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RADIOACTIVE TRACERS IN GEOTHERMAL UNDERGROUND WATER FLOW STUDIES

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ABSTRACT

Radioactive tracers have been used to study the movement of water in several geothermal fields, including Wairakei and Broadlands, in New Zealand. This technique has been particularly useful in hot water reinjection investigations for detecting the invasion of reinjected water into the production zone. Iodine-131 has been used as the tracer and the methods and equipment used to inject, sample and measure it are described. The single well dilution method of estimating horizontal flow velocities was found to be useful as a preliminary step to multi-well testing. A number of tests in both fields are discussed, and some details of the results presented. Peak velocities as high as 17 m/hr were observed and tracer recoveries of over 10% obtained. Possible interpretation of some of the results in relation to available geological descriptions are made. The dominating influence of faulting on water movement, and the inadvisability of relying on distance alone to prevent cold water re-entering into a production field, is stressed.

KEYWORDS:

IODINE-131
FLUID INJECTION
BROADLANDS
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GROUND WATER
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FLOW RATE
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THERMAL WATERS
TRACERS

RADIOACTIVE TRACERS IN GEOTHERMAL UNDERGROUND WATER FLOW STUDIES

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1. INTRODUCTION

Radioactive tracers have been used worldwide in groundwater hydrology studies for many years now, but very little has been reported on their use in geothermal systems. Some data are available on tritium and carbon-14 of atmospheric origin but the levels generally are so low as to make interpretation of the results difficult, if not impossible. The earliest tritium results were those of Buttlar and Libby (1955) which included a result of TR = -0.56 ± 0.54 from Lardarello hot springs, and judging from its sample number probably collected late in 1953. Perhaps the earliest C-14 measurements were reported by Fergusson and Knox (1959).

Cusicanqui, Mahon and Ellis (1975) were able to interpret a tritium content of TR = 3.2 in El Tatio water as indicating a rate of water movement in the field of around 1 km/year by determining the input area from the D/H ratio.

The first use of deliberately introduced radioactive tracers into geothermal waters appears to be that reported by Ariizumi and Kando (1963). Using five radionuclides they traced the movement of hot spring water infiltrating into ground on the side of a mountain to where it emerged 200 m below by a stream.

The first use of a deliberately introduced tracer, in this case tritium, in the investigation of a geothermal field, would appear to be that reported by Einarsson, Vides and Cuellar (1975) in 1971. They found a sharp response in a well some 400 m from the injection well in around two days. Though it is a little hard to determine, from the graph of the data supplied, it would appear that the maximum concentration occurred on the third to fourth days indicating a peak velocity of around 5 m/hr.

The use of artificial radioactive tracers in New Zealand began in May 1974, with a series of single well tests in an attempt to establish an "order of magnitude" figure of underground hot water velocities in the Broadlands geothermal field (McCabe et al., 1975). The "single well" approach arose from the preparation of a safety assessment of a proposed multiple well test to answer such questions as:

1. Is there a general flow direction?
2. What is the flow velocity?

Consideration of geophysical data available on the permeability of the rocks present, on the km^3 scale, indicated flow velocities orders of magnitude too low for making tests between wells situated several hundreds of metres apart. However, at the other extreme, as Grindley (1965) points out, geothermal formations are anything but homogeneous. "At many intersections, not only is there complete loss of drilling fluid, but the bit and drill string may drop as much as 2 metres". Therefore, possible mechanisms existed for tests, using tracers other than C-14 or tritium, to be made in practical times. The "single well" tests, which are described later, did show that apparent horizontal velocities approaching 0.1 m/hr could be found in most of the wells tested, with one well giving approximately 1 m/hr.

From that foundation progress has been made to a continuing programme of tracer testing, usually combined with reinjection trials. Along with these has gone the development of the instrumentation necessary to monitor and record the tests and which is described in this paper.

2. TRACERS

The choice of a tracer in geothermal systems is, if anything, more restricted than that for conventional groundwater studies. Due to the high temperatures encountered, metal organic complexes are unlikely to be stable and frequently the scale of the system under study is much larger so that quantities and costs become prohibitive.

Tritium is an obvious choice, but any temptation to use it has so far been resisted because of our interest in environmental tritium as a tracer. Further, long-term tracers are probably best reserved for studies once some good understanding of the system has been gained from short-lived tracer tests. The introduction of one source of tritium into a field precludes further tritium testing for a very long time.

The halogens, as in conventional groundwater hydrology, offer several useful possibilities. Chlorine-36 ($t_{\frac{1}{2}} = 3 \times 10^5$ yr) will become valuable as a natural tracer as the accelerator method of dating becomes more generallly available, but as an artificial tracer it is too long-lived and expensive.

Bromine-82 ($t_{\frac{1}{2}} = 1.5$ d) has limited usefulness because of its short half-life and very high energy gamma radiation. This latter factor is not so important if transport from the production site is by road or sea, but transport by air reduces the maximum quantity in one shipment to around 3 GBq. Bromine-82 has been used to test the suitability of iodine-131 as a tracer.

Iodine-131 ($t_{\frac{1}{2}} = 8$ d) has been found to be a very satisfactory tracer in the geothermal systems tested. Whereas for groundwater tracing iodine may be unreliable due to the presence of organic matter, low pH or oxidising conditions, in the geothermal systems investigated so far conditions have been ideal. These are pH values around 7-8, and reducing solutions free of organic debris.

Its moderate energy gamma emission makes shipment and handling in the field relatively easy and yet it is easily monitored at the collection site. Up to 200 GBq can be air-freighted in a single transport package containing a depleted uranium pot with more than one packet per plane load possible. Experience indicates that the eight-day half-life limits field tests to four to five weeks by which time a combination of decay corrections and variation of background signals are producing unacceptably large errors.

Against these advantages iodine-131 is one of the more toxic radionuclides and some care is required in designing test procedures to comply with safety regulations.

There is a definite need for a good longer term tracer. Two possibilities are iodine-125 ($t_{\frac{1}{2}}$ 60 d) and sulphur-35 ($t_{\frac{1}{2}}$ 87 d). Unfortunately, owing to their low energy emissions, both would require sampling and concentration techniques rather than the present continuous "in situ" monitoring. From work done so far, the detection sensitivity for iodine-125 by liquid scintillation and iodine-131 by the present monitoring process, could be made somewhat similar. The cost of iodine-125 could be several times greater than iodine-131 for similar activities.

We intend investigating the use of $^{35}SO_4^=$. At pH 7, the rate of exchange of sulphate sulphur with other forms is very slow. The behaviour of the sulphate ion will be studied.

3. TRACER INJECTION

Essentially two methods have been used to inject the tracer. The first method used was to load the solution contained in a 10 ml sealed glass vial into a modified Klyen downhole sampler (Kleyn, 1973). The sample bottle section of the sampler was replaced by a short weighted section turned out to hold the vial with its flat bottom uppermost. The vial is then broken by the inertial hammer when the support wire is pulled. This device can be lowered to any predetermined point in the well before releasing the tracer.

Unfortunately, the rubber capped vials used for shipping the tracer are not suitable for loading into the downhole breaker. Not only is the vial glass too thick to break, but the rubber cap cannot be relied on to retain the solution in the vial on its journey down the well. As the supplier cannot be persuaded to send the tracer in a sealed vial, a transfer must be made by the customer.

The second method can be employed when water is being pumped down a well such as when a reinjection test is in progress. The simplest situation is shown in Fig. 1, where a by-pass flow can be established. The vial breaker is a 2-inch steam valve surrounded by a lead shield. The vial is simply lifted with long reachers from the transport container and dropped into the open top of the breaker. A pin across the centre of the valve stops the vial dropping past the gate. The blanking plug is screwed into the top of the breaker and the vial is crushed by partly closing the valve. The system is then flushed with the injection fluid.

4. WELL MONITORING

With the use of iodine-131 there is a choice available between "in situ" gamma measurement and sample collection with subsequent laboratory processing and counting. The latter choice probably has the potential to be developed to give the greater sensitivity, and for long-term tests could be the preferred method. For shorter tests, and particularly when the frequency of sampling necessary to detect and measure the response is not known, continuous monitoring is to be preferred.

The separated water phase of the well discharge is sampled, if available, and its radioactivity measured in a tank of known size with a calibrated detector. Thus, with a record of the tracer concentration, and knowing the rate of water discharge from the well, the total quantity of tracer discharged can be calculated.

The small cyclone separator is included when no well head separator is available. It is fitted with a gauge and bursting disc designed to blow at 8 bars. It usually operates at 1.5 to 2 bars, any higher pressure indicating a build up of silica in the cooling tubes.

As it is recommended that the photomultiplier tubes that are used should not be heated to greater than 50°C, and the sodium iodide crystal detectors will not stand rates of heating greater than 0.5°C/min, the sample must be cooled before being measured. Figure 2 shows the collection and cooling system which also acts as a low background shield for the sample and detector. The detector count rate in the 200-litre tank filled with water is around 50 c/s, but with the outer tank filled this drops to around 5 c/s. The sensitivity of this system is approximately 0.5 c/s for an iodine-131 solution containing 1 Bq/1.

With sample flow rates into the inner tank of about 5 1/min, there is usually no problem of keeping the temperature of the water below 40°C or even 30°C. A daily measurement of the flow rates to the tank and from the separator is made along with any others necessary to obtain the total water discharge of the well.

The ability to operate without a continuous cold water supply would simplify the operation considerably. RCA have recently brought out an experimental photomultiplier tube, Type C83027E, rated for an operating and storage temperature range of -85 to +175°C. The dark current is specified as 0.1 nA at 22°C. It is intended to try this.

5. COUNTING EQUIPMENT

The equipment described here and shown in Figs 3 and 4 has been built up over a number of years and suits the particular conditions and services usually available in geothermal fields in New

Zealand. The aim has been to obtain long-term stability of all components over a considerable environmental temperature range of -10°C to +40°C. Both analogue and digital data recording are very desirable. The first is for the moment by moment monitoring of the test and equipment by the field operator, and the second is to handle conveniently the considerable amount of data from each test.

The equipment is available commercially except for the logarithmic converter units, and the exterior cases of the detector systems, both of which are modifications of concepts developed at Lucas Heights AAEC Research Establishment, Australia. Single logarithmic ratemeters are available for the AAEC type 519 ratemeter/scalers.

5.1 The underwater detector

This has a stainless steel housing for a ruggedised 2 in x 2 in NaI(Tl) crystal detector, a photomultiplier tube EMI type 9804B and a dynode chain assembly. It is designed for continuous under-water use at a depth of around 100 m.

The detector to coaxial cable connector was designed for use with a stainless steel centred cable to withstand a maximum manual pull.

5.2 The AAEC type 519 ratemeter/scaler

This is a small rugged battery operated radiometric field survey meter for use with the above type detector. It is designed to withstand short immersion in water to a depth of 3 metres, and to operate within specifications between 0°C and +60°C. The four decade liquid crystal display provides a counts per second reading with three integration times from 1 to 100 seconds, and also a scaler.

It operates from rechargeable batteries, but to ensure a very stable operating condition a system of continuous charging which uses the same cable for both power and signal was developed. This allows a single run of light, cheap and readily available twin core lighting flex to each station.

Unlike the earlier Type 239 AAEC ratemeter, it does not have a recorder output of the count rate. Consequently, pulses of greater than 3 volts are sent from the detection stations to a central recording station. Attenuation of the pulses or ground loop currents are not a problem, as they would be if small analogue current signals were being sent.

A word of warning is probably necessary here. The detector case or an earth point on the ratemeter must be provided with a good direct connection to ground other than through the water in the tanks. If this is not done spectacular corrosion of the stainless steel detector case can result. This arises from the current flowing in the return conductor from the ratemeter to the earthed equipment of the recording station. Over, say, 1 km of cable, a potential of about 1.5V is generated. Corrosion rates for stainless steel immersed in a conducting solution at that potential are very high.

5.3 Logarithmic converter

These units take up to six pulse inputs and provide logarithmic pulse rate signals of 1V F.S. for the pen recorders, and pulse signals for the data loggers. The main reason for choosing a logarithmic rather than a linear record is that it avoids range switching.

5.4 Data logger

The Tasman mini data logger is a four-channel, self-contained battery operated logger using a COSMAC microprocessor as its controlling element. It simply scans its four inputs at times ranging from 7½ minutes to two hours, and stores the data in a low power semi-conductor memory. The data can be read out via a simple tape recorder onto a cassette tape or directly into a computer.

5.5 Chart recorder

The units used are six pen Rikadenki recorders. The only problem experienced over years of use has been sulphide attack of the silver contacts on the range switches. This requires periodic dismantling and cleaning of the switches. For geothermal use, gold plated contacts would be preferred.

6. SINGLE WELL TESTS

The method used in these tests was a slight variant of the borehole dilution method which was reviewed by Halevy et al. (1967). No reference to its use on geothermal wells has been found.

The basis of the method is that the rate of removal of a tracer of quantity A from a length of well of volume V is given by the product of the concentration C of the tracer, and the flow Q of water through the section of V.

$$\frac{dA}{dt} = V.\frac{dC}{dt} = -\ CQ.$$

On integration

$$\ln \frac{Co}{C} = \frac{Q.t}{V} \ .$$

The apparent horizontal velocity U is then given by:

$$U = \frac{\pi.r}{2t} \ln \frac{Co}{C}$$

$$= \frac{\pi.r.\ 0.693}{2.t_{\frac{1}{2}}} \qquad \text{where } t_{\frac{1}{2}} = \text{half value time in hours.}$$

For a well of radius r = 0.075 m

$$U = \frac{8.2 \times 10^{-2}}{t_{\frac{1}{2}}} \ \text{m/hr.}$$

This relationship assumes that there is no vertical flow in the well and that the solution in the volume being considered is well mixed.

As it is necessary to bring the water to the surface to measure it, certain other initial assumptions had to be tested. These were:

1) That quantitative measurements of tracer recoveries from the well were possible.
2) That it was possible to differentiate between tracer still within the well and that which had been removed into the country rock. These are discussed later.

6.1 Method

A known amount, approximately 10M Bq, of iodine-131 tracer was injected into a well at a predetermined depth, and after a suitable delay time, during which it was shut in, the well was discharged at a bleeding rate of about 1 m^3/hr. The activity of the discharge was continuously monitored and sufficient measurements of the water discharge rate were made to estimate the flow on a continuous basis.

6.2 Analysis

The products of the time related concentrations and flow increments, on summation, give the recovered activity.

The chart recorder trace of activity with time showed a rapid rise and generally an elongated tail. It was observed, however, that an injection made in the cased part of the well, where no escape of tracer was possible, returned as a very symmetrical pulse with little tail. This was also true in most cases where there was a zero delay time. It was therefore argued that tracer remaining within the slotted liner of the well at the end of the delay period would return to the surface as a symmetrical pulse and that the activity drawn back into the well from the country rock by the action of discharging the well would be seen as a tail to the pulse.

Table 1. Single well tests - Broadlands 1974

BR no.	Date	Depth		Delay hr	% remaining in well
		m	ft		
	June 1974				
8 cased to		444	1458		
	8	427	1400	0	86+
	9	463	1520	0	87+
	13	463	1520	0	86+
	10	463	1520	0.5	102
	14	463	1520	1.01	71
	11	463	1520	2.28	33
9 cased to		500	1639		
	8	477	1565	0	85+
	9	530	1739	0	90+
	10	560	1839	0	~100
	14	560	1839	0	105
	13	560	1839	0.55	97
	15	591	1939	0.55	83+
	17	621	2039	1.23	99
	18	621	2039	5.00	57
	19	686	2250	1.00	96
	22	748	2450	0	100
	20	748	2450	1.78	77
	21	748	2450	5.01	40
	May 1974				
11 cased to		484	1588		
	13	457	1500	0	123
	14	495	1625	0	68
	11	533	1750	0	16
	4	549	1800	~0.7	0
	June 1974				
17 cased to		597	1960		
	8	561	1840	0	101
	11	561	1840	0	125
	9	628	2060	0	98
	14	628	2060	1.07	81+
	15	628	2060	4.08	97
	17	689	2260	1.00	69
	18	689	2260	5.12	80
	21	750	2460	0	96
	19	750	2460	1.00	53
	20	750	2460	5.00	16
	22	811	2660	1.33	86
	May 1974				
18 cased to		538	1765		
	13	518	1700	0	124
	10	564	1850	6	68
	8	564	1850	24	8
	June 1974				
	22	625	2050	0	86
	20	625	2050	1.00	53
	21	625	2050	5.55	<4

The tracer remaining in the well could thus be estimated by doubling that measured from the beginning to the peak of the pulse.

6.3 Results

Table 1 gives the conditions and the results of the 1974 tests at Broadlands. Figures 5 & 6 show the semilog plots of recoveries against discharge delay time from which the half value times were measured for the most rapidly diluting parts of each well.

In BR11, any delay at all resulted in complete loss of the tracer. Consideration of the time available during which dilution could take place as the tracer moved upward through the length of slotted liner from the release point to the casing, indicate half value times of 0.1 to 0.2 hours. These equate to velocities of 0.8 to 0.4 m/hr. Table 2 summarises the maximum apparent horizontal velocities in each well. Also, remembering that the point of these tests was to obtain some idea as to whether a tracer with an eight-day half-life might yield a positive result for a particular array of wells, the distances between the proposed injection well BR17 and the observation wells are given and for comparison purposes, the velocities required to move the tracer between wells in an arbitrary 32 days.

Table 2.

BR no.	Depth ft	Depth m	Distance from BR17 (m)	Apparent Velocity m hr^{-1}	*Required Velocity m hr^{-1}
8	1520	463	256	0.072	0.33
9	2450	747	179	0.023	0.22
11	1850	564	152	0.8-0.4	0.20
17	2460	750	0	0.044	-
18	2050	625	212	0.07	0.28

*The required velocity is that needed to move the distance between the bore in question and BR17 in 32 days.

6.4 Conclusions

As the required velocity fell within the range of the measured velocity, it was concluded that a multi-well test had some chance of success, and that it should be attempted.

7. MULTIWELL TESTS

7.1 Broadlands

Fig. 7 shows the location of wells in the Broadlands fields and Table 3 summarises in chronological order the tests made.

7.1.1 BR11 Injection -

The aim of the first multiwell test was to find if there was water movement in the field in the undisturbed state, i.e., without any of the wells discharging. At that time (1974) the field had been shut in since the closing of all wells in 1971 following three years of output testing.

BR17 was selected as the injection well on the basis of it being at the centre of a group of closely spaced wells, BR18, 9, 8 and 11, and monitoring stations were set up at these positions.

On 23 May 1974, 74 GBq of iodine-131were injected at 730 m depth in BR17. Five weeks later no return of tracer had been detected at any monitoring point and the test was discontinued.

It should be noted that during the 1974 tests the sample collection drum was only of 50 litre capcity and there was no external water shield. Hence the background count rate was approximately 10 times greater than that obtained in the equipment described in section 4.

Despite this lack of success a second test was made on 4 October 1974 by injecting a similar quantity of iodine-131 into BR11 at 564 m. Wells BR18, 17, 8 and 4 were monitored with BR4 being replaced by BR2 on 10 October 1974. Four days later, activity began appearing at BR8 and the concentration increased for the next 15 to 20 days, Fig. 8. A total of 0.6 GBq was discharged in 53 days with a mean flow around 600 1/hr. It is estimated from the slope of the tail of the peak that a further 0.3 GBq would ultimately have been discharged at the same flow rate. This corresponds to 1.2% of the injected tracer. To some extent this recovery depends on the discharge rate. If the peak of the discharge curve is taken to be at 27 days, then the peak velocity between BR11 and BR8 is 0.3 m/hr.

Though the flow direction appears to be directly southward, it is more likely that it is along the fault running south-westward from BR18.

Reference to Fig. 9, however, shows the possibility of horizontal flow in the Waiora formation.

7.1.2 BR33 Re-injection -

BR33 was drilled to 365 m as a shallow reinjection experimental well. A re-injection system as shown in Fig10 was set up early in 1977 and run for over six months during which time pilot plant studies on silica removal were made. The discharge from BR11 passed through the cooling pond which had a capacity of about 1000 m^3. The water at a temperature of about 80°C was pumped to BR33. Full discharge from BR11 was around 300 m^3/hr.

On 21 May 1977, 270 GBq of iodine-131 were injected into the outflow of the cooling pond. Wells BR8 and 11 were monitored, and the results are given in Fig. 11. The results after around day 30 start to have unacceptably large errors due to a combination of statistical uncertainties on the background subtracted data and large decay correction factors. The tail of the BR11 curve is an exponential extrapolation.

On the assumption that the BR11 curve continues to decay with a half value time of 18 days, the integrated return of activity is very close to 37 GBq or 13.7% of that injected. This sum includes material which has been recycled continuously. If f is the fraction recycled through BR11 in a single pass, then the observed concentration of tracer results from the sum to infinity of the terms $f + f^2 + f^3$ ---- , that is

$$\frac{f}{1-f} = 0.137$$

$$\therefore \quad f = 0.12.$$

In other words, 12% of the material (tracer or water) re-injected in BR33 reappears in BR11 in a single cycle.

Table 3. Summary of Broadlands tests 1974-1980

Date	Injection well	Iodine-131 GBq	Wells Monitored	Days monitored	% tracer return Monitored	Total
23/ 5/74	BR17	74	18,9,8,11	35	0	0
4/10/74	BR11	74	18,17,8,4,2	53	0.8	1.2
21/ 5/77	BR33	270	11	44	10	12
			8	44	2.5	5
10/12/78	BR34	55		see Table 4		
3/11/80	BR13	95		see Table 5		
10/11/80	BR28	80		see Table 5		

A further 2.5% of the tracer was recovered from BR8 over 44 days which would indicate a total return there of at least 5%. It is possible to consider this figure in a different way. The discharge at BR8 contained 5% of the water re-injected at BR33, i.e., 15 m^3/hr, but as the total discharge at BR8 was 106 m^3/hr then 14% of the discharge is re-injected water. This is termed this the "re-injection contamination factor".

The travel time from BR33 to BR11 was two days to the first appearance, eight days to the peak, and the mean residence time was about 30 days.

From BR33 to BR8 there were seven days to the first appearance, and somewhere between 30 and 40 days to the peak.

It is interesting to compare the results of this test in which both wells were discharging fully, with those of the 1974 test when the wells were essentially closed. The travel time from BR11 to BR8 for the first appearance in one case was four days, and the other, five days, which when the vastly different conditions are considered is not much different. Can this be interpreted as saying that the driving forces within the system are so great that activities such as re-injection and well discharge on the scale used do not significantly perturb the system?

7.1.3 BR34 Re-injection -

In this test water from BR2, separated at atmospheric pressure but not exposed directly to air at any time, was injected for a period of several months into BR34. Two small four-inch diameter monitor wells had been drilled to a depth of 400 m. BRM2 is 45 m to the north, and BRM4 is 70 m SE of BR34, which was at that time about 400 m deep.

An injection of 55 GBq was made at the BR34 wellhead on 10 December 1978. The results are shown in Table 4 and Fig. 12.

While the table headings are self-explanatory, some may need comment. The very first arrival time of the tracer is difficult to determine precisely due to background variations, but the time of reaching 10% of the ultimate peak value is usually readily determined as the curve is rising sharply. To eliminate the effects of injecting different amounts of tracer in the various tests, the concentrations of tracer per litre as measured are normalised by dividing by the amount injected and then, to always have whole numbers, multiplied by 10^{12}. Complete returns have been estimated by matching an exponential decay to the tail of the tracer response measured.

Table 4. Summary of BRM2 and BRM4 responses from tracer injected in BR34

	Days to 10% of peak	peak arrival days	peak concentration $10^{-12}\ \ell^{-1}$	32-day return	estimated final return
M2:	15	3.3	14,000	2.3%	2.9%
M4:	10	2.5	5,700	1.5%	1.9%

The bumps particularly noticeable on the BRM2 curve are due to the sample flow being stopped while the air lift pumps were being serviced.

A detailed consideration of the flow rates in the three wells which were around 162 m^3/hr into BR34 and 5 m^3/hr from BRM2 and BRM4, permitted the calculation of "re-injection contamination factors" of 75% for BRM2 and 50% for BRM4.

From the similarity of the concentrations in the monitor wells during the latter half of the test and the divergent directions of the wells from BR34, it might be inferred that the injected water was approximately uniformly dispersed around the injection well. However, the relative sharpness of the BRM2 peak and the similarity of the ratios of peak times to distances does suggest a significant component of linear as well as radial symmetry in the injected field.

7.1.4 BR19 to BR13 and BR35 to BR28 re-injection -

These tracer tests were run in conjunction with two hot water (160°C) re-injection tests being run during most of 1980 concurrently in different parts of the field. The re-injection wells were selected as being toward the edge of the field but still within the high temperature zone. In both cases the re-injection rates were around 150 m^3/hr and the injection wellhead pressure was 3 to 4 bars. The tracer injection data are given in Table 3 and the test results summarised in Table 5. The tracer return graphs are given in Figs 13 and 14.

Several instrument failures prevented a continuous record of data at wells BR25 and BR35. However, a positive though small return was obtained at BR25 starting on the sixth day, while the best assessment of the BR35 data was that no return occurred there. No responses were recorded at any other monitored well.

7.1.4.1 - Discussion on BR19 to BR13 re-injection

Despite the evidence of good pressure connections between wells BR13, 19, 20 and 23, a flow connection was demonstrated only from BR13 to BR23. The full discharge of BR19 was not able to induce a flow in that direction.

Part way through the test (7 days after injection) the discharge from BR23 was increased from about 1 t/hr to 47 t/hr, because of a falling bleeding rate which was incorrectly diagnosed as the well cooling off. It was feared that it might stop discharging altogether. Activity had actually started to appear in the output at the beginning of the fifth day after injection. It should also be remembered that at a discharge rate of 1 t/hr the water being taken into the well takes a day or more to reach the surface. Therefore water from the re-injection would have arrived in the vicinity of BR23 late in the third day. Whether the con-

Table 5.

Well	Days to 10% of Peak	Days to Peak	Peak concentration $l^{-1}. 10^{-12}$	Discharge t/hr.	Tracer Return %	Days Monitored	Reinjection contamination factor - %.
BR 25	7.5 (±0.2)	15 (±1)	130 (± 50)	0.9	0.0033 (±0.0015)	28	0.6 (± 0.3)
BR 23	6.9 (±0.05)	16.5 (±0.5)	2500 (± 250)	0.9 to 10.11.80 47 from 10.11.80	5.9 (± 0.5)	34	19 (±0.2)
BR 19				150	0	34	0
BR 20				0.6	0	34	0
BR 24				1	0	28	0
BR 27				40	0	28	0
BR 35				150	0	28	0

Uncertainties in concentrations and return at BR 25 are 30% due to probe calibration.
and 20% " " background.
" " " " " " BR 23 are 10% " " probe calibration.

centration would have reached the same level as that recorded from the higher discharge rate cannot be determined, but differences in the concentrations would indicate different feed patterns.

The only obvious connection between BR13 and 23 is that illustrated in Fig. 9, which shows feed zones for both wells in the Rangitaiki Ignimbrite. Feed zones for BR20 are in the next higher formation, the Rautawiri Breccia, and for BR19 in that formation and in the much higher Waiora Formation.

7.1.4.2 Discussion on BR35 to BR28 reinjection

The response at BR25 may be via a fault shown by Grindley and Browne (1975) (reproduced here as Fig. 15), from which both wells feed.

Both test results show the potential for rapid movement of re-injected water back into the field.

7.1.5 1981 tests

The conditions for the four tests made so far this year are given in Table 6.

Table 6

Location	Date	Injection well	Injection fluid	I-131 GBq	Wells monitored	Duration days
Broadlands	6/3/81	BR30	Hot water (BR35)	181	BR25,27,28, 35	36
"	13/3/81	BR13	Cold water (river)*	63	BR19,20,23	29
"	11/6/81	BR 7	Hot water (BR27)	163	BR10,16,27, 29,36	39
"	11/6/81	BR34	Cold water	167	BR6,13,19,31	39

* approx. twice volume of well (32 m^3), i.e., 66 m^3.

7.1.5.1 - Discussion

No sign of the tracer has been detected at any of the observation wells in any of these tests.

The most surprising result was that at BR23, which in the previous test (November 1980) had shown a total tracer return of around 10% from a continuous injection of 150 tonnes/hr of hot water from BR19. This emphasises the perturbing effects which reinjection can have on the field. This is in contrast to the early results from BR11 to BR8 in which the BR33 re-injection had virtually no effect on the transit time with no reinjection and all wells closed in.

Perhaps it could be argued that the natural flow, if any, is from NW to SE along the faults, as demonstrated in the BR11-8 test, and that an injection in BR23 could test this. Unfortunately, BR6 was not monitored in the March test.

The no-response situation, while not very interesting from an experimental point of view, is very encouraging as far as re-injection of waste water into the field is concerned. Partly as a result of the tests reported here, and partly as a result of overseas experiences, the quest for reinjection sites has moved to the outer limits of the field. A negative result on a four or five week test is, of course, no guarantee of the safety of years of reinjection on a production basis. The need for a reliable longer term tracer is very apparent.

7.2 Wairakei

Over the years since the opening of the Wairakei field a number of wells in the north-west corner of the field have failed due to the inflow of relatively cool water. Some have been grouted up, some, like WK101 and WK107, are still in existence but no longer producing, and others such as WK80 have shown signs of reduced /output due to inflowing cool (160°C) water below the steam production level, which actually flows down the well. In the case of WK107 this downflow has been measured by the downhole spinner method at up to 300 m^3/hr. With a decision to grout up the well pending, it was suggested that a tracer test could indicate whether this cool water inflow was adversely affecting the production from nearby wells. The details of that test and others that derived from it are given in Table 7.

Table 7. Summary of Wairakei tests

Date	Time	Injection well	Tracer Nuclide	Tracer Quantity GBq	Injection depth m
2/12/78	1555	WK107	I-131	74	304
14/ 3/79	0920	WK107	"	152	334
29/ 6/79	1120	WK101	"	162	400
22/ 8/79	1044	WK107	Br-82	3.1	320
5/ 2/80	1534	WK80	I-131	155	397

The results are presented in Tables 8-11, and are summarised graphically in Fig. 16. The continuous, arrowed lines indicate returns of >1%, the dashed lines 1% to 0.1%, and the dotted lines <0.1%.

Figs 17-26 place on record the responses of all wells in this series of tests.

7.2.1 Discussion -

From the December 1978 injection in WK107 the very rapid response of WK48, Table 8a, and the sharpness of the peak in Fig. 17 provided a dramatic start to these tests. The underground flow velocity as measured by the peak arrival time was about 7 m/hr in marked contrast to that observed at the other nearby wells WK67 and WK66 along the Waiora fault. Does this indicate a slow north-eastern flow along the Waiora fault? A second test in the same well in March 1979 with a much wider array of monitor wells helped to answer that question. Table 9 and Fig. 18 show the results at WK48 and WK67 to be very reproducible, with an even sharper response and larger return at WK24. The peak velocity in this latter case was 21 m/hr. Examination of Table 9 and Figs 19 and 20 reveals no significant difference in the arrival or peak times at the remaining wells along the Waiora fault. There does not

Table 8: Tracer recovery from injections in WK107

(a) December 1978

Well	Days to 10% of peak	Days to peak arrival	Total % recovered - in -	Days monitored
WK48	0.3	0.7	1.4 ± 0.1	35
WK66	4.0 ± 0.5	~11	0.4 ± 0.2	35
WK67	4.5 ± 0.5	11	0.3 ± 0.1	35
WK108	0	2	0 ± 0.1	35
WK76	-	-	not detected	35

(b) August 1979 Bromine - 82

Well	Days to 10% of peak	Days to peak arrival	Total % recovered - in -	Days monitored
WK 24	0.2	0.5		5
WK 48	0.3	0.7		5
No response in WK18, 44, 55, 76, 88, 103, 116,121.				5

Table 9: Tracer recovery from injection in Wk107 - March 1979

Bore	Days to 10% of peak	Days to peak arrival	Peak Concentration	Total % recovered	- in -	Days Monitored
WK24	0.2	0.4	10900	3.73		29
WK48	0.3	0.7	2360	1.33		26
WK67	2.2	>10	46	0.32		29
WK70	4.0	9.5	43	0.25		29
WK68	4.0	>10	39	0.07		26
WK30	4.5	9.0	55	0.28		29
WK83	4.5	11.0	53	0.34		29
WK81	4.8	9.5	21	0.09		29
WK55	5.5	>10	29	0.18		29
WK108	10	>10	17	~0.1		29

Table10: Tracer recovery from injection in WK101 - June 1979

Bore	Days to 10% of peak	Days to peak arrival	Peak Concentration	Total % recovered	- in -	Days Monitored
WK121	1.2	2.5	10500	5.80		26
WK103	2.0	5.0	30	0.09		26
WK116	2.5	7.5	23	0.05		26
WK76	2.5	7-12	10	0.05		22
WK18	no response					
WK22	"					
WK24	"					
WK44	"					
WK48	"					
WK55	"					
WK74	"					
WK88	"					

Table 11: Tracer recovery from injection in WK80 - February 1980

Bore	Days to 10% of peak	Days to peak arrival	Peak Concentration	Total % recovered	- in -	Days Monitored
WK116	3.3	7.6	230	0.40		20
WK76	4.0	8.7	88	0.24		14
WK108	5.5	10.0	16	0.06		20
WK18	no response					
WK24	"					
WK44	"					
WK48	"					
WK55	"					
WK70	"					
WK83	"					
WK88	"					

appear to be any particular horizontal flow direction of water feeding these wells.

The majority of the wells were drilled to a depth of around 600 m which coincides with the top of the Wairakei Ignimbrite formation where the maximum temperatures occur. Two wells were drilled much deeper. These are WK48 and WK24. According to Grindley (1965) WK48 intercepts the Waiora Fault at a depth of 760 m or more, within the ignimbrite, while WK24 intercepts the Wairakei Fault at about the same depth. These faults intercept each other about 300 m lower still in the same formation. As WK107 probably also intercepts the Wairakei Fault, it is postulated that the more dense cool water flows deep from WK107 down into the fissured fault zone in the ignimbrite where a rapid south-westerly flow exists. WK24 is feeding directly from this zone, as must also be WK48. The other wells along the Waiora Fault are being fed by a slow vertical flow up the fault which would account for the roughly simultaneous arrival of tracer at all the wells.

The smooth curves in Fig. 20 are obtained by a running mean and frequency filtering technique. Daily signal variations due to temperature cycling and spikes due to electrical storms, are removed but this is probably a less satisfactory way of treating the data than that discussed later and shown in Fig. 25. It was however the best that could be done in the circumstances, as all the wells monitored had shown some response so that no purely background data for the duration of the test were available.

With fast responses obtainable from a tracer injection in WK107, it was decided to test the performance of iodide tracer against bromine-82. The results are shown in Table 8(b) and Fig. 21. There was no detectable difference in the arrival times or the shapes of the response curves. This was a more rigorous test of the tracer than the single well

Broadlands tests which showed that quantitative recoveries of iodine-131 were obtained from the vicinity of a well.

For the June 1979 test centred on WK101, well WK121 was included. It is not a production well, because of its poor output. It is a very deep well, being cased to 1600 m with slotted liner to 2246 m. Production from that depth is very poor. Recently the casing had been perforated at around 975 m with the result that it discharged about 67 m^3/hr of water at 200°C. It was included in the test thus extending coverage to the west as far as possible. As Table 10 and Fig. 22 show, the result was spectacular with again a much smaller and slower response from intervening wells. Apart from WK76, which must be affected by the transverse fault, there was no response on the south side of the Kaiapo fault. Again, there is the situation of the cool water flowing rapidly at some limiting depth along the fault zone, and subsequently feeding vertically to the production wells.

Figs 24 and 25 show the method used to obtain and correct for the background in recent tests. It had been noticed that the major conponents of variability in the background were common, though of different magnitudes, at all monitoring stations. Thus when continuous background records are available for a test, and this is now standard practice, an average background is prepared and then normalised to some characteristic point or points of a response curve before being subtracted. Figs 23 and 26 are computed on this basis.

Reference was made earlier to a plan to close and cement up WK107. Instead, it was decided to cement grout off the inflow zone with the aim of returning the well to production. It was planned to run another tracer test on the well when the cool water inflow had been stopped. However, considerable difficulty was experienced in stopping the inflow, and with the tracer on hand it was decided, rather than waste it, to run an alternative injection test at WK80.

The results are given in Table 11 and Fig. 26. Unfortunately, WK121 could not be discharged as the temporary silencer and weir box had been removed soon after the previous test, and it would not discharge at a bleeding rate. The first arrival times in this last test are a little longer than the WK101 test, due to the longer distances involved, but the percentage returns are approaching an order of magnitude greater. This raises the question that if WK121 had been available, would it have given a 50% return and could this explain the 200°C temperature of its output.

It is hoped to extend knowledge of the flow patterns in this field by injections further to the north-east, and observing at the nearest well on the Kaiapo fault, over a kilometer to the south-west.

8. CONCLUSION

The use of iodine-131 as a tracer and 'in situ' continuous monitoring have been demonstrated to be useful tools in the investigation of geothermal production fields. Reproducible quantitative data are obtainable which can be interpreted in relationship to geological structures. In the two fields examined, hot water can flow at very high velocities in the direction of the fault planes and for distances of hundreds of metres. Cool, dense water may well provide some of the driving force for this movement, but where the water is going to is not at all evident.

As a technique for checking the reentry of reinjected water into a production field, it is very useful in the short term. In this regard, it is a much more sensitive test of reentry than measuring enthalpy changes or changes in chemical composition. Longer-lived tracers are necessary for testing reinjection on a longer time scale.

The need to make the tests under actual reinjection conditions has become apparent. While reinjection in high permeability zones may not upset the natural flow systems, where lower permeabilities exist unnatural flow patterns may be impressed on the system by pressurisation.

Distance alone cannot be relied on to prevent reinjection flow back into the field. Faulting structure must also be taken into account.

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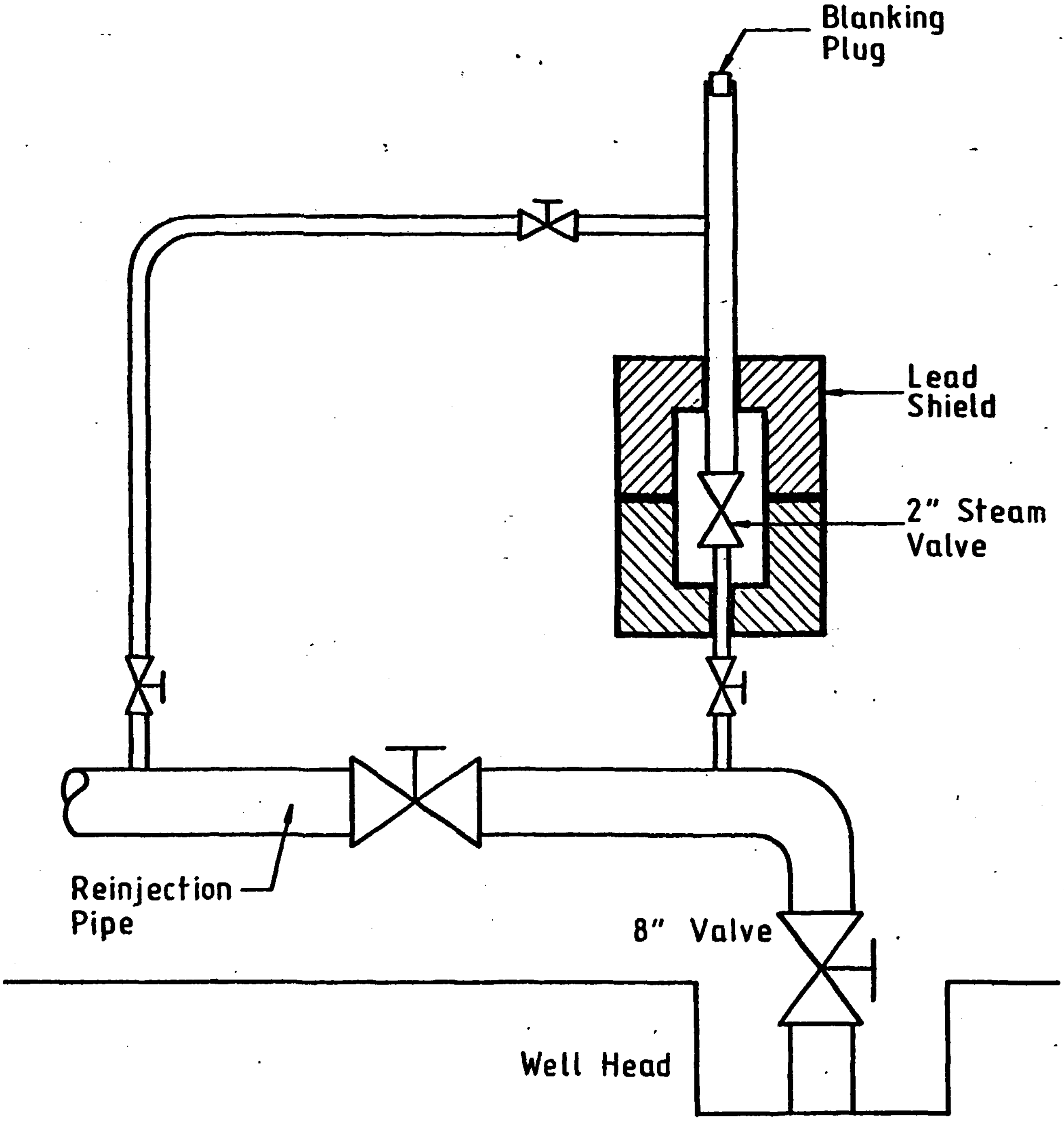


Fig. 1. Tracer Injection System.

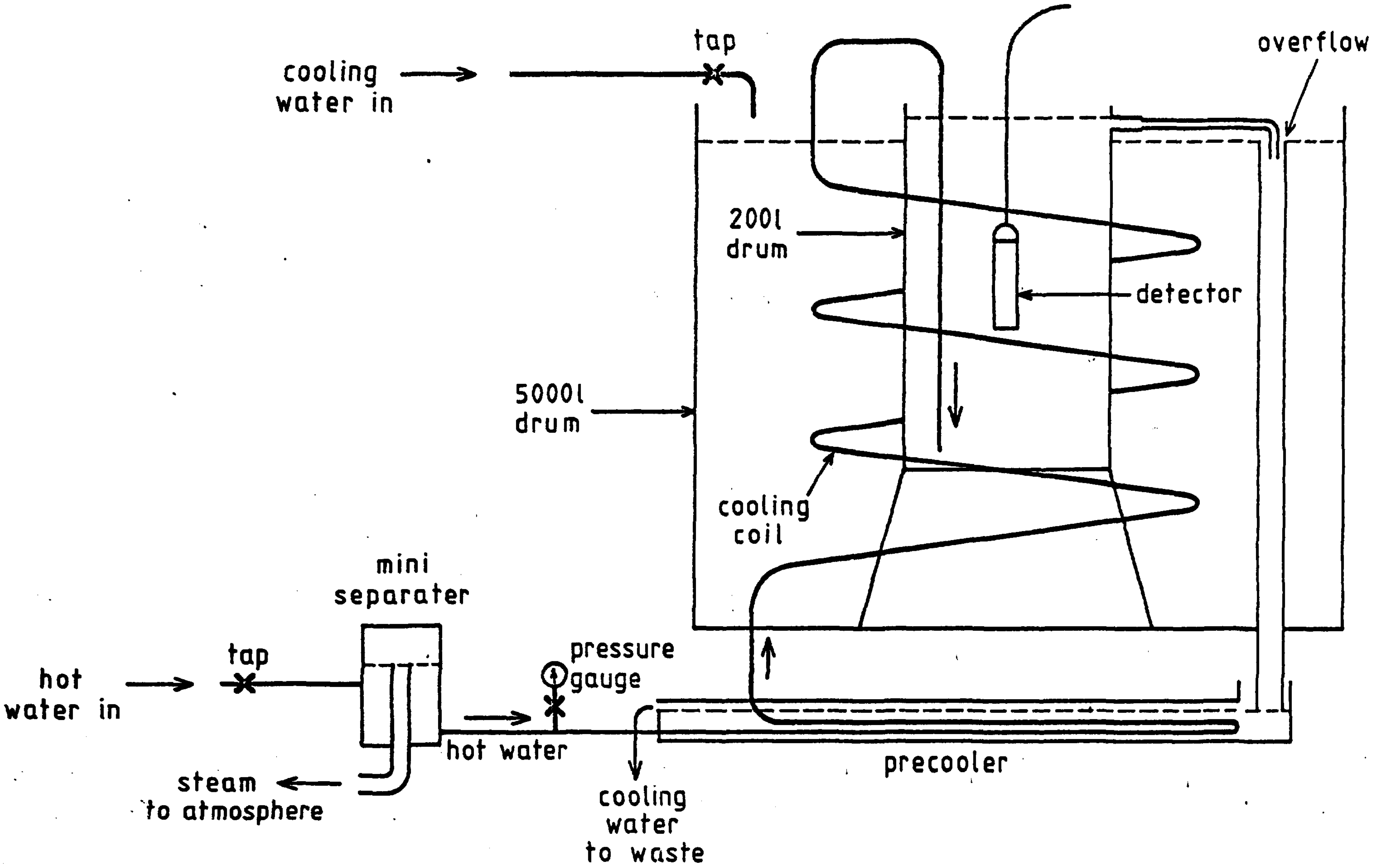
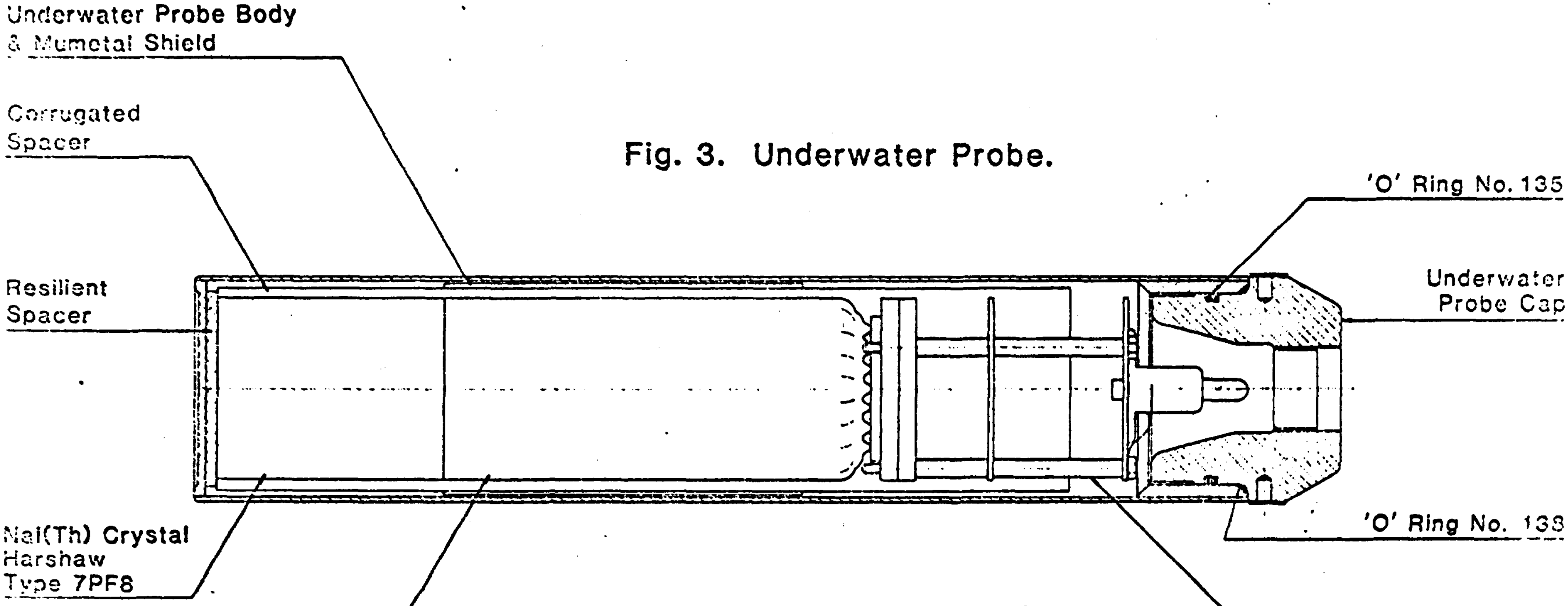
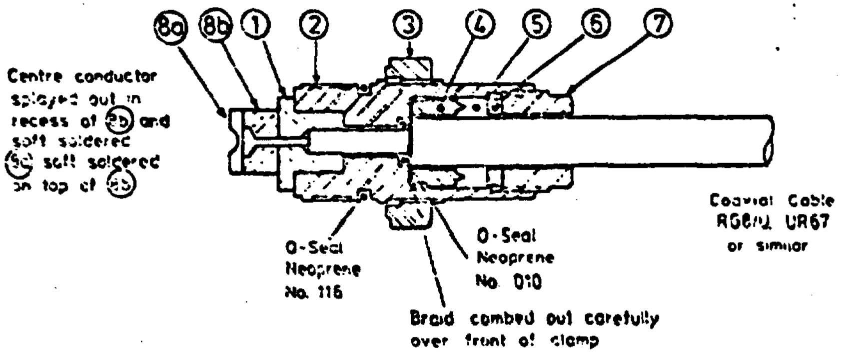


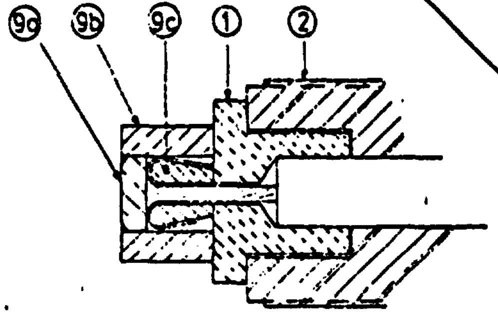
Fig. 2. Well Sampling – Cooling System.

Fig. 3. Underwater Probe.





Assembly of Plug to Standard Coaxial Cable



1. Assemble items ① to ⑦ to cable as for standard cable.
2. Fit (9c) around cable core and turn back 18 strands over it and cut off. Cut centre strand short.
3. Fit (9b) and (9a) as shown.
4. Squeeze items ⑨ in die $\frac{1}{2}$" dia. and $\frac{3}{8}$" long.
5. Remove flash.

Assembly of Plug to High-Tensile Coaxial Cable

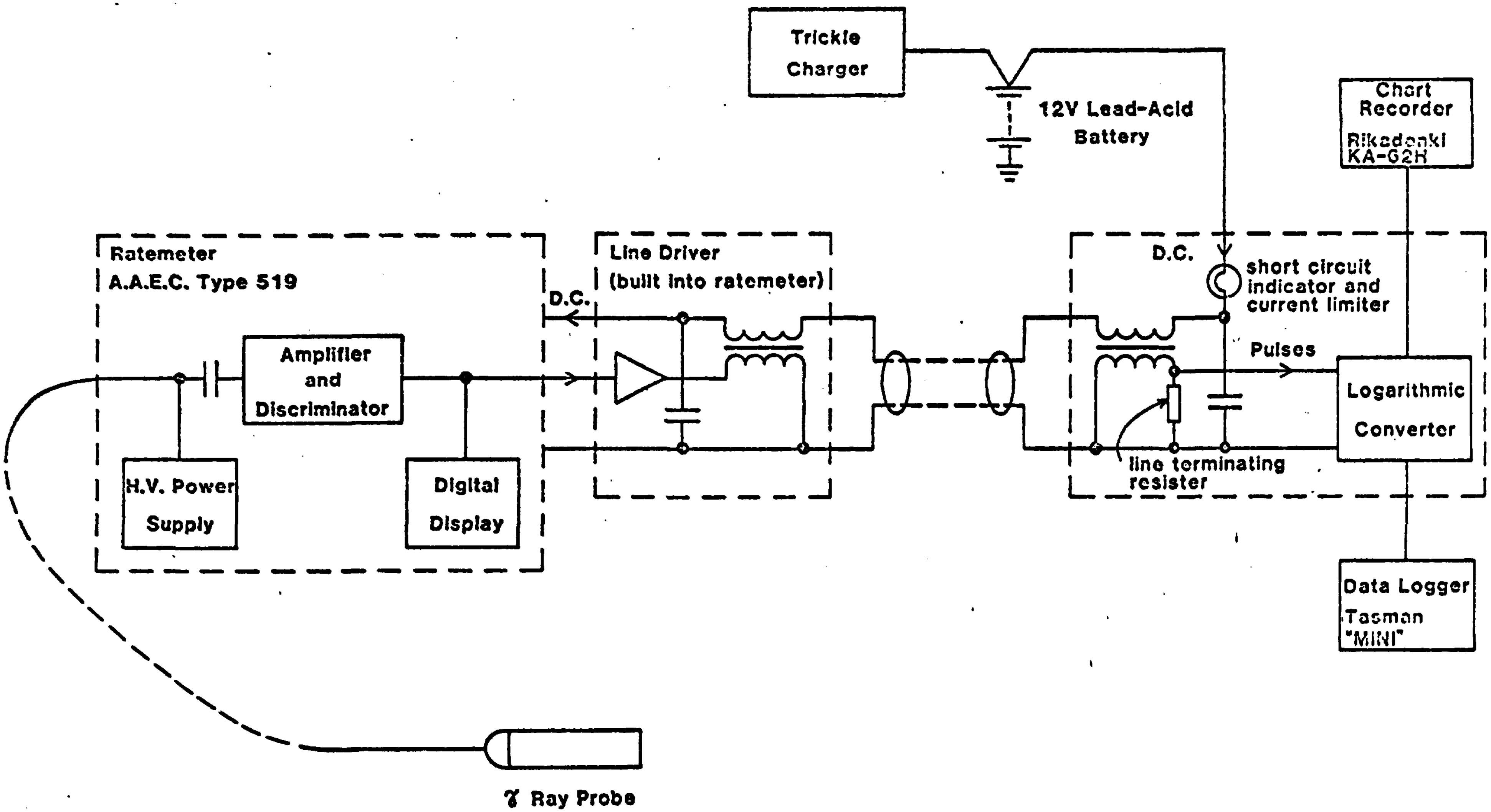
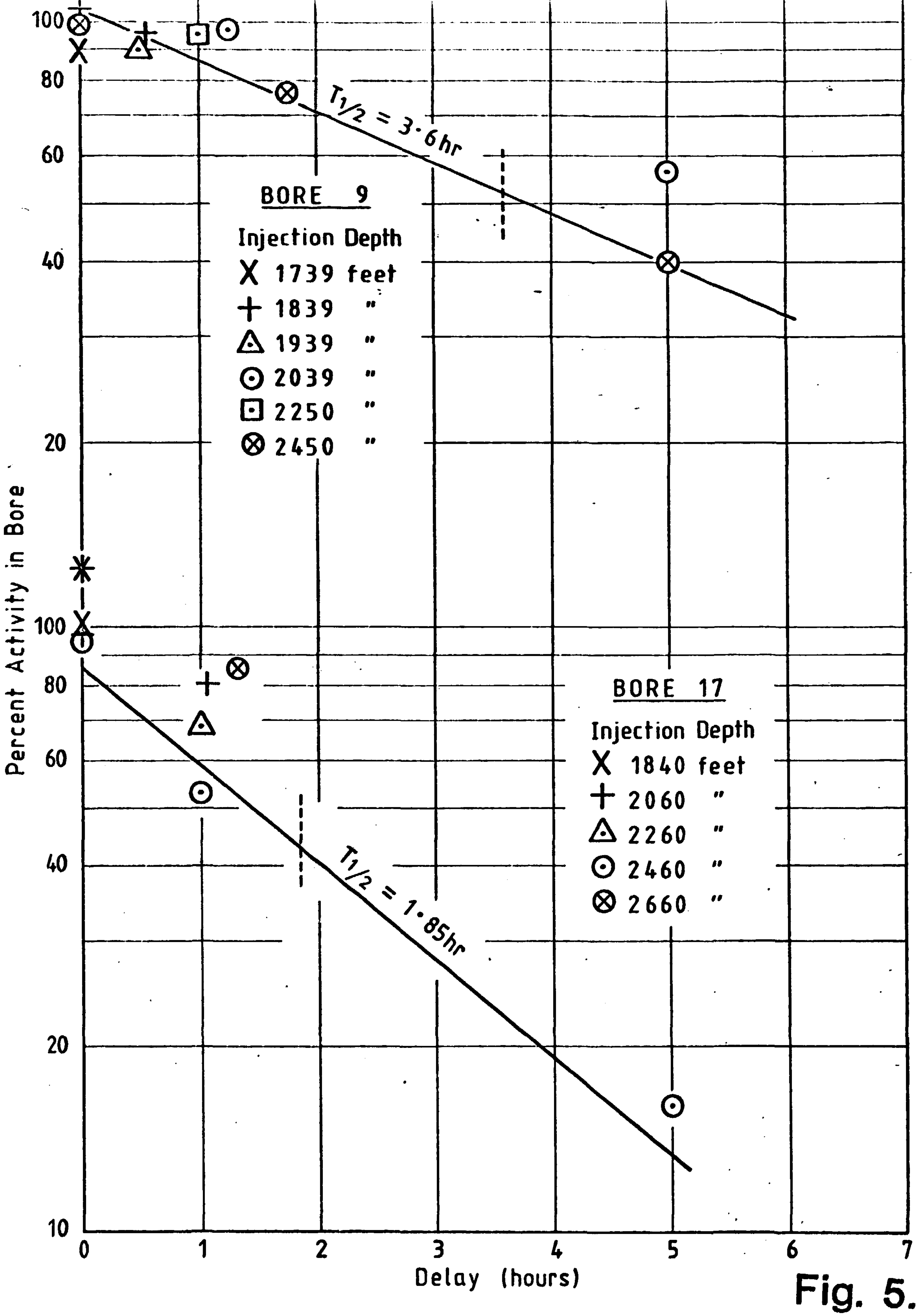
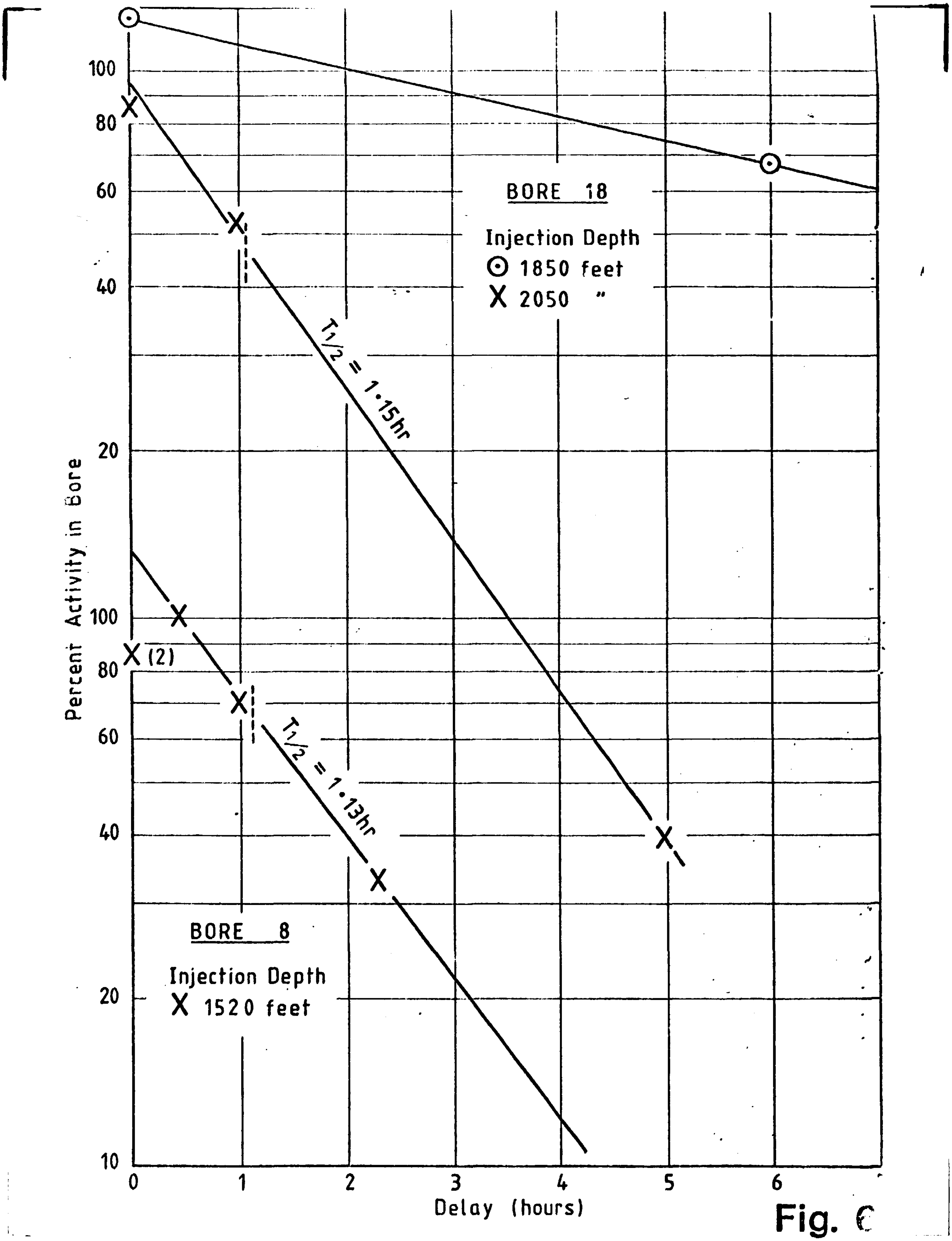


Fig. 4. Detection System.



Percent Activity in Bore
Delay (hours)
0
1
2
3
4
5
6
7
100
80
60
40
20
100
80
60
40
20
10
T1/2 = 3·6hr
BORE 9
Injection Depth
X 1739 feet
+ 1839 "
△ 1939 "
⊙ 2039 "
⊡ 2250 "
⊗ 2450 "
T1/2 = 1·85hr
BORE 17
Injection Depth
X 1840 feet
+ 2060 "
△ 2260 "
⊙ 2460 "
⊗ 2660 "

Fig. 5.



BORE 18
Injection Depth
⊙ 1850 feet
X 2050 "
$T_{1/2}$ = 1·15hr
BORE 8
Injection Depth
X 1520 feet
$T_{1/2}$ = 1·13hr
X (2)
Percent Activity in Bore
100
80
60
40
20
100
80
60
40
20
10
0
1
2
3
4
5
6
Delay (hours)

Fig. 6

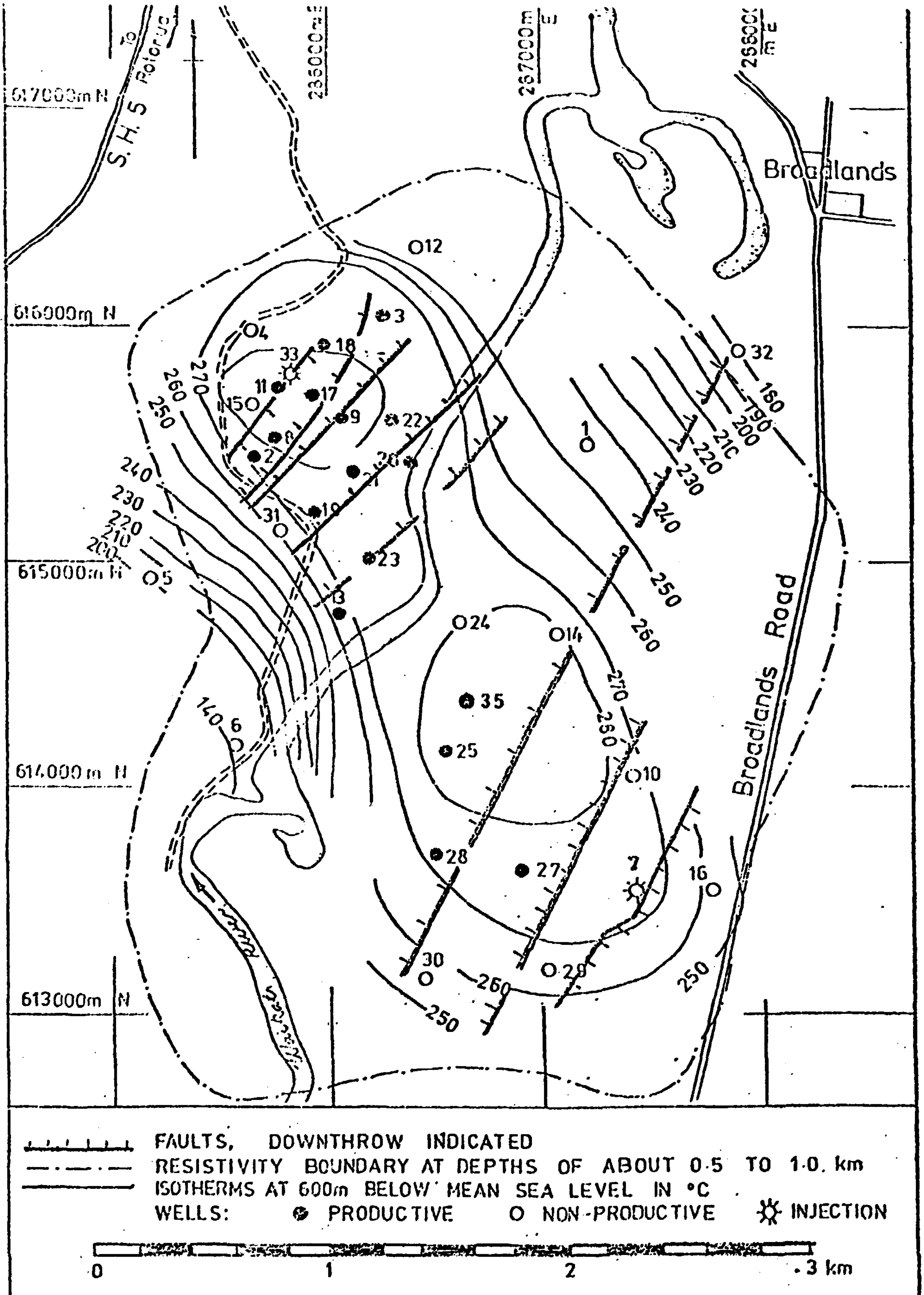


Fig. 7. Broadlands Geothermal Field.

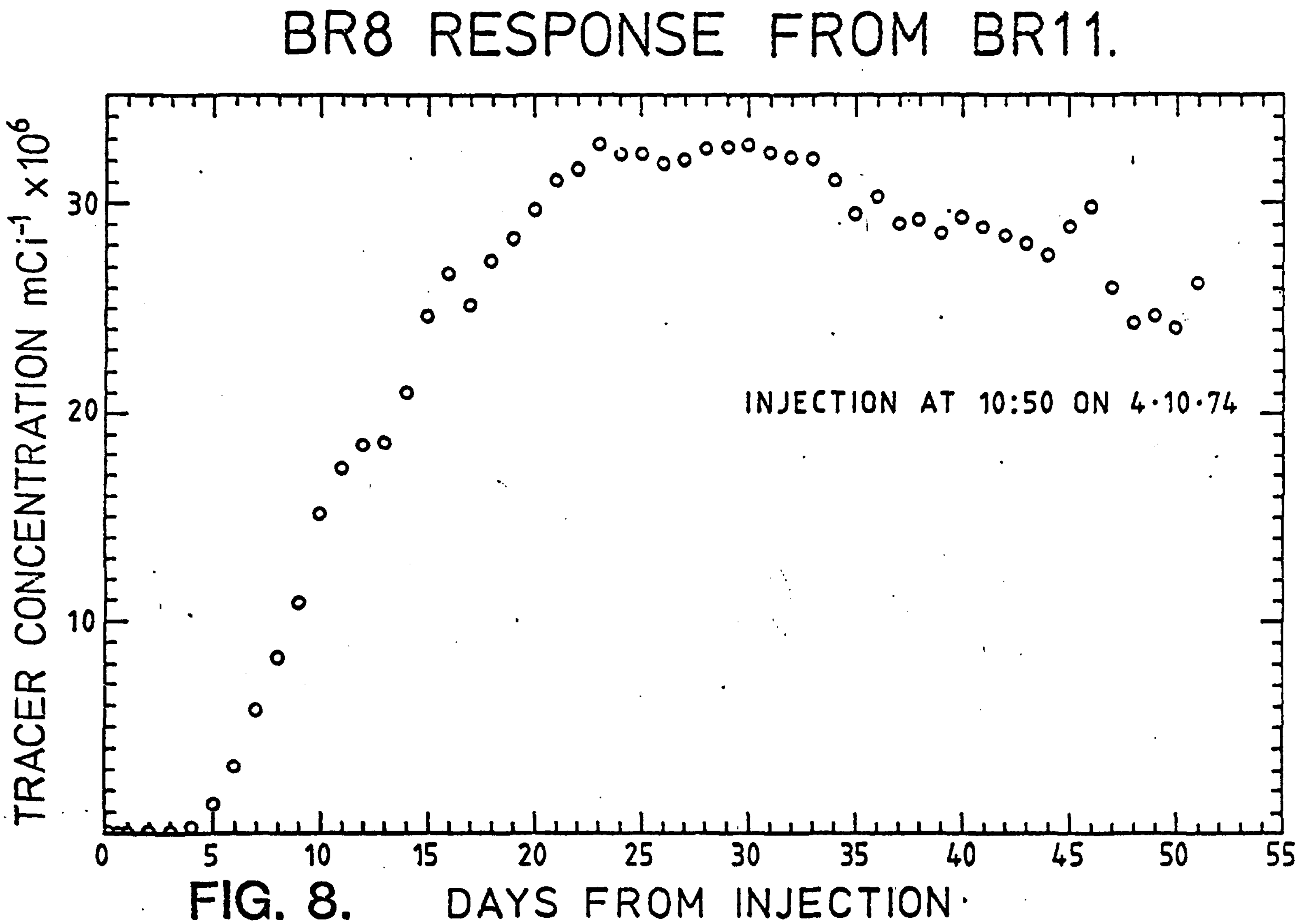
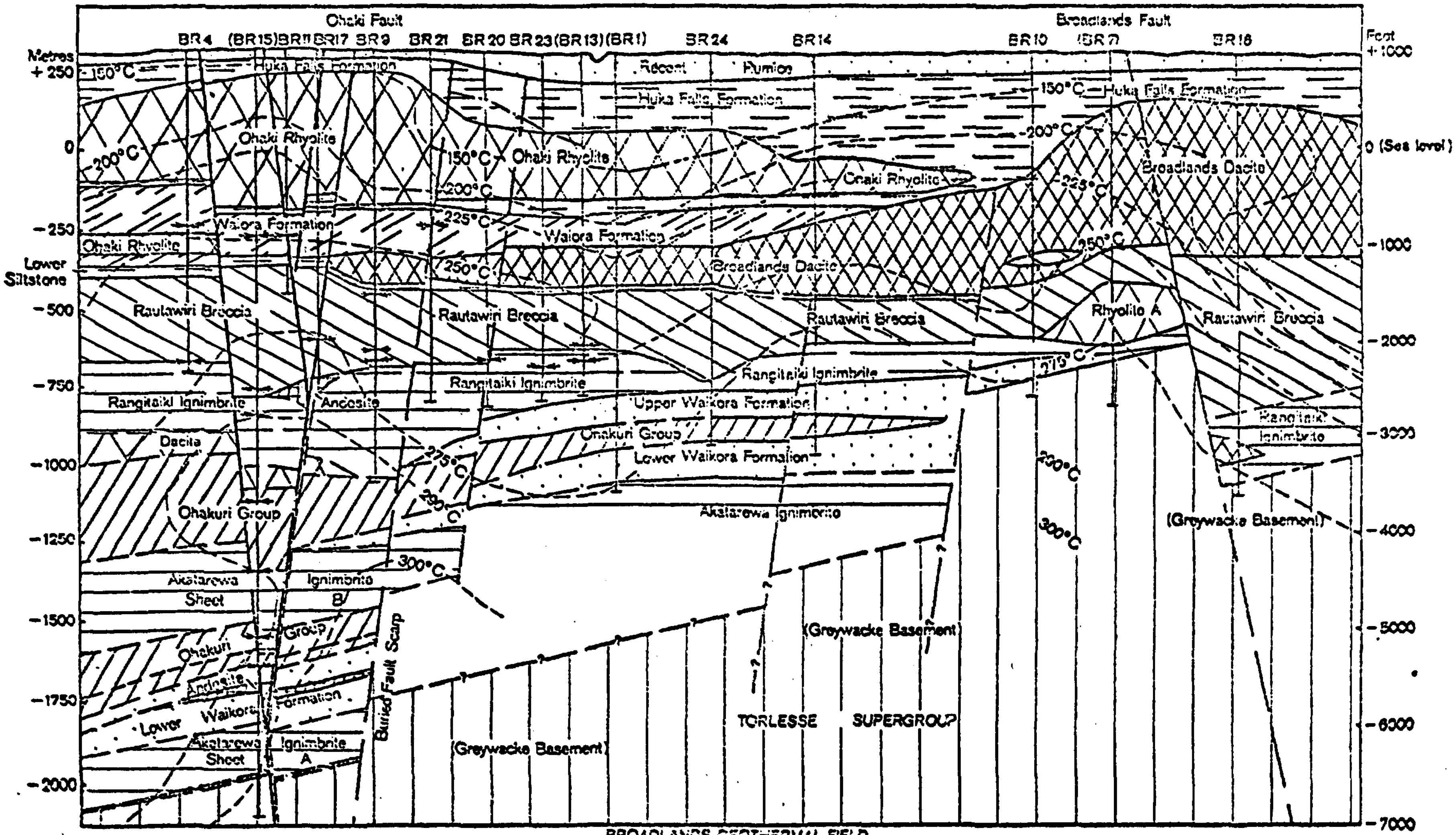

BR8 RESPONSE FROM BR11.
TRACER CONCENTRATION mCi^{-1} x10^{6}
30
20
10
0
5
10
15
20
25
30
35
40
45
50
55
INJECTION AT 10:50 ON 4·10·74
DAYS FROM INJECTION·

FIG. 8.



BROADLANDS GEOTHERMAL FIELD

Cross Section of Ohaki Geothermal Area
BR11 Drillhole on line of section
(BR13) Drillhole projected on to line of section
⟵ Zones of circulation loss

Cross Section of Broadlands Geothermal Area
BR14 Drillhole on line of section
(BR7) Drillhole projected on to line of section
⟶ Zones of circulation loss

0 1 km

Fig. 9.

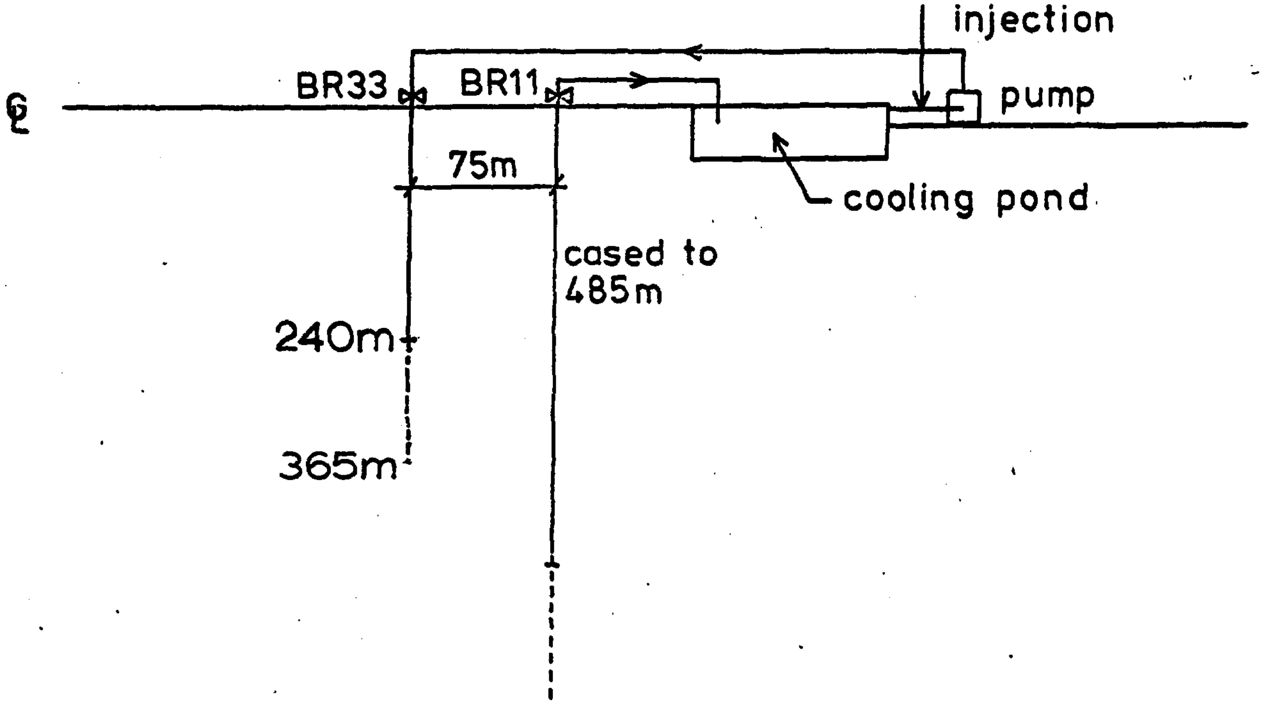


Fig. 10. Broadlands Reinjection Test

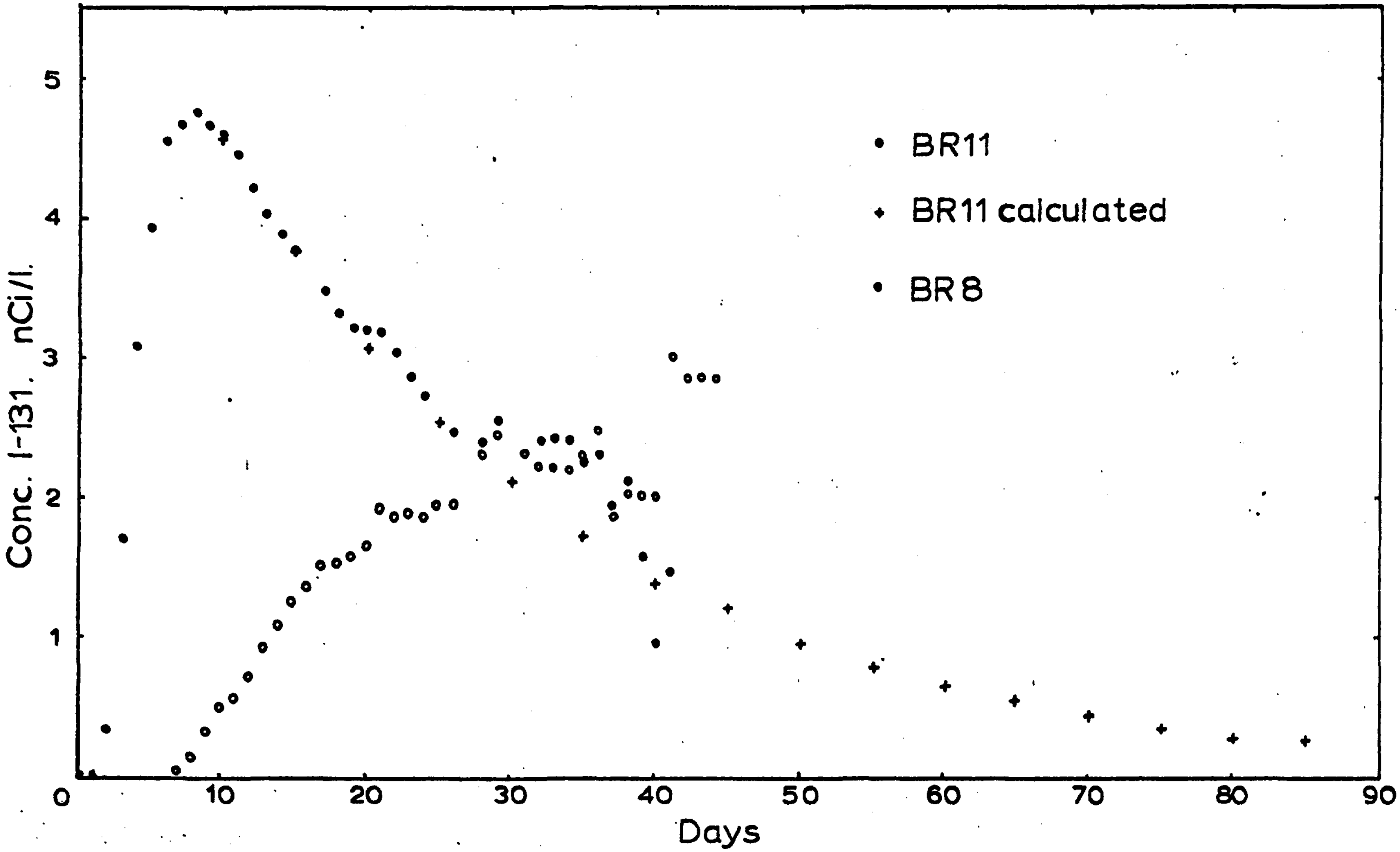


Fig. 11. Tracer Discharge from BR11 & BR8.

FIGURE 12. BRM2 AND BRM4 RESPONSE FROM BR34. DEC-78.

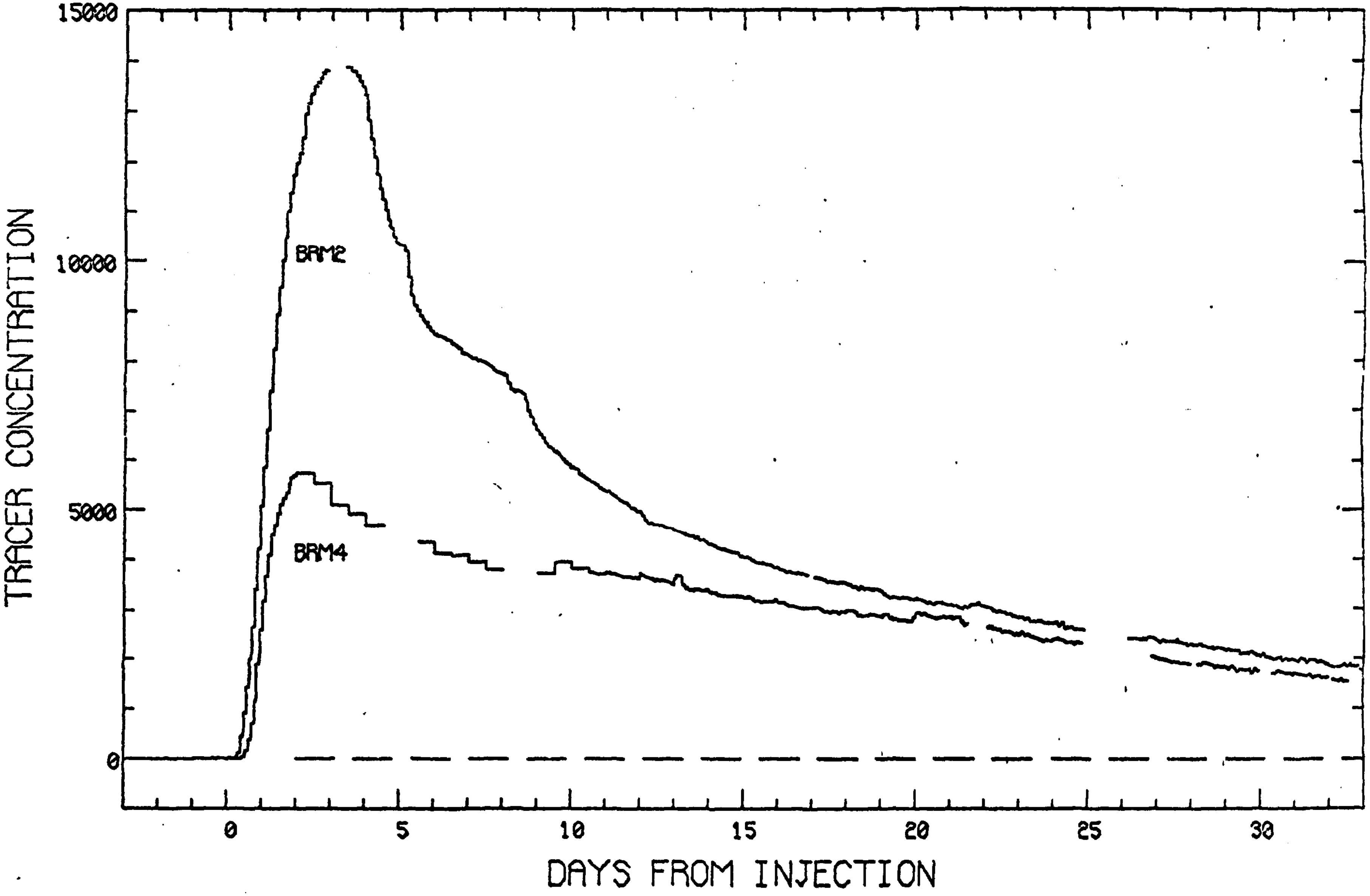


FIGURE 13. BR23 RESPONSE FROM BR13. OCT-80.

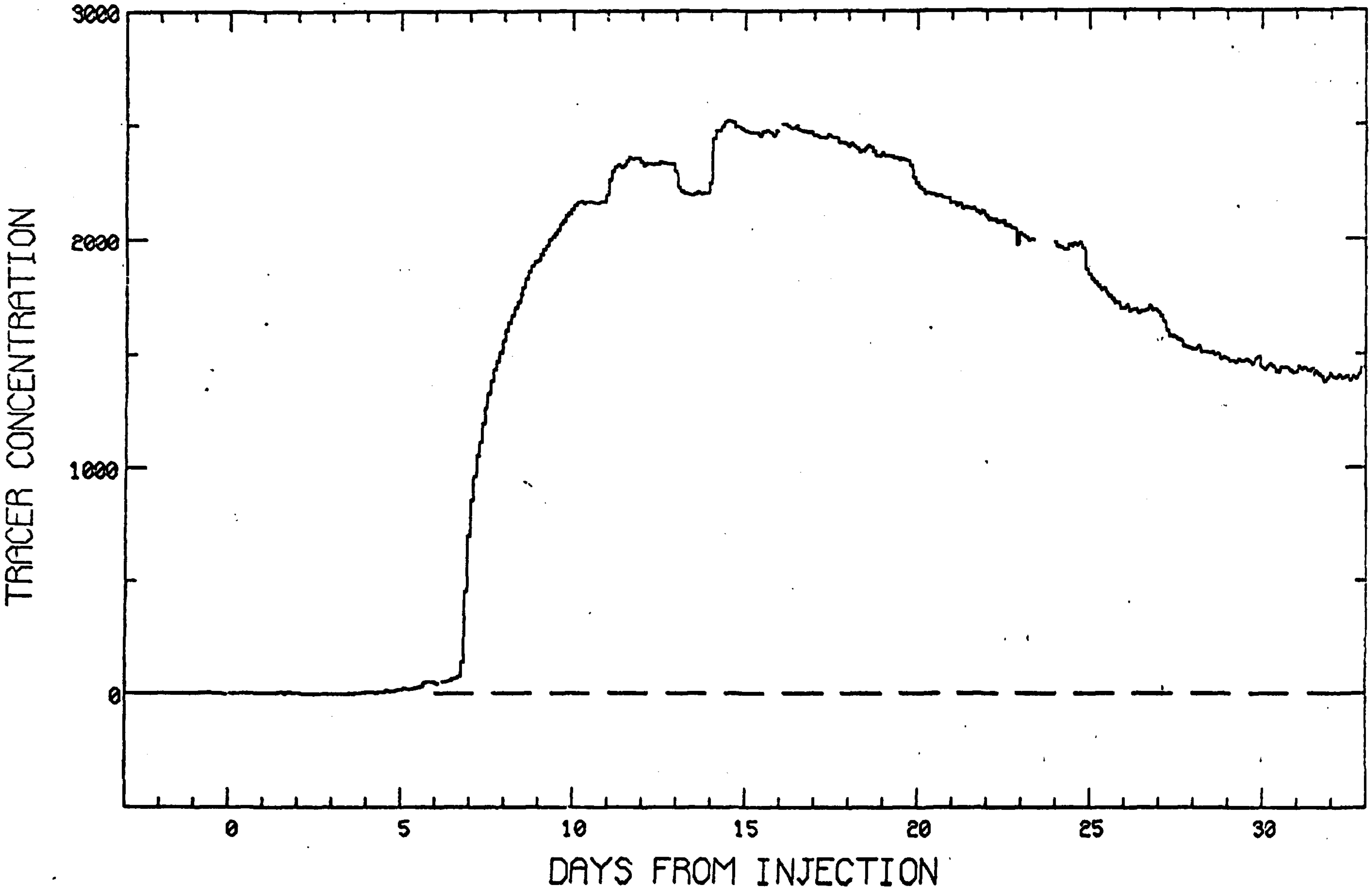
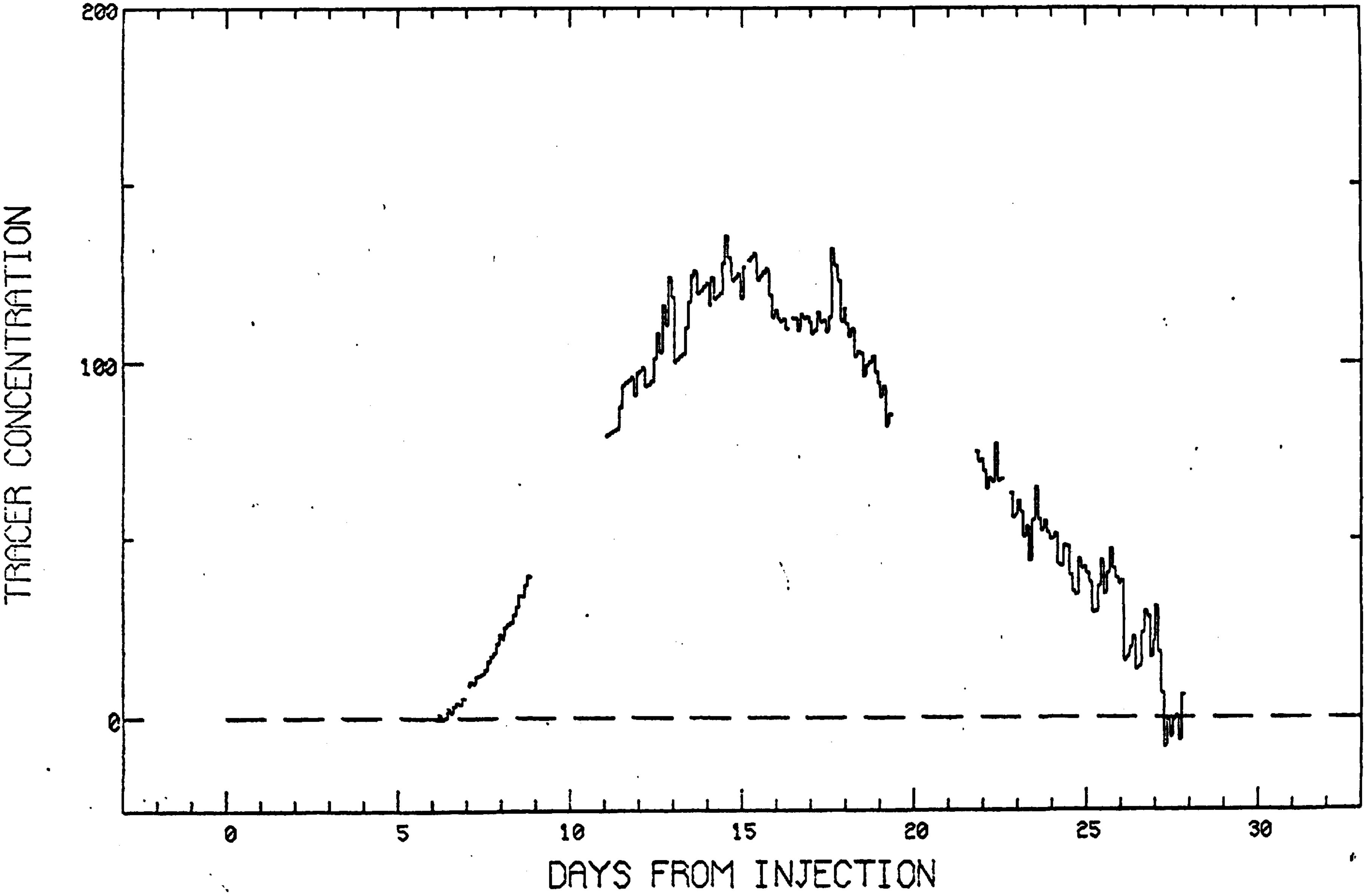


FIGURE 14. BR25 RESPONSE FROM BR28. OCT-80.



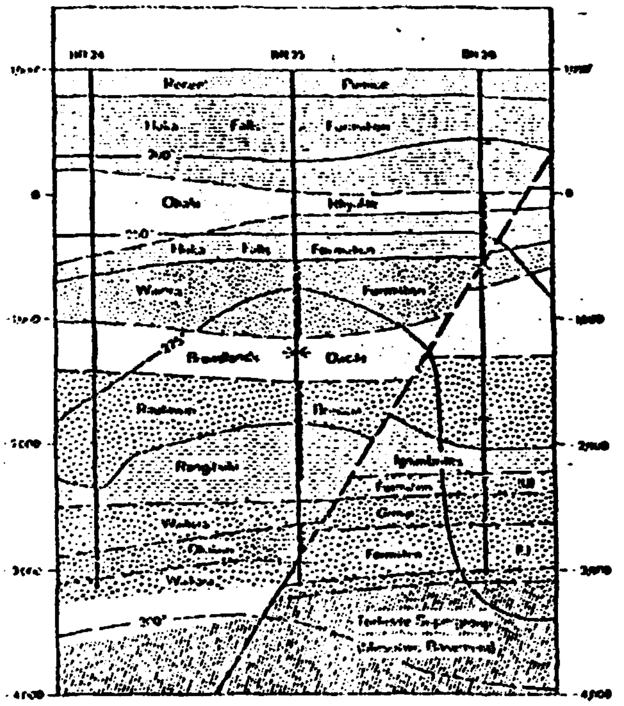


Figure 15. Cross section of BR24 to BR28, showing structure, distribution of adularia (black) where not coexisting with albite, faults, isotherms, and loss-of-circulation/inflow zones, Broadlands. Scale in feet, with no vertical exaggeration.

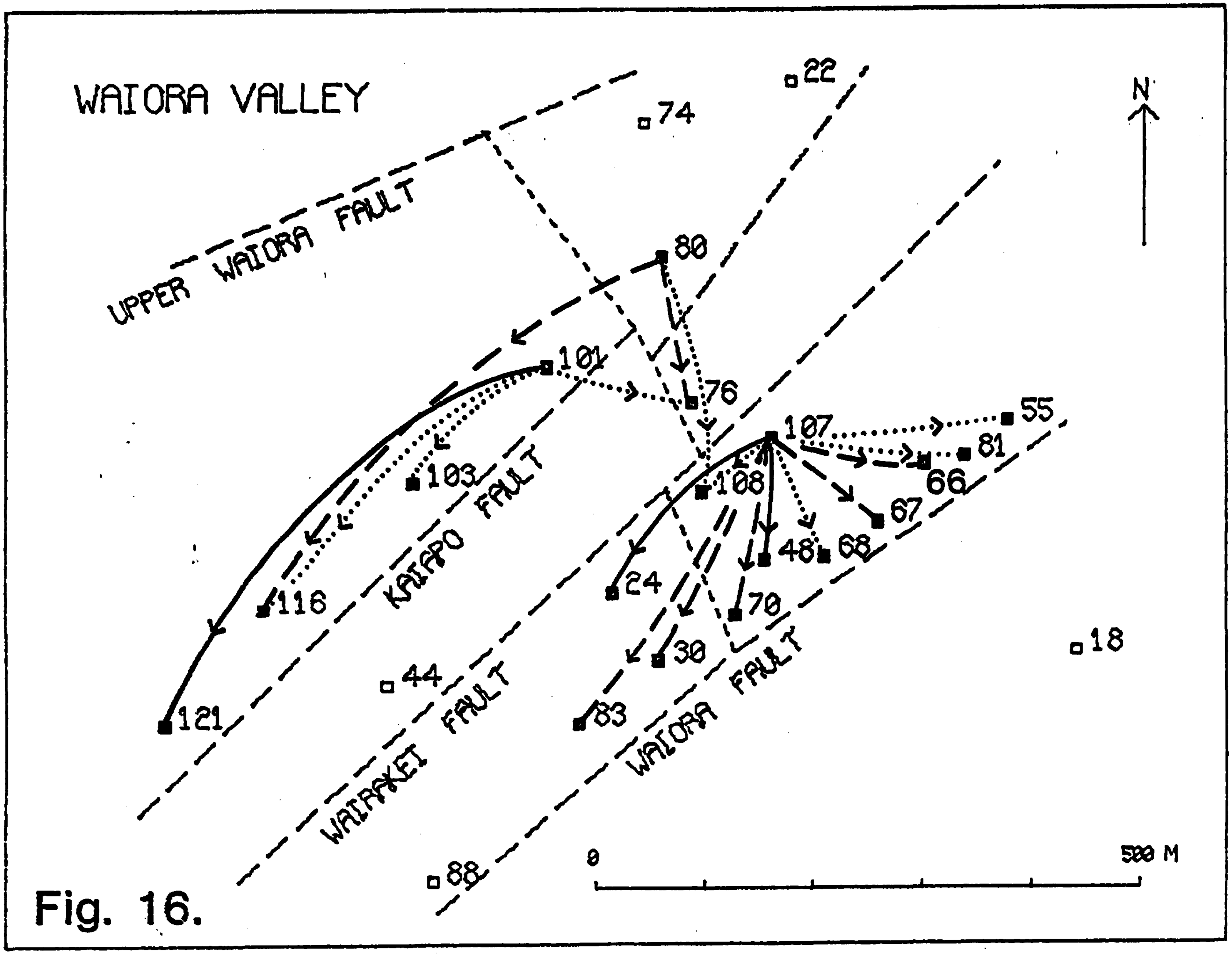

WAIORA VALLEY
N
UPPER WAIORA FAULT
KAIAPO FAULT
WAIRAKEI FAULT
WAIORA FAULT
22
74
80
101
76
107
55
81
66
67
68
48
108
103
116
121
24
70
30
83
44
18
88
0
500 M

Fig. 16.

FIGURE 17. RESPONSES FROM WK107. DEC-78.

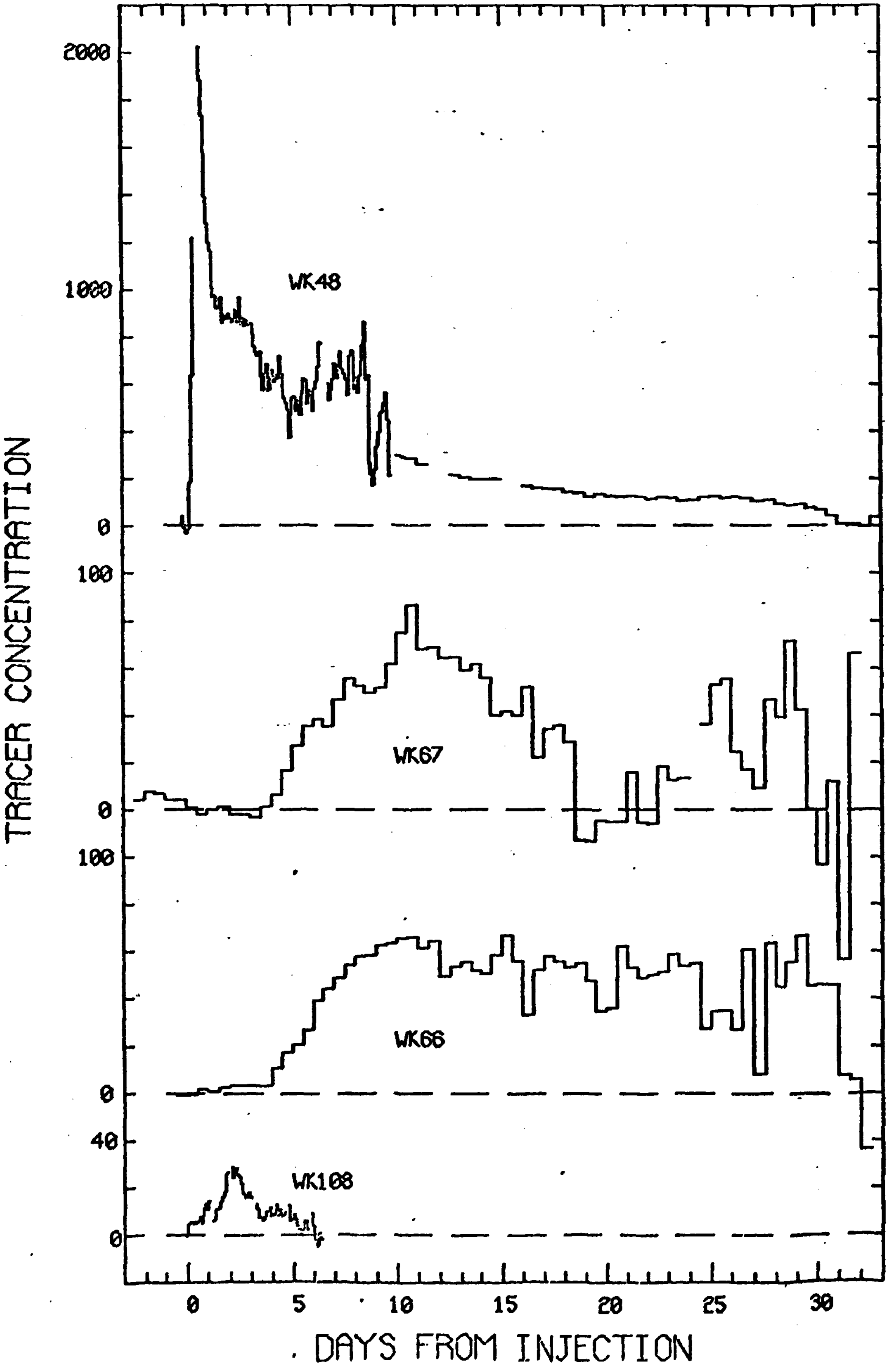


FIGURE 18. WK24 AND WK48 RESPONSE FROM WK107. MAR-79.

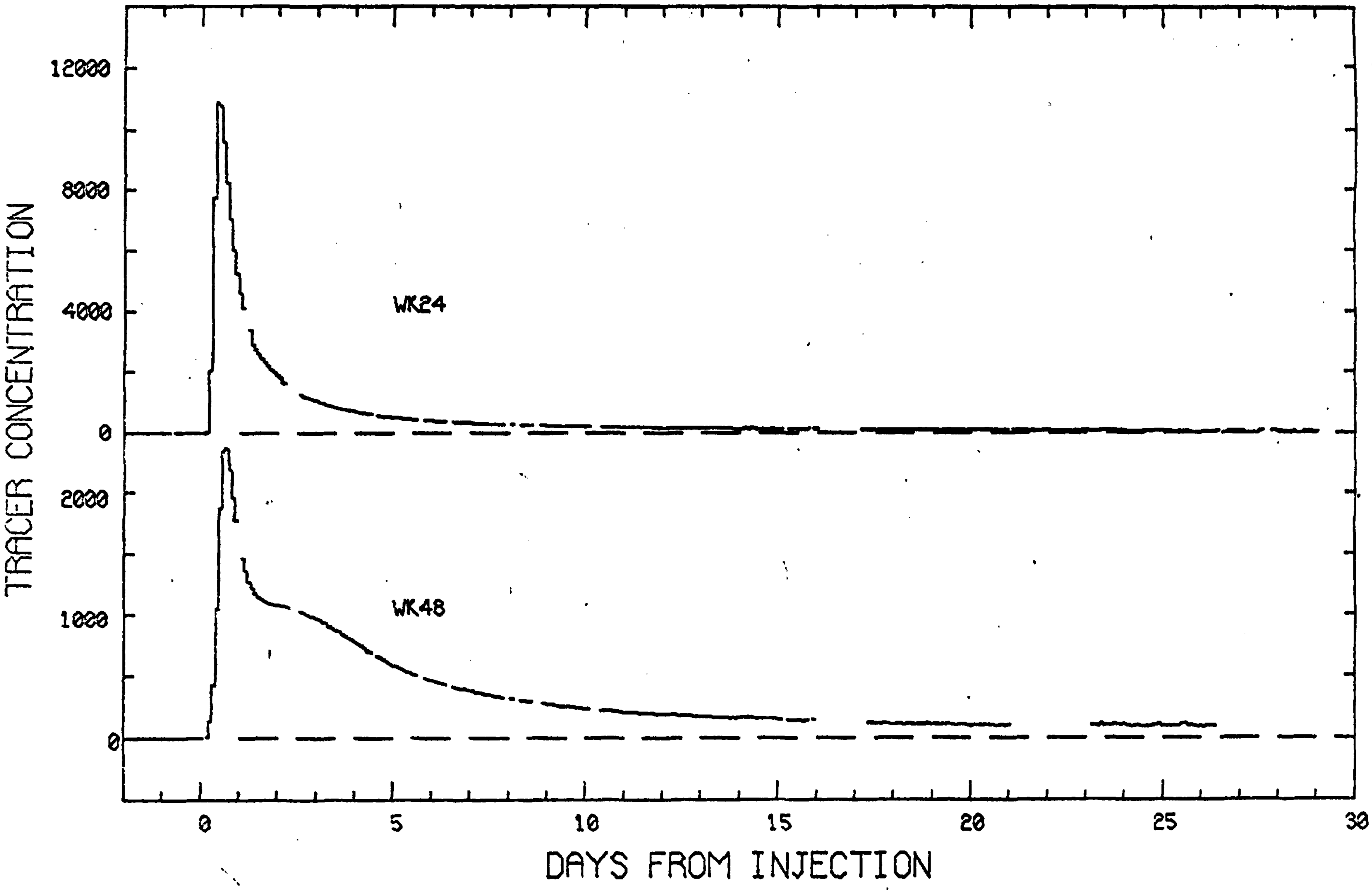


FIGURE 19. LOW RESPONSES FROM WK107. MAR-79.

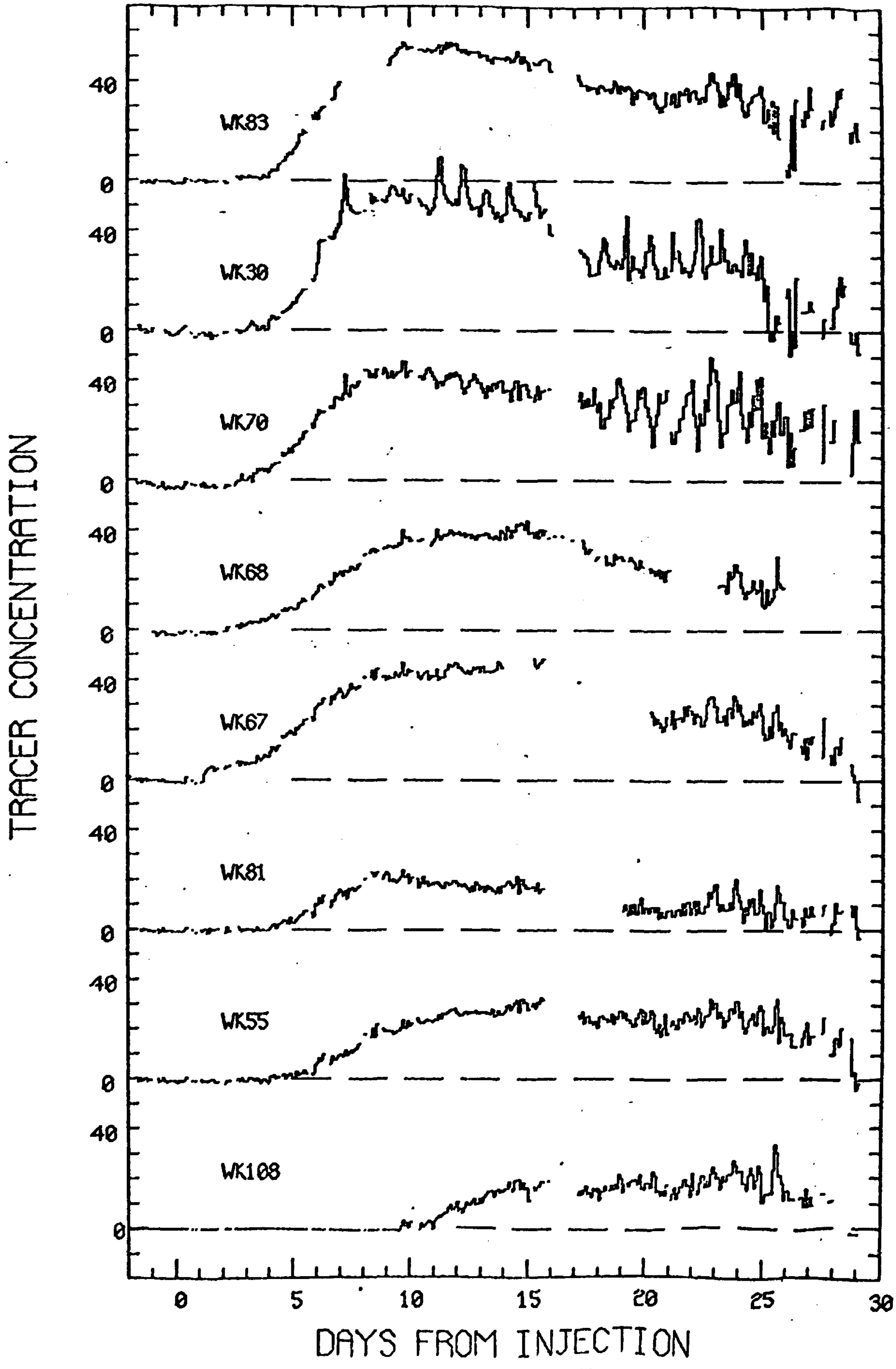


FIGURE 20. LOW RESPONSES FROM WK107. MAR-79.

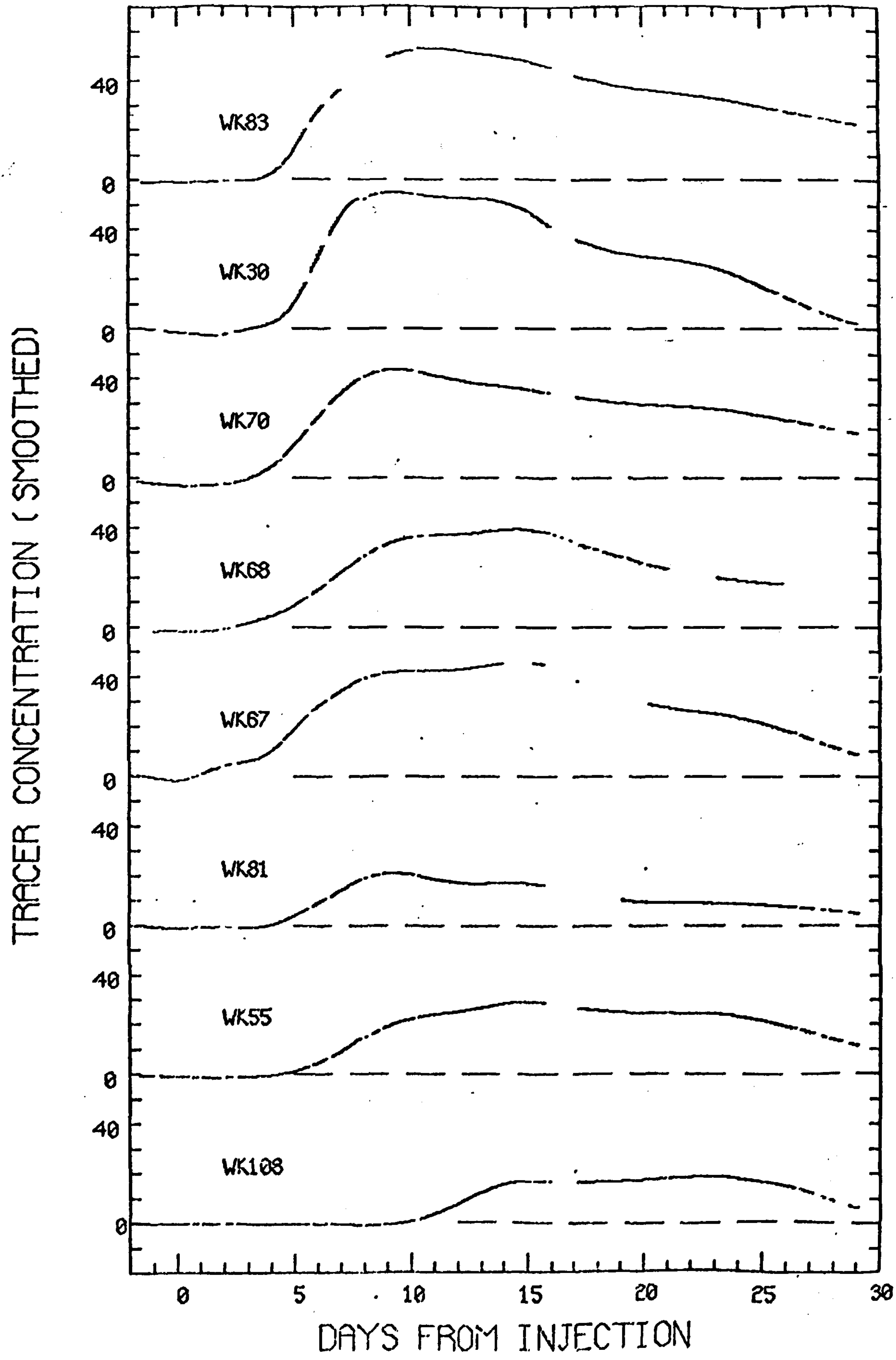


FIGURE 21. COMPARISON OF BR AND I AS TRACERS.

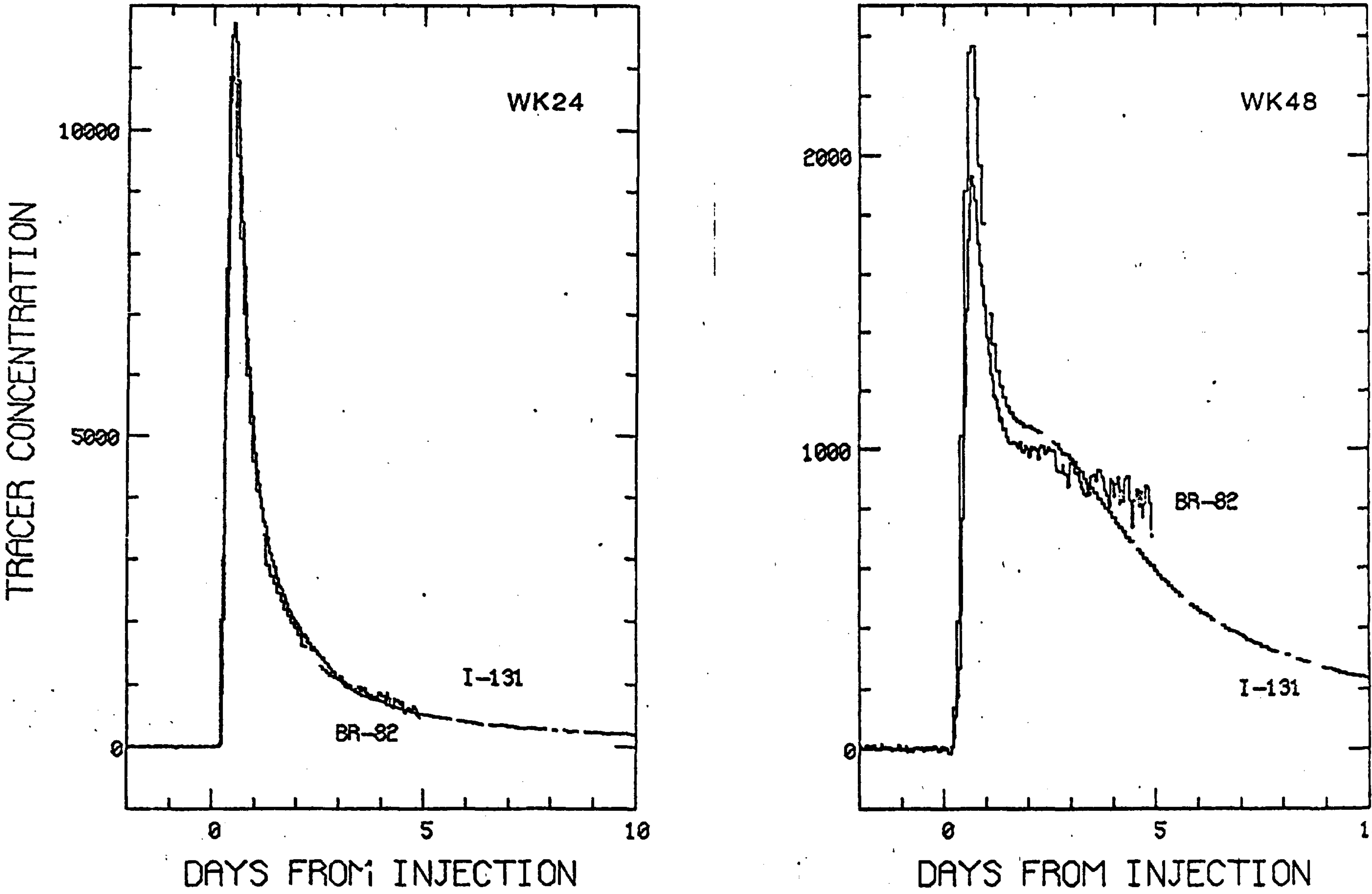


FIGURE 22. WK121 RESPONSE FROM WK101. JUL-79

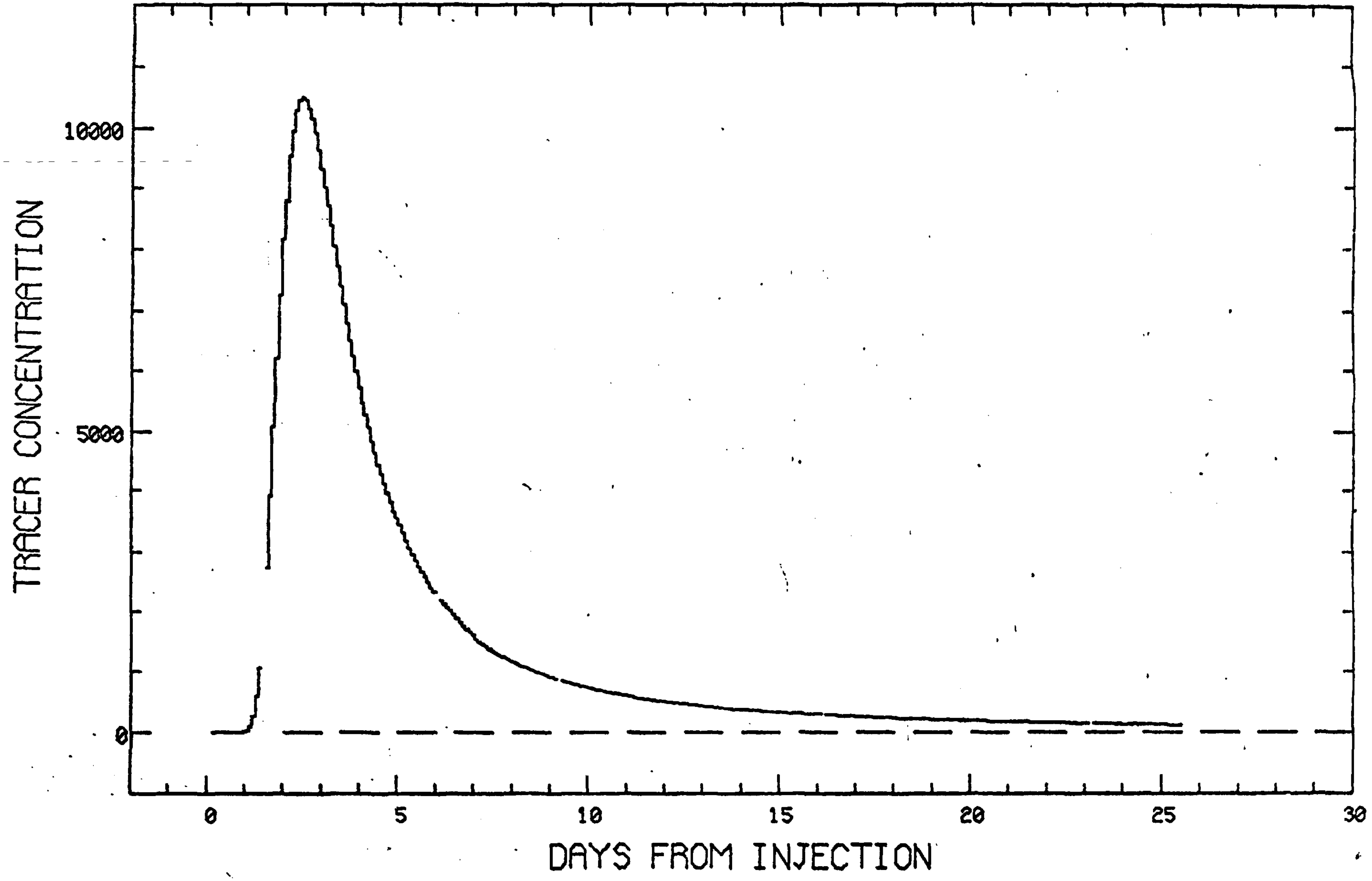
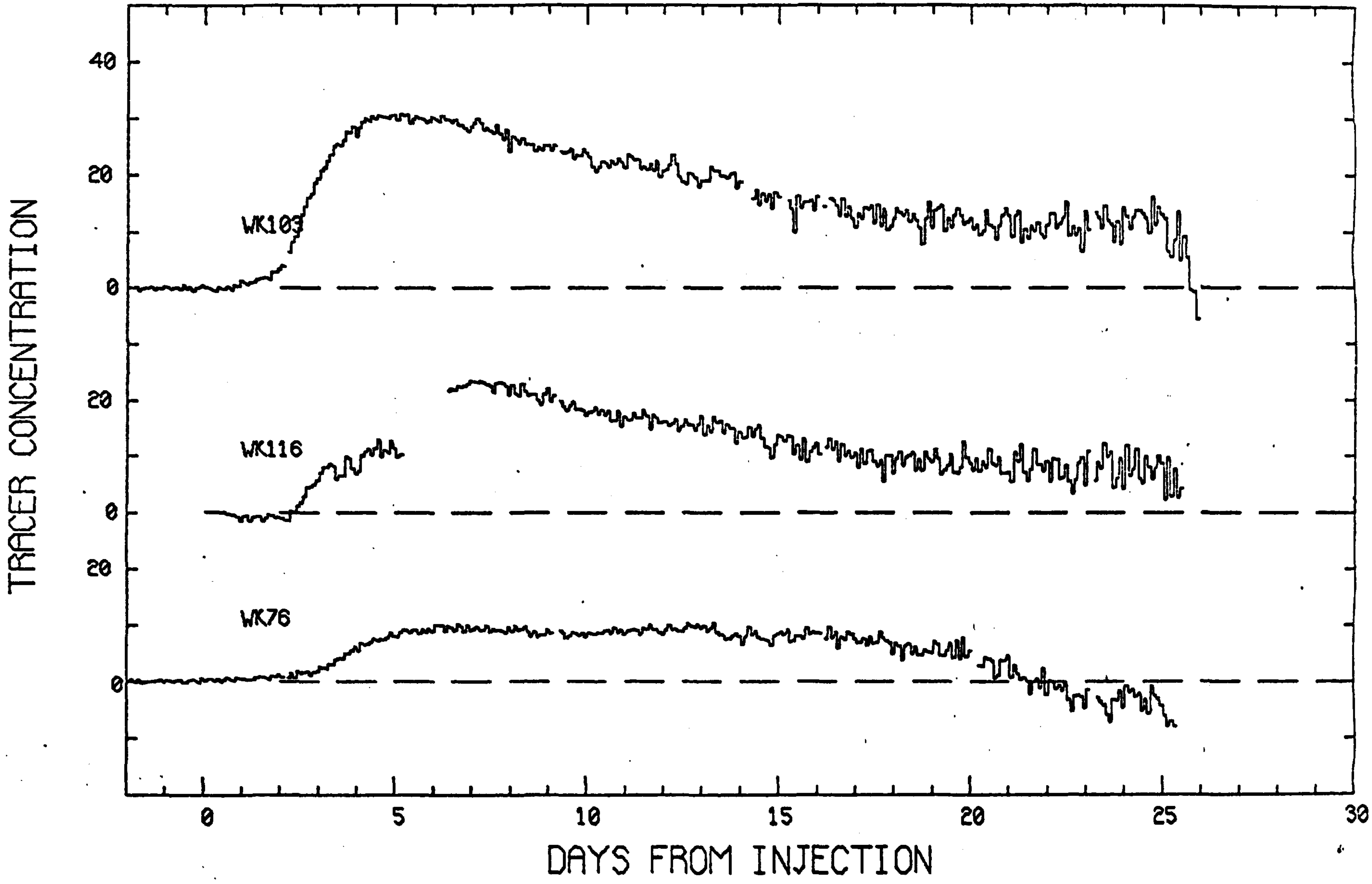


FIGURE 23. LOW RESPONSES FROM WK101. JUL-79.



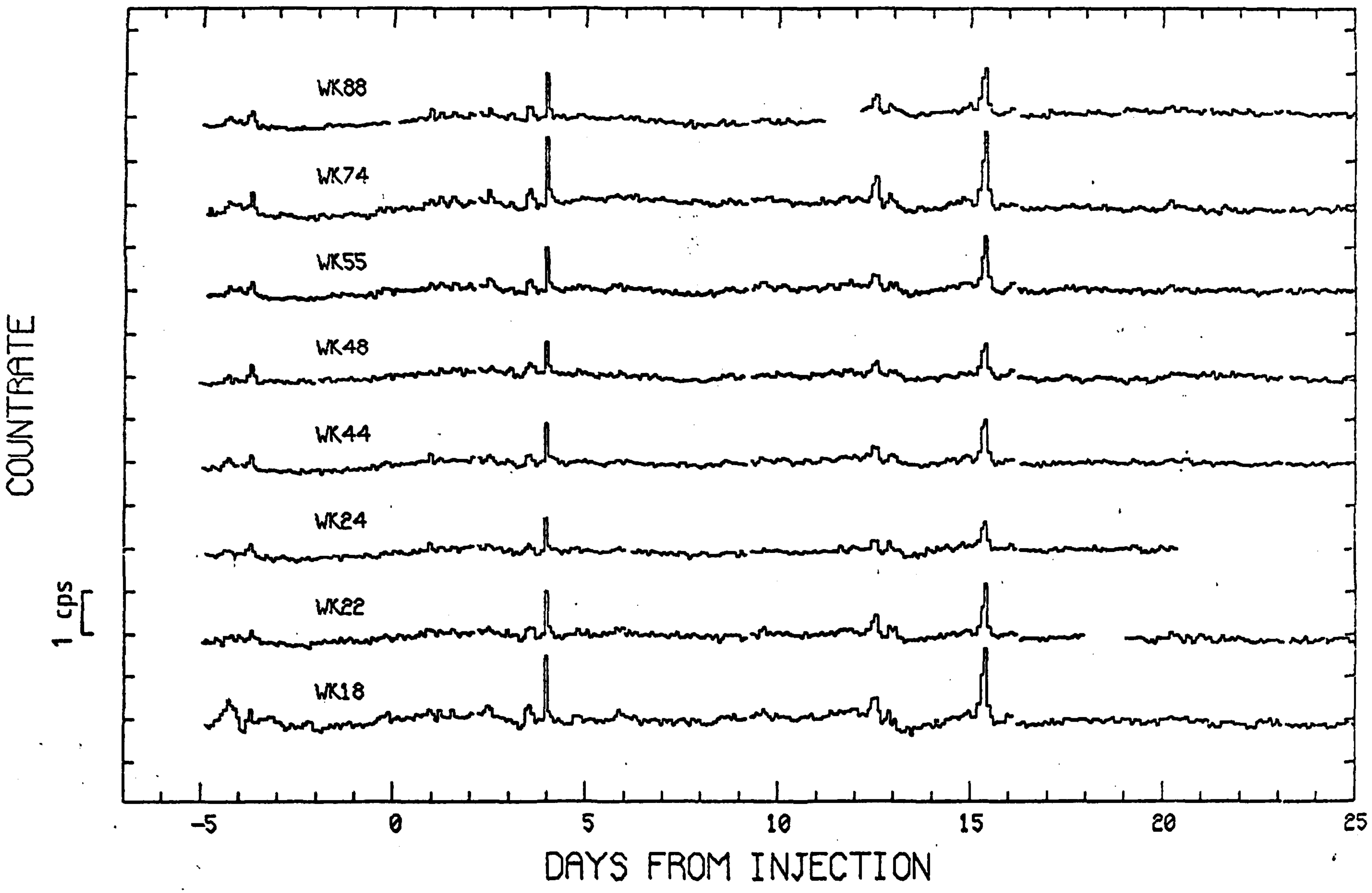
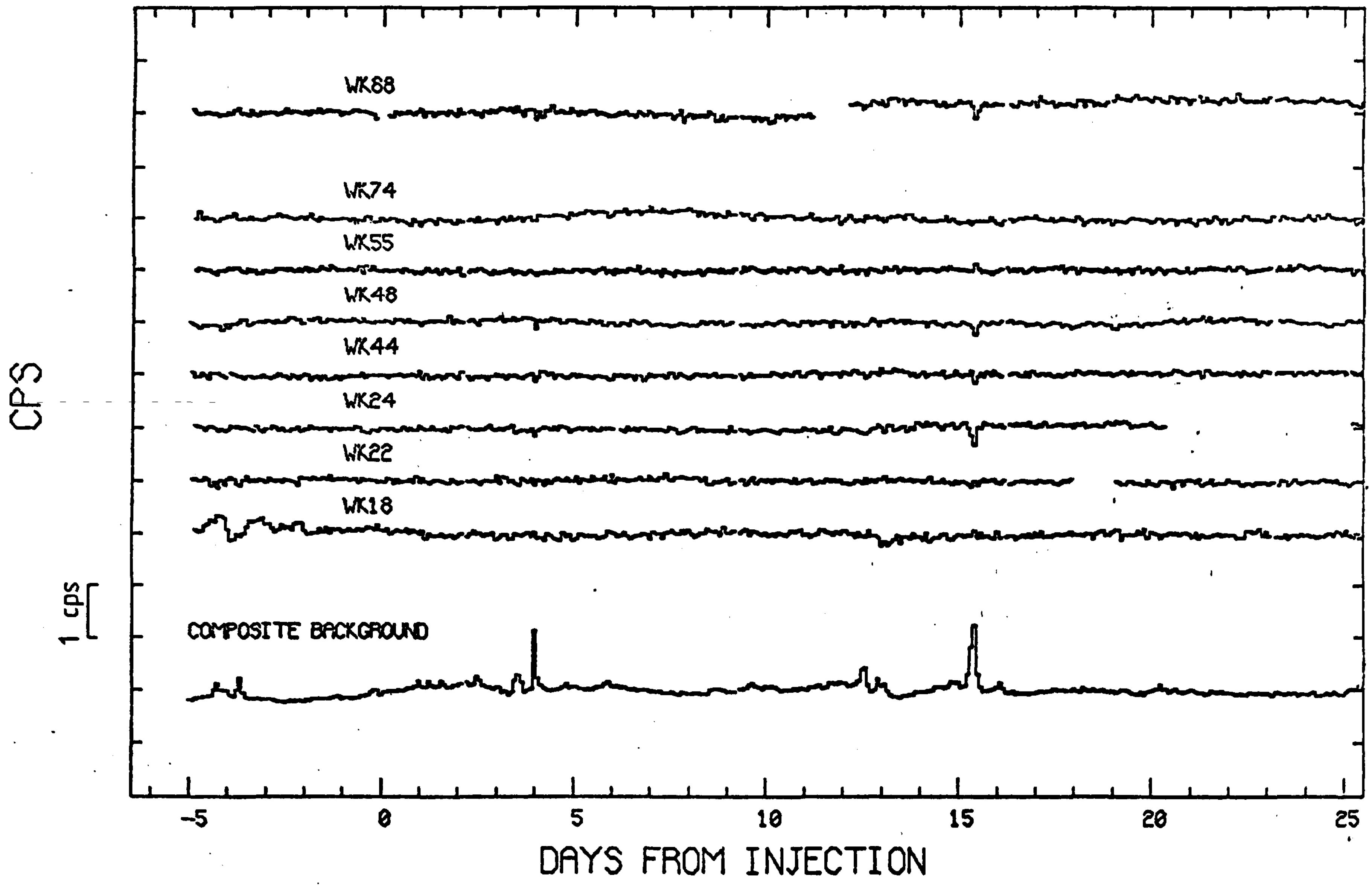


FIGURE 24. NULL RESPONSES FROM WK101. JUL-79.

FIGURE 25. NO RESPONSE WELLS FROM WK101 - JULY 79.



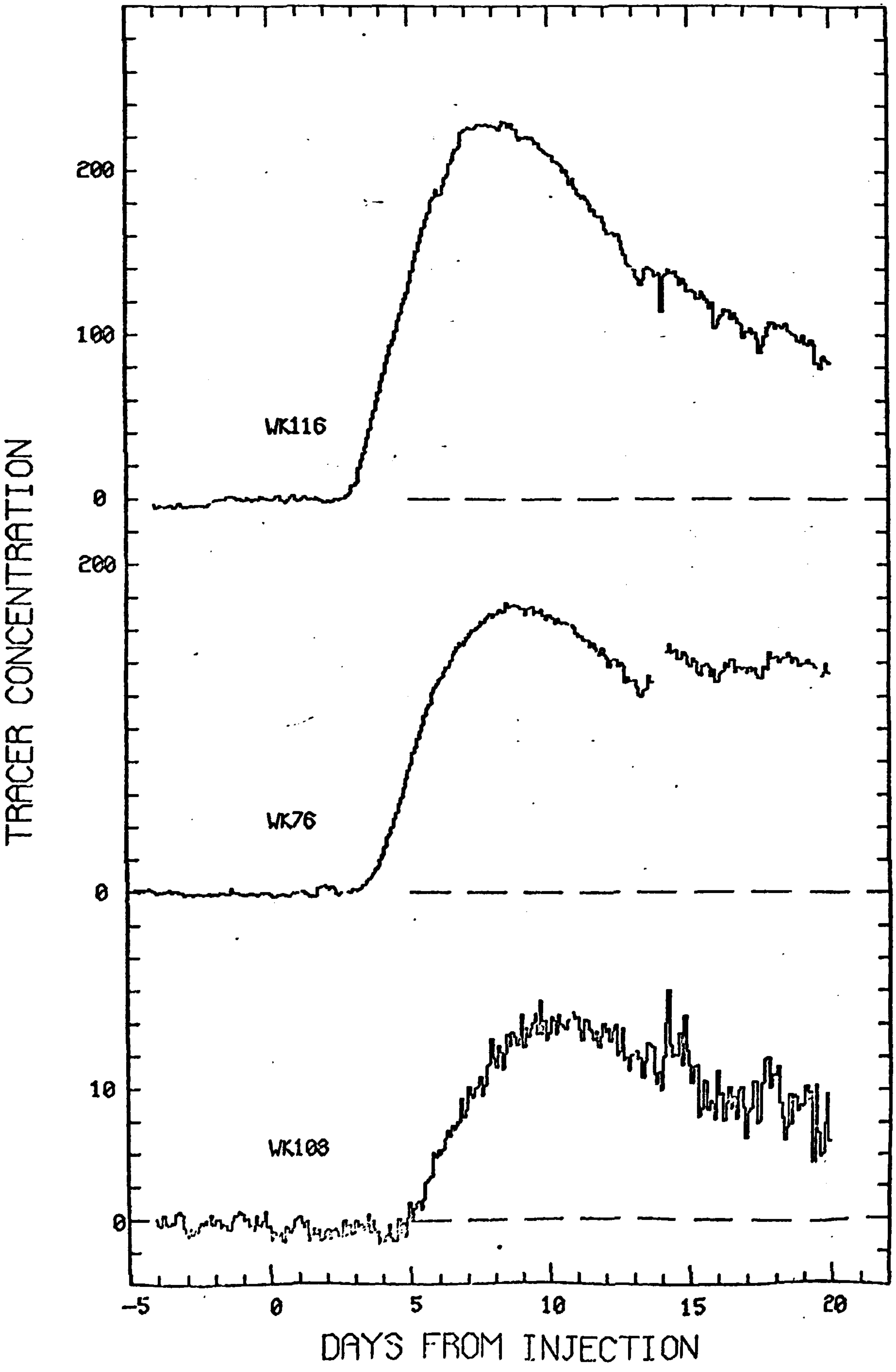


FIGURE 26. RESPONSES FROM WK80. FEB-80.

GEOTHERMAL CIRCULAR WJMcC4

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