	8.76E-09	-
	2.08E-08	1.08E-08	1.06E-08	-	8.15E-09	-
	------	------	------	------	------	------
mean	2.08E-08	1.16E-08	1.04E-08	1.05E-08	8.46E-09	-
	2.10E-08	1.16E-08	1.08E-08	1.05E-08	7.93E-09	-
	2.14E-08	1.14E-08	9.94E-09	1.01E-08	7.40E-09	-
	2.14E-08	1.09E-08	9.26E-09	1.01E-08	8.23E-09	-
	------	------	------	------	------	------
mean	2.13E-08	1.13E-08	1.00E-08	1.02E-08	7.85E-09	-
	-	1.10E-08	-	-	9.80E-09	-
	-	1.12E-08	-	-	8.59E-09	-
	-	1.07E-08	-	-	8.79E-09	-
	------	------	------	------	------	------
mean	-	1.10E-08	-	-	9.06E-09	-

DAY 24 (Sol C)

	Blank	Silic	Calcar	Chalk	Clay	Peat
	2.01E-08	-	-	-	-	9.94E-09
	2.00E-08	-	-	-	-	9.66E-09
	1.99E-08	-	-	-	-	9.52E-09
	------	------	------	------	------	------
mean	2.00E-08	-	-	-	-	9.71E-09
	2.06E-08	-	-	-	-	1.06E-08
	2.13E-08	-	-	-	-	1.05E-08
	2.07E-08	-	-	-	-	1.02E-08
	------	------	------	------	------	------
mean	2.09E-08	-	-	-	-	1.04E-08
	2.00E-08	-	-	-	-	9.69E-09
	2.01E-08	-	-	-	-	1.00E-08
	2.04E-08	-	-	-	-	-
	------	------	------	------	------	------
mean	2.02E-08	-	-	-	-	9.84E-09

AQUIFER MATERIAL INTERACTION TESTS

concentrations (g/l)

DAY 35 (Sol A)

	Blank	Silic	Calcar	Chalk	Clay	Peat
	1.71E-08	7.31E-09	7.88E-09	6.61E-09	5.98E-09	-
	1.72E-08	7.27E-09	5.31E-09	6.58E-09	5.17E-09	-
	1.73E-08	7.89E-09	6.97E-09	6.33E-09	6.04E-09	-
	------	------	------	------	------	------
mean	1.72E-08	7.49E-09	6.72E-09	6.51E-09	5.73E-09	-
	1.79E-08	7.66E-09	7.31E-09	6.82E-09	5.48E-09	-
	1.82E-08	7.71E-09	7.36E-09	6.94E-09	6.46E-09	-
	1.76E-08	7.76E-09	7.37E-09	6.75E-09	6.16E-09	-
	------	------	------	------	------	------
mean	1.79E-08	7.71E-09	7.35E-09	6.84E-09	6.03E-09	-
	1.72E-08	-	8.05E-09	6.77E-09	-	-
	1.68E-08	-	7.44E-09	6.73E-09	-	-
	1.73E-08	-	7.14E-09	6.87E-09	-	-
	------	------	------	------	------	------
mean	1.71E-08	-	7.54E-09	6.79E-09	-	-

DAY 152 (Sol A)

	Blank	Silic	Calcar	Chalk	Clay	Peat
	1.59E-08	4.90E-10	9.49E-09	1.78E-09	4.62E-09	-
	1.64E-08	5.28E-10	1.01E-08	1.46E-09	1.76E-09	-
	1.66E-08	5.10E-10	1.07E-08	2.22E-09	4.69E-09	-
	------	------	------	------	------	------
mean	1.63E-08	5.09E-10	1.01E-08	1.82E-09	3.69E-09	-
	1.44E-08	1.01E-09	9.56E-09	7.09E-09	4.46E-09	-
	1.53E-08	1.07E-09	9.55E-09	1.97E-09	4.08E-09	-
	1.47E-08	1.00E-09	-	2.07E-09	3.96E-09	-
	------	------	------	------	------	------
mean	1.48E-08	1.03E-09	9.55E-09	3.71E-09	4.17E-09	-
	1.53E-08	5.40E-10	8.81E-09	1.29E-09	4.89E-09	-
	1.48E-08	5.08E-10	8.02E-09	2.00E-09	5.47E-09	-
	1.41E-08	5.27E-10	8.87E-09	1.59E-09	4.89E-09	-
	------	------	------	------	------	------
mean	1.47E-08	5.25E-10	8.57E-09	1.63E-09	5.08E-09	-

ATMOSPHERIC SAMPLES

Sampled: Wallingford

Date	Time	SF6 (g/l)	WIND Direct (deg)	WIND Speed (m/s)	Date	Time	SF6 (g/l)	WIND Direct (deg)	WIND Speed (m/s)
30-11-87	1210	1.20E-08	360	0.5 *	15-02-88		8.04E-09	176	2.2 +
	1216	1.17E-08	360	0.5 *			7.75E-09	176	2.2 +
	1235	1.14E-08	360	0.5 *	26-02-88	1119	1.02E-08	2	3.1
1-12-87	1544	9.83E-09	21	3.2		1127	9.71E-09	2	3.1
	1555	5.87E-09	21	3.2	1-03-88	1044	4.60E-09	350	4.2
3-12-87	1449	6.29E-09	71	1.5		1051	4.72E-09	350	4.2
	1456	6.59E-09	71	1.5	16-03-88	1113	9.03E-09	334	4.4
	1504	6.13E-09	86	1.7		1121	8.86E-09	334	4.4
	1534	6.22E-09	86	1.7	22-03-88	1342	7.86E-09	216	3.3
	1542	6.28E-09	86	1.7		1350	7.54E-09	216	3.3
11-12-87	1207	9.82E-09	331	0.3		1357	7.44E-09	216	3.3
	1216	8.62E-09	331	0.3	23-03-88	1235	3.92E-09	273	6.5
	1223	7.60E-09	331	0.3	24-03-88	1341	4.96E-09	260	8.9
	1231	6.51E-09	331	0.3		1426	5.09E-09	250	8.9
	1240	4.47E-09	331	0.3	7-04-88		1.03E-08	21	3.7 +
	1249	3.70E-09	331	0.3			9.33E-09	21	3.7 +
	1350	3.84E-09	320	0.5	27-04-88	1330	9.77E-09	10	2.1 *
	1400	3.78E-09	317	0.5		1338	9.64E-09	10	2.1 *
	1408	3.55E-09	317	0.5		1345	8.91E-09	10	2.1 *
	1420	2.74E-09	317	0.5		1353	8.50E-09	10	2.1 *
	1438	3.38E-09	317	0.5		1401	8.31E-09	10	2.1 *
15-12-87	902	3.30E-09	151	1.2	10-05-88	1157	9.37E-09	356	2.8
	911	4.29E-09	151	1.2		1204	9.53E-09	356	2.8
	918	4.11E-09	151	1.2	23-08-88	1635	7.87E-09	210	1.6
	925	4.18E-09	151	1.2		1643	7.92E-09	210	1.6
	957	4.47E-09	151	1.2	24-08-88	1059	8.47E-09	229	3.4
	1004	3.84E-09	153	1.3		1105	7.97E-09	229	3.4
	1056	3.29E-09	153	1.3	5-09-88	1155	6.35E-09	270	1.5 *
	1103	3.53E-09	135	1.8		1205	6.93E-09	270	1.5 *
	1201	4.50E-09	137	1.6	6-09-88	1134	8.46E-09	150	1.0 *
	1208	4.46E-09	137	1.6		1147	8.01E-09	150	1.0 *
	1257	3.71E-09	137	1.6		1202	8.12E-09	150	1.0 *
	1304	4.48E-09	140	1.3	1-12-88		5.92E-09	340	3.1 *
	1312	4.26E-09	140	1.3			4.06E-09	340	3.1 *
	1356	3.92E-09	140	1.3	2-12-88		3.00E-09	345	0.5 +
	1406	4.20E-09	134	2.0			2.69E-09	345	0.5 +
	1456	4.74E-09	134	2.0			2.28E-09	345	0.5 +
	1503	4.27E-09	125	2.4	8-02-89		7.37E-09	158	1.7 +
	1557	4.53E-09	125	2.4			7.66E-09	158	1.7 +
	1614	5.16E-09	131	2.8	13-06-89		7.50E-09	171	3.0 +
	1623	5.07E-09	131	2.8			7.52E-09	171	3.0 +
	1631	4.68E-09	131	2.8	19-06-89		8.18E-09	25	2.3 +
	1643	4.04E-09	131	2.8			8.49E-09	25	2.3 +
16-12-87	1409	4.37E-09	193	2.4	12-09-89		9.84E-09	21	1.3 +
	1417	6.29E-09	193	2.4			1.09E-08	21	1.3 +
24-12-87	1134	5.40E-09	193	2.0			9.68E-09	21	1.3 +
	1204	5.75E-09	193	2.0	15-09-89		7.96E-09	232	2.8 +
	1213	6.92E-09	193	2.0			1.03E-08	232	2.8 +
	1221	6.98E-09	193	2.0			1.03E-08	232	2.8 +

ATMOSPHERIC SAMPLES

Sampled: Wallingford

Date	Time	SF6 (g/l)	WIND Direct (deg)	WIND Speed (m/s)
7-01-88	1114	7.65E-09	287	3.6
	1121	7.50E-09	287	3.6
	1128	7.48E-09	287	3.6
	1135	6.45E-09	287	3.6
8-02-88	1440	5.81E-09	294	5.2
	1510	4.58E-09	287	4.3
12-2-88		8.96E-09	230	3.9 +
		8.17E-09	230	3.9 +
		8.19E-09	230	3.9 +
1-02-90	1629	5.57E-09	170	6.6
	1629	4.76E-09	170	6.6
5-0290	1003	2.32E-09	185	2.8
	1003	6.12E-09	185	2.8
	1003	3.19E-09	185	2.8
	1450	3.10E-09	185	2.8
	1450	2.67E-09	185	2.8
	1450	2.84E-09	185	2.8

Mean	6.45E-09
Minimum	2.28E-09
Maximum	1.20E-08
Std dev	2.42E-09
Variance	5.84E-18

WIND
hourly mean of 12 readings
+ 1200-1300 GMT reading
* 0900 GMT reading

ATMOSPHERIC SAMPLES

Didcot Power Station

Date	Time	SF6 (g/l)	SF6 (g/l)	Grid Ref
1-02-90	1435	7.06E-09	5.30E-09	SU515864 (Upton)
	1443	7.08E-09	7.05E-09	SU531894 (B4015 Didcot)
	1448	6.46E-09	5.91E-09	SU513910 (Didcot Power Stn)
	1458	9.65E-09	6.56E-09	SU480968 (A34 Abingdon)
	1506	5.03E-09	6.29E-09	SU501957 (Culham)
	1511	7.29E-09	6.38E-09	SU521953 (A415 Culham)
	1516	6.76E-09	5.25E-09	SU546954 (Clifton Hampden)
	1527	6.40E-09	5.15E-09	SP539014 (A423 Sandford)
	1535	6.73E-09	4.60E-09	SP495020 (Boars Hill)
	1545	7.40E-09	4.43E-09	SP462019 (A420 Besseleigh)
	1559	8.71E-09	4.57E-09	SP564030 (B480 Cowley)
	1607	2.82E-09	5.38E-09	SU593990 (B480 Chiselhampton)
	1613	5.52E-09	5.72E-09	SU560977 (A423/B4015)
	1629	5.57E-09	4.76E-09	SU617898 (IoH)

ATMOSPHERIC SAMPLES

M25 Motorway

Date	Time	SF6 (g/l)	SF6 (g/l)	SF6 (g/l)	Grid Ref
5-02-90	1003	2.32E-09	6.12E-09	3.19E-09	SU617898 (IoH)
	1050	7.38E-09	4.04E-09	2.61E-09	TQ040752 (Jct 14)
	1105	2.76E-09	4.11E-09	6.90E-09	TQ031940 (Jct 17)
	1113	6.87E-09	3.94E-09	2.22E-09	TL078014 (Jct 20)
	1123	2.14E-09	3.44E-09	7.32E-09	TL190035 (Jct 22)
	1201	7.98E-09	3.47E-09	3.24E-09	TL228002 (Jct 23)
	1216	2.85E-09	2.80E-09	8.46E-09	TL349001 (Jct 25)
	1224	7.77E-09	2.74E-09	2.88E-09	TQ407998 (Jct 26)
	1238	1.08E-08	8.93E-09	1.44E-08	TQ567924 (Jct 28)
	1249	6.37E-09	5.19E-09	2.42E-09	TQ575801 (Jct 30)
	1301	2.09E-09	5.00E-09	7.41E-09	TQ558720 (Jct 2)
	1315	7.09E-09	4.87E-09	3.98E-09	TQ496569 (Jct 5)
	1329	2.74E-09	4.39E-09	5.63E-09	TQ351529 (Jct 6)
	1338	4.83E-09	3.19E-09	2.18E-09	TQ259526 (Jct 8)
	1353	7.91E-09	3.60E-09	4.54E-09	TQ081592 (Jct 10)
	1404	3.51E-09	3.09E-09	7.49E-09	TQ040752 (Jct 14)
	1450	3.10E-09	2.67E-09	2.84E-09	SU617898 (IoH)

STANTON HARCOURT TRACING RESULTS

Borehole: SH-1

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	4.40E-08	2.70E-02	5.00E-09
1.10	4.40E-08	2.80E-02	1.80E-07
2.82	7.27E-06	3.00E-02	5.68E-06
4.57	5.12E-03	2.48E-01	4.91E-04
5.95	7.99E-03	5.90E-01	7.14E-04
7.02	7.83E-03	6.30E-01	7.61E-04
9.47	3.26E-03	4.75E-01	7.33E-04
13.08	1.82E-03	2.65E-01	6.20E-04
17.08	5.37E-04	1.28E-01	4.37E-04
19.83	3.10E-04	8.70E-02	3.43E-04
22.83	1.72E-04	6.10E-02	2.46E-04
25.83	1.27E-04	5.00E-02	1.89E-04
47.08	6.08E-05	3.70E-02	7.61E-05
71.17	6.24E-05	3.50E-02	4.80E-05
95.33	4.62E-05	3.20E-02	1.96E-05

Borehole: SH-3

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	6.00E-08	2.70E-02	2.50E-08
1.10	4.00E-08	2.70E-02	2.50E-08
2.82	2.00E-08	2.70E-02	2.50E-08
4.57	8.20E-07	2.70E-02	4.90E-08
5.95	2.44E-05	2.80E-02	4.00E-06
7.02	1.34E-04	3.80E-02	1.38E-05
9.47	3.34E-04	5.00E-02	2.93E-05
13.08	5.58E-04	7.90E-02	4.99E-05
17.08	7.51E-04	1.40E-01	1.16E-04
19.83	4.49E-04	1.26E-01	1.33E-04
22.83	3.20E-04	9.10E-02	1.15E-04
25.83	3.33E-04	7.50E-02	1.06E-04
47.08	1.38E-04	4.30E-02	5.93E-05
71.17	2.27E-05	3.10E-02	3.00E-05
95.33	6.05E-06	2.80E-02	1.16E-04

Borehole: SH-2

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	5.10E-08	3.00E-02	2.70E-08
1.10	3.90E-08	3.00E-02	-
2.82	2.10E-08	3.00E-02	3.20E-08
4.57	6.40E-08	2.90E-02	1.20E-07
5.95	-	4.30E-02	1.25E-05
7.02	1.11E-03	1.36E-01	1.33E-04
9.47	2.29E-03	2.20E-01	2.85E-04
13.08	2.13E-03	2.52E-01	3.82E-04
17.08	2.83E-03	2.40E-01	3.47E-04
19.83	1.37E-03	2.20E-01	3.16E-04
22.83	5.69E-04	2.16E-01	3.16E-04
25.83	4.60E-04	2.10E-01	3.16E-04
47.08	1.26E-03	1.68E-01	3.08E-04
71.17	6.51E-04	1.12E-01	2.46E-04
95.33	-	7.40E-02	1.43E-04

Borehole: SH-4

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine WT (g/l)
0.00	5.00E-08	2.80E-02	2.70E-08
1.10	2.00E-08	2.70E-02	2.70E-08
2.82	3.00E-08	2.70E-02	2.70E-08
4.57	4.20E-07	2.70E-02	1.88E-07
5.95	3.63E-05	2.90E-02	2.07E-06
7.02	8.79E-05	3.50E-02	1.04E-05
9.47	1.52E-04	4.10E-02	1.91E-05
13.08	1.45E-04	4.60E-02	2.54E-05
17.08	7.00E-05	4.60E-02	2.30E-05
19.83	5.32E-05	4.70E-02	2.15E-05
22.83	1.82E-05	4.30E-02	1.89E-05
25.83	3.10E-05	4.10E-02	1.80E-05
47.08	5.40E-06	3.40E-02	8.90E-06
71.17	4.20E-06	3.00E-02	5.30E-06
95.33	3.10E-06	2.80E-02	2.60E-06

STANTON HARCOURT TRACING RESULTS

Borehole: SH-5

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	3.00E-08	2.80E-02	5.00E-08
1.10	-	-	-
2.82	-	-	-
4.57	-	3.20E-02	2.81E-06
5.95	3.91E-04	5.40E-02	2.77E-05
7.02	4.93E-04	7.30E-02	7.53E-05
9.47	4.53E-04	7.40E-02	1.01E-04
13.08	4.66E-04	7.40E-02	1.07E-04
17.08	4.74E-04	8.00E-02	1.12E-04
19.83	5.46E-04	8.00E-02	1.18E-04
22.83	3.09E-04	7.50E-02	1.20E-04
25.83	2.27E-04	6.60E-02	1.14E-04
47.08	1.11E-04	3.80E-02	6.59E-05
71.17	3.01E-05	3.20E-02	4.10E-05
95.33	6.90E-06	2.90E-02	1.52E-05

Borehole: SH-7

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	6.10E-08	2.70E-02	2.70E-08
1.10	-	-	-
2.82	-	-	-
4.57	4.70E-08	2.70E-02	2.70E-08
5.95	1.76E-07	2.80E-02	2.70E-08
7.02	1.32E-07	2.70E-02	2.70E-08
9.47	9.60E-08	2.80E-02	3.20E-08
13.08	1.03E-07	2.80E-02	5.20E-08
17.08	1.41E-07	2.70E-02	3.20E-08
19.83	1.87E-07	2.80E-02	4.90E-08
22.83	1.76E-07	2.70E-02	4.90E-08
25.83	1.49E-07	2.70E-02	3.70E-08
47.08	3.10E-08	2.60E-02	4.40E-08
71.17	3.70E-08	2.70E-02	4.40E-08
95.33	-	2.60E-02	3.70E-08

Borehole: SH-6

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	5.00E-08	2.80E-02	3.00E-08
1.10	-	-	-
2.82	-	-	-
4.57	3.00E-08	2.70E-02	3.00E-08
5.95	3.90E-07	2.80E-02	3.00E-08
7.02	8.90E-05	3.10E-02	1.78E-06
9.47	5.43E-04	6.80E-02	3.43E-05
13.08	8.49E-04	1.20E-01	1.09E-04
17.08	4.63E-04	1.24E-01	1.72E-04
19.83	4.62E-04	1.10E-01	1.90E-04
22.83	2.26E-04	9.00E-02	1.88E-04
25.83	2.77E-04	7.50E-02	1.75E-04
47.08	8.45E-05	3.60E-02	8.52E-05
71.17	1.50E-05	3.10E-02	4.33E-05
95.33	6.20E-06	2.80E-02	1.40E-05

Borehole: SEEPAGE

Time since injection (hours)	SF6 (g/l)	Chloride (g/l)	Rhodamine (g/l)
0.00	5.50E-08	2.80E-02	2.70E-08
1.10	2.70E-08	2.70E-02	-
2.82	2.10E-08	2.70E-02	3.20E-08
4.57	4.80E-08	2.70E-02	-
5.95	3.70E-07	2.80E-02	3.00E-08
7.02	1.17E-05	2.80E-02	5.40E-08
9.47	4.48E-05	3.00E-02	1.78E-06
13.08	8.70E-05	3.30E-02	3.47E-06
17.08	2.80E-04	5.10E-02	1.80E-05
19.83	2.17E-04	5.10E-02	2.22E-05
22.83	1.32E-04	5.40E-02	3.32E-05
25.83	1.26E-04	5.20E-02	3.98E-05
47.08	5.13E-05	3.50E-02	3.28E-05
71.17	3.53E-05	3.00E-02	3.04E-05
95.33	5.30E-06	2.60E-02	7.20E-06

WALLINGFORD TRACING RESULTS

Borehole: Wall-59

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)
4.10	-	-	2.47E-08
4.92	-	-	2.22E-08
5.19	4.75E-10	-	2.22E-08
5.94	-	-	-
6.17	2.89E-10	-	3.21E-08
6.92	5.00E-11	-	2.22E-08
7.14	7.38E-10	3.00E-06	1.98E-08
8.13	-	-	2.22E-08
8.92	2.84E-09	1.50E-05	2.22E-08
9.97	-	5.10E-05	2.72E-08
10.17	1.03E-08	8.20E-05	2.47E-08
10.97	3.33E-07	1.40E-04	-
11.19	6.62E-08	1.75E-04	2.96E-08
11.92	2.26E-08	2.80E-04	3.95E-08
12.13	2.51E-08	3.00E-04	3.70E-08
12.97	1.17E-08	4.00E-04	6.17E-08
13.97	1.48E-08	4.40E-04	8.64E-08
14.97	1.61E-08	-	1.31E-07
16.03	1.51E-08	-	2.00E-07
16.99	9.16E-09	4.60E-04	2.65E-07
18.01	9.36E-09	-	3.16E-07
18.92	1.04E-08	-	-
19.90	9.77E-09	-	3.51E-07
20.92	8.19E-09	2.40E-04	3.75E-07
21.92	7.03E-09	-	3.98E-07
22.95	5.37E-09	-	4.13E-07
23.94	4.85E-09	1.65E-04	3.94E-07
24.93	4.62E-09	-	3.90E-07
26.01	2.84E-09	-	3.75E-07
27.12	3.20E-09	-	3.28E-07
27.99	2.18E-09	7.40E-05	2.81E-07
28.99	-	-	-
29.94	-	-	-
31.10	-	-	-
31.97	2.33E-09	1.60E-04	2.34E-07
32.97	1.99E-09	-	2.11E-07
33.97	1.58E-09	-	2.07E-07
34.97	1.03E-09	1.50E-05	1.87E-07
36.15	-	7.00E-05	-
37.12	-	-	-
37.99	6.10E-10	-	1.53E-07
38.97	9.30E-11	-	1.95E-07
39.99	5.60E-11	-	1.73E-07
41.12	-	-	1.28E-07
41.99	-	5.00E-06	1.04E-07
43.15	-	-	8.89E-08
44.01	-	-	-
45.00	4.60E-11	-	1.18E-07
46.97	-	-	1.01E-07
48.97	-	4.00E-06	1.26E-07
51.97	-	-	1.01E-07

Borehole: Wall-58

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)
4.10	-	-	-
4.92	-	-	-
5.19	-	-	-
5.94	-	-	-
6.17	-	-	-
6.92	-	-	-
7.14	-	-	-
8.13	-	-	-
8.92	-	-	-
9.97	-	-	-
10.17	-	-	-
10.97	-	3E-06	1.98E-08
11.19	-	-	1.98E-08
11.92	-	-	3.95E-08
12.13	-	-	3.46E-08
12.97	-	-	6.67E-08
13.97	1.67E-10	5E-06	2.22E-08
14.97	5.92E-10	-	2.47E-08
16.03	2.21E-10	-	2.96E-08
16.99	1.15E-10	5E-06	2.96E-08
18.01	8.27E-10	4E-06	2.72E-08
18.92	8.33E-10	-	3.46E-08
19.90	7.9E-10	-	2.47E-08
20.92	2.13E-09	7E-06	2.22E-08
21.92	1.29E-09	-	2.22E-08
22.95	1.48E-09	-	1.98E-08
23.94	1.33E-09	1.6E-05	2.47E-08
24.93	1.75E-09	-	2.72E-08
26.01	1.81E-09	-	2.96E-08
27.12	1.81E-09	-	2.22E-08
27.99	1.83E-09	2.7E-05	3.46E-08
28.99	-	-	-
29.94	-	-	-
31.10	-	-	-
31.97	2.27E-09	2.7E-05	2.34E-08
32.97	2.24E-09	2.9E-05	2.11E-08
33.97	2.17E-09	-	1.43E-08
34.97	2.02E-09	2.7E-05	1.63E-08
36.15	-	-	-
37.12	-	-	-
37.99	1.15E-09	1.9E-05	8.64E-08
38.97	1.88E-09	-	2.96E-08
39.99	2.02E-09	1.5E-05	1.46E-08
41.12	1.41E-09	-	3.46E-08
41.99	1.31E-09	1.1E-05	3.7E-08
43.15	-	-	4.2E-08
44.01	-	-	-
45.00	9.05E-10	-	3.46E-08
46.97	8.29E-10	-	4.44E-08
48.97	5.88E-10	6E-06	2.47E-08
51.97	6.05E-10	-	3.7E-08

WALLINGFORD TRACING RESULTS

Borehole: Wall-59

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)
53.97	-	-	8.89E-08
55.96	-	-	6.91E-08
58.92	-	-	6.42E-08
60.97	-	-	9.38E-08
62.97	-	-	6.30E-08
65.99	-	-	5.18E-08
67.99	-	-	-
70.10	-	-	-
73.12	-	-	-
73.98	-	-	-
75.11	-	-	-
76.09	-	-	-
76.97	-	-	-
78.17	-	-	-
79.00	-	-	-
79.97	-	-	-

Borehole: Wall-58

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)
53.97	6.14E-10	-	6.42E-08
55.96	5.06E-10	1.5E-05	3.7E-08
58.92	5.14E-10	4E-06	3.21E-08
60.97	5.56E-10	5E-06	2.96E-08
62.97	5.16E-10	4E-06	3.46E-08
65.99	-	-	6.42E-08
67.99	-	-	8.89E-08
70.10	-	4E-06	3.21E-08
73.12	-	-	3.95E-08
73.98	-	-	6.67E-08
75.11	-	-	1.38E-08
76.09	-	-	-
76.97	-	-	3.46E-08
78.17	-	-	-
79.00	-	-	-
79.97	-	-	-

WALLINGFORD TRACING RESULTS

Borehole: Wall-57				Borehole: Wall-PW				
Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)	Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)	Discharge SF6 (g/l)
4.10	-	-	-	4.10	-	-	-	-
4.92	-	-	-	4.92	-	-	-	-
5.19	-	-	-	5.19	-	-	-	-
5.94	-	-	-	5.94	-	-	-	-
6.17	-	-	-	6.17	-	-	-	-
6.92	-	-	-	6.92	-	-	-	-
7.14	-	-	-	7.14	-	-	-	-
8.13	-	-	-	8.13	-	-	-	-
8.92	-	-	-	8.92	-	-	-	-
9.97	-	-	-	9.97	-	-	-	-
10.17	-	-	-	10.17	-	-	-	-
10.97	-	-	-	10.97	-	-	-	-
11.19	-	-	-	11.19	-	-	-	-
11.92	2.54E-10	-	2.27E-08	11.92	-	-	-	-
12.13	-	-	-	12.13	-	4.00E-06	3.21E-08	-
12.97	3.47E-10	-	-	12.97	-	-	1.98E-08	3.23E-10
13.97	4.21E-10	4.00E-06	4.44E-08	13.97	-	-	1.98E-08	3.32E-10
14.97	2.91E-10	-	-	14.97	-	-	3.95E-08	3.91E-10
16.03	1.84E-10	-	2.96E-08	16.03	1.50E-10	-	3.21E-08	1.61E-10
16.99	-	5.00E-06	2.96E-08	16.99	4.01E-10	5.00E-06	2.22E-08	4.37E-10
18.01	6.25E-10	3.00E-06	2.47E-08	18.01	2.84E-10	-	1.98E-08	6.27E-10
18.92	5.84E-10	-	2.22E-08	18.92	2.71E-10	-	2.47E-08	7.16E-10
19.90	7.23E-10	-	1.73E-08	19.90	5.75E-10	4.00E-06	2.47E-08	4.12E-10
20.92	9.31E-10	-	1.48E-08	20.92	-	-	3.46E-08	9.33E-10
21.92	1.02E-09	-	1.98E-08	21.92	4.62E-10	-	2.47E-08	9.07E-10
22.95	1.57E-09	7.00E-06	4.20E-08	22.95	5.79E-10	6.00E-06	1.73E-08	1.08E-09
23.94	1.84E-09	-	2.47E-08	23.94	7.33E-10	8.00E-06	2.72E-08	1.43E-09
24.93	3.22E-09	1.50E-05	1.98E-08	24.93	5.92E-10	9.00E-06	2.47E-08	1.98E-09
26.01	3.54E-09	-	2.22E-08	26.01	4.17E-10	-	2.72E-08	2.01E-09
27.12	4.43E-09	-	2.22E-08	27.12	4.51E-10	-	2.96E-08	2.08E-09
27.99	5.05E-09	4.00E-05	5.68E-08	27.99	4.95E-10	5.00E-06	2.10E-07	2.59E-09
28.99	5.66E-09	-	1.98E-08	28.99	-	-	-	3.29E-09
29.94	8.78E-09	-	2.22E-08	29.94	-	-	-	4.40E-09
31.10	8.64E-09	7.60E-05	2.22E-08	31.10	7.77E-10	7.00E-06	2.22E-08	3.54E-09
31.97	9.69E-09	-	2.22E-08	31.97	7.16E-10	-	2.22E-08	4.63E-09
32.97	7.63E-09	-	2.47E-08	32.97	5.62E-10	-	2.47E-08	2.83E-09
33.97	7.50E-09	-	2.47E-08	33.97	6.94E-10	-	1.98E-08	3.93E-09
34.97	1.49E-08	1.30E-04	2.47E-08	34.97	1.10E-09	1.50E-05	2.96E-08	4.88E-09
36.15	1.31E-08	-	3.46E-08	36.15	7.88E-10	-	1.98E-08	3.98E-09
37.12	1.18E-08	-	-	37.12	1.41E-09	-	1.98E-08	4.09E-09
37.99	1.62E-08	1.45E-04	2.72E-08	37.99	3.73E-09	2.30E-05	2.96E-08	3.75E-09
38.97	1.56E-08	-	2.47E-08	38.97	1.16E-09	-	4.20E-08	6.30E-09
39.99	1.57E-08	-	1.98E-08	39.99	1.20E-09	-	1.73E-08	5.34E-09
41.12	1.52E-08	1.70E-04	2.47E-08	41.12	6.68E-10	-	2.22E-08	5.10E-09
41.99	1.44E-08	1.82E-04	3.46E-08	41.99	9.31E-10	1.60E-05	1.98E-08	4.96E-09
43.15	1.65E-08	1.80E-04	2.22E-08	43.15	9.70E-10	-	1.98E-08	5.77E-09
44.01	1.68E-08	-	2.72E-08	44.01	9.09E-10	-	1.48E-08	5.58E-09
45.00	1.40E-08	1.95E-04	3.46E-08	45.00	7.27E-10	1.30E-05	2.47E-08	4.22E-09
46.97	1.66E-08	-	-	46.97	6.42E-10	-	1.73E-08	4.87E-09
48.97	1.51E-08	1.30E-04	3.46E-08	48.97	6.42E-10	1.00E-05	2.47E-08	3.40E-09
51.97	1.34E-08	-	5.18E-08	51.97	-	-	-	3.08E-09

WALLINGFORD TRACING RESULTS

Borehole: Wall-57

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)
53.97	9.82E-09	-	7.16E-08
55.96	1.18E-08	4.80E-05	4.69E-08
58.92	1.09E-08	-	6.91E-08
60.97	8.31E-09	-	4.69E-08
62.97	6.82E-09	5.50E-05	5.93E-08
65.99	4.74E-09	-	-
67.99	6.14E-09	-	4.94E-08
70.10	5.69E-09	3.20E-05	5.93E-08
73.12	5.03E-09	-	7.41E-08
73.98	-	-	7.65E-08
75.11	3.40E-09	-	6.42E-08
76.09	3.19E-09	-	-
76.97	3.35E-09	1.20E-05	-
78.17	3.59E-09	-	-
79.00	2.78E-09	-	-
79.97	3.20E-09	9.00E-06	7.41E-08

Borehole: Wall-PW

Time since injection (days)	SF6 (g/l)	Iodide (g/l)	Rhodamine (g/l)	Discharge SF6 (g/l)
53.97	-	-	1.73E-08	2.94E-09
55.96	-	5.00E-06	2.22E-08	2.38E-09
58.92	-	-	1.98E-08	1.59E-09
60.97	-	-	4.69E-08	1.53E-09
62.97	-	-	3.21E-08	1.13E-09
65.99	-	-	2.47E-08	6.86E-10
67.99	-	-	2.72E-08	1.05E-09
70.10	-	-	1.98E-08	1.01E-09
73.12	-	-	3.21E-08	1.05E-09
73.98	-	-	-	9.05E-10
75.11	-	-	-	8.70E-10
76.09	-	-	-	8.61E-10
76.97	-	-	-	8.27E-10
78.17	-	-	-	8.72E-10
79.00	-	-	-	8.53E-10
79.97	-	-	-	5.03E-10

OXFORD TRACING RESULTS

Time since injection (days)	SF6 (g/l)			RHODAMINE WT (g/l)		
	UFS73	UFS75	UFS78	UFS73	UFS75	UFS78
0.00	-	-	-	1.30E-07	1.20E-07	1.20E-07
3.04	-	-	-	1.20E-07	-	1.20E-07
5.06	1.17E-08	1.08E-08	1.28E-08	-	-	1.20E-07
5.96	1.84E-08	3.46E-08	4.41E-08	-	1.20E-07	1.20E-07
6.96	2.52E-08	3.48E-08	9.07E-08	1.20E-07	1.50E-07	1.30E-07
7.92	2.68E-08	6.39E-08	1.19E-07	1.30E-07	1.30E-07	1.20E-07
8.92	2.03E-08	7.71E-08	1.84E-07	1.30E-07	1.50E-07	1.50E-07
10.06	1.85E-08	8.95E-08	1.54E-07	1.50E-07	2.00E-07	1.80E-07
11.06	1.70E-08	6.59E-08	1.91E-07	1.80E-07	2.00E-07	2.20E-07
11.92	9.24E-09	7.64E-08	2.10E-07	1.80E-07	2.50E-07	2.50E-07
12.94	6.86E-09	8.29E-08	1.66E-07	1.70E-07	3.00E-07	2.70E-07
14.06	5.75E-09	5.98E-08	1.67E-07	2.00E-07	3.80E-07	3.50E-07
14.90	6.16E-09	4.68E-08	1.31E-07	1.80E-07	3.80E-07	3.80E-07
15.98	6.62E-09	3.11E-08	1.09E-07	1.80E-07	3.50E-07	4.00E-07
17.08	4.77E-09	2.54E-08	1.00E-07	2.00E-07	3.80E-07	4.60E-07
18.04	3.80E-09	2.87E-08	9.29E-08	1.80E-07	5.30E-07	5.10E-07
18.90	3.28E-09	2.47E-08	6.68E-08	1.80E-07	5.10E-07	5.00E-07
19.92	1.63E-09	1.48E-08	6.23E-08	2.00E-07	4.60E-07	5.80E-07
20.92	1.89E-09	1.45E-08	4.43E-08	1.80E-07	4.00E-07	5.50E-07
23.98	1.43E-09	1.03E-08	2.73E-08	2.00E-07	5.60E-07	6.60E-07
25.92	-	-	-	1.70E-07	5.60E-07	4.80E-07
27.92	-	-	-	1.80E-07	4.30E-07	7.30E-07
31.06	-	-	1.52E-08	1.80E-07	4.00E-07	5.30E-07
32.96	1.50E-09	4.80E-09	8.33E-09	1.70E-07	4.30E-07	6.10E-07
34.96	1.37E-09	2.76E-09	7.25E-09	1.70E-07	3.50E-07	6.10E-07
37.96	5.60E-10	2.06E-09	4.17E-09	1.70E-07	3.50E-07	5.50E-07
40.96	4.60E-10	1.76E-09	3.17E-09	1.80E-07	3.80E-07	5.50E-07
44.96	1.02E-09	2.60E-09	2.69E-09	1.70E-07	4.00E-07	4.30E-07
47.88	-	1.04E-09	1.61E-09	1.50E-07	3.00E-07	4.10E-07

MENDIP (LONGWOOD - CHEDDAR) TRACING

Mendip1 (high flow)

Time since injection (hours)	Relative Fluoresence (RF)	Discharge Longwood (l/s)
0.00	0.8	57
21.05	0.8	63
22.08	1.2	
23.00	1.6	68.5
24.42	5.0	
25.00	6.6	
26.05	10.6	
27.00	14.5	
28.08	18.0	
29.03	20.2	
30.08	20.5	
31.12	20.2	
32.08	16.8	
33.00	15.2	
34.05	13.3	
35.08	11.3	
36.08	10.2	
37.12	10.4	
38.08	10.8	
39.00	11.7	
40.42	13.3	
41.00	14.4	472
42.17	15.8	
43.08	15.6	282
45.08	14.4	
47.02	8.8	203
49.08	4.1	
51.08	2.4	
53.03	1.8	
55.05	1.6	
57.00	1.6	
61.58	1.5	
65.00	1.4	135
68.00	1.4	103

Mendip2 (low flow)

Time since injection (hours)	Relative Fluoresence (RF)	Discharge Cheddar (l/s)
0.00	3.0	390
27.10	4.5	
43.00	3.0	370
47.00	3.0	375
63.10	4.0	
65.00	3.0	345
67.00	6.0	377
68.90	3.5	411
71.10	3.5	
72.70	3.0	365
78.75	3.0	
80.80	3.5	
84.80	5.0	
87.10	6.5	
88.80	8.0	361
91.10	10.0	
92.90	12.5	338
95.10	14.5	
96.90	16.5	336
99.25	18.5	
100.90	19.0	
103.00	21.5	
105.20	21.5	
107.00	21.0	
109.20	21.5	
111.00	21.5	317
113.10	20.5	
115.00	20.0	
117.00	19.0	
119.10	18.0	
120.90	16.5	
123.30	15.5	
125.10	14.5	
127.50	13.0	
129.00	12.0	
132.90	11.5	
135.00	10.5	
137.00	10.5	
139.30	9.0	
140.90	8.5	
143.10	8.0	
145.10	8.5	272
150.90	6.5	
153.20	7.0	
154.90	6.5	
159.10	6.0	
163.00	5.5	
165.00	5.0	
167.10	6.0	
168.90	5.5	
171.00	5.0	
182.90	4.5	

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