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LUCAS HEIGHTS



THE USE OF RADIOISOTOPES AS GROUND-WATER TRACERS IN  
THE BURDEKIN DELTA AREA OF NORTH QUEENSLAND, AUSTRALIA

by

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ABSTRACT

The radioisotopes iodine-131 and tritium were used to determine aquifer porosities and permeabilities in a series of pumped bore tests. If reasonable values for porosity can be assumed, the methods can also be used to estimate the thickness of an aquifer.

The direction and rate of flow of natural ground-water was also determined by means of a free flow test, using these isotopes.

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## 1. INTRODUCTION

The Burdekin Delta area is of considerable economic significance to North Queensland, supporting as it does, extensive sugar cane cultivation. A large number of cane farms in the area draw their irrigation water from underground and concern had been expressed about the ultimate effect that this large scale utilisation of water would have on the aquifer.

As part of the investigation of this area by the Bureau of Mineral Resources, Geology and Geophysics, in 1962 and 1963, it was decided to carry out some tests of the properties of aquifers with radioactive tracers.

In the investigation of an underground water reservoir it is desirable to know the effective porosity of the aquifer; this is defined as the ratio of the volume of water which, after saturating the rock, can be drained, divided by the volume of that rock, and is expressed as a percentage. Henceforth by *porosity* is meant *effective porosity*. If the thickness of the aquifer is known, the total usable water capacity may be computed. Following the procedure of Halevy and Nir (1962) the product of aquifer thickness and effective porosity can be easily determined by dosing a bore or well near a pumping bore with a radioactive tracer, and plotting the count rate as measured at the pump outlet against time.

Although it is possible to determine the permeability from pumping tests, the method is not as direct as the radioactive technique whereby the transmission times and gradients are determined from the measured count rates at different levels in observation bores located between a pumping bore and a dosed bore-hole. Further, the natural direction and rate of flow of underground water may be determined by a free flow test with radioactive tracers between bores.

Personnel from the Bureau of Mineral Resources and the Australian Atomic Energy Commission carried out tests in the Burdekin Delta area in December 1963, to ascertain the suitability of radioactive tracers for determining effective porosity and permeability, and their use to estimate direction and rate of ground-water flow.

The experiments were carried out on properties belonging to Messrs. Joe Ahern, plot 399, portion 1, parish of Northcote; John Ahern, plot 399, portion 2, parish of Northcote; Floyd Fowler, plot 220, parish of Leichhardt Downs; Ray Hoey, plot 481, parish of Jarvisfield; and Eddie Jordan, Rita Island, plot 108, parish of Morrill (see Figure 1). Without the active co-operation and assistance of these property owners, it would not have been possible to carry out the experiments. Mr. S. James and the late Mr. W. Roman of the Queensland Irrigation and Water Supply Commission, assisted in the selection of sites for the experiments, and in obtaining the co-operation of the farmers concerned.

## 2. CHOICE OF ISOTOPE

One of the principal requirements for an isotope to be used in ground-water tracing is that it shall not be absorbed or adsorbed to any great extent in the soil through which it passes. Generally, this is no great problem when the soil is sandy, but can be important when the soil has a substantial clay content.

Iodine-131 has been used on many occasions and has been generally satisfactory (Kaufman and Orlob 1956a, 1956b; Halevy et al. 1958; Nir et al. 1959; Heemstra et al. 1961). Laboratory work, carried out at the A.A.E.C. Research Establishment, using sand and iodine-131 solution which were shaken together for extended periods and iodine-131 solution which was percolated through sand columns, confirmed that there was virtually no loss of radioactivity when iodine-131 solution was in contact with soils from the Burdekin area (Campbell et al. unpublished).

In addition, iodine-131 has other properties which make it suitable for this application, for example:

- (1) It emits fairly low energy gamma rays (principal energy 0.36 MeV) which means that while it can be detected efficiently in the field, its range in soil is small (half-thickness 2-3 inches) so that its position can be fairly well defined.

(2) Its half-life of 8.04 days is sufficient to allow a project of reasonable length to be undertaken, but still short enough for the isotope to be self disposing within a few months.

(3) Although not yet produced at the A.A.E.C. Research Establishment, it is readily available from overseas sources.

(4) The maximum permissible concentration of iodine-131 in drinking water, under Queensland regulations, for persons other than radiation workers is  $3 \times 10^{-6}$  microcurie/ml (Queensland Government Gazette 1961). Although this figure is lower than for most isotopes, it is not unduly restrictive.

The above factors made iodine-131 the best choice for the field detection aspects of the work. However, as a check on the possibility of any iodine adsorption, it was also decided to use tritium (radioactive hydrogen) in the form of tritiated water.

For all practical purposes this material behaves exactly as ordinary water. However, tritium emits only pure beta radiation of very low energy and thus cannot be detected in situ under field conditions. It is necessary to take samples of the water and return them to the laboratory for counting by the liquid scintillation technique (Kohl et al. 1961).

Tritium has a long half life of 12.26 years but its maximum permissible drinking water concentration according to Queensland regulations for persons other than radiation workers is as high as  $3 \times 10^{-6}$  microcurie/ml.

For the above reasons, iodine-131 and tritium were used together in the tests described in this report.

### 3. METHOD OF PREPARATION OF SITES

A total of four pumped bore tests and one free flow test followed by pumping were made. The pumped bore tests were carried out on the properties of Messrs. John Ahern, Joe Ahern, Fowler, and Jordan, and the free flow test on the property of Mr. Hoey.

For the pumped bore tests, several bore-holes were put down into the aquifer in a line with the pumped bore used for irrigation. In some of these experiments holes were also put down on both sides of the main line of bores in order to check the lateral movement of the radioactive tracers (Figures 3 - 6). The first hole was used for dosing and the others, between the dosing hole and the pumped bore, were used for measuring.

For the free flow test a central injection hole was put down to the aquifer and a series of measuring holes put down around it at a distance of 5 ft and 3 to 4 ft apart (Figure 2).

The dosing and measuring holes were prepared in a similar manner. A hole was drilled with a rotary proline drill with a 3 inch bit to a depth about 5 ft greater than required. The hole was then cleared and the drill flights removed. The holes would generally stay open as far as the water table, but tended to collapse below it. A spear was inserted, made of 2 inch int. dia. galvanised iron pipe, 3 ft long with 1/8 inch holes drilled at 1 inch intervals over most of its length. This was connected to 20 ft lengths of 2 inch int. dia. galvanised iron pipe. When the spear reached the blocked portion of the hole it was driven down with a lead-filled wooden "monkey". The pipe was filled with water, and if the spear holes were not cleared the bore-hole was surged with a piston. After surging, a sand pump was used to clear the material that collected inside the spear. Difficulty was encountered in clearing the holes and two other techniques were tried. A charge of 4 ounces of gelignite was exploded in the bottom of a spear after filling the hole with water. This method was successful on one of the two occasions it was tried. A further attempt to clear the holes was made by injecting compressed air down the hole, and surging the hole from the bottom. This gave good results at first, but compressor trouble forced the abandonment of the method.

#### 4. PROCEDURE

For the pumped bore tests, the pump was started a few hours or days in advance of the test to establish the draw-down of the water table. After equilibrium conditions had been established, as ascertained by depth measurement and/or logging, the tritiated water and the iodine-131 solution (with potassium iodide carrier) (Kohl et al. 1961) were added to the injection bore-hole opposite the aquifer. This was achieved by lowering a perforated steel tube, containing the isotope in a glass bottle, by means of a steel wire, to the appropriate depth in the bore-hole. A steel breaker rod inside the perforated tube was then operated from ground level by means of another wire to break the bottle.

The radioactive solution was washed into the surrounding aquifer by adding a few gallons of water to the bore-hole.

The observation or measurement bore-holes were monitored for iodine-131 by means of water-proof scintillation counters which contained a 1-1/4 inch long x 3/4 inch diameter NaI(Tl) crystal and a 1 inch photomultiplier tube and were connected to an A.A.E.C. type 59 portable ratemeter. The detectors were lowered into the bore-holes and readings were taken at appropriate depths.

The water pumped out of the last bore (the pumped bore) was monitored by means of a waterproof scintillation counter containing a 1 inch long x 1-1/2 inch diameter NaI(Tl) crystal and 2 inch diameter photomultiplier tube connected to an A.A.E.C. type 59 portable ratemeter and a "Record" clockwork-operated portable recorder. The scintillation counter was immersed in a large volume of water continuously pumped from the bore, (using a tank or large section of large pipe), thus giving close to "infinite volume" detection conditions.

During each test, a few samples of water were taken for subsequent tritium assay by liquid scintillation counting at the A.A.E.C. Research Establishment.

Prior to the pumped bore tests, fluorescein was added to the dosing spear in an attempt to obtain some preliminary information on the behaviour of the underground water. Fluorescein was observed in the water from only some of the pumped bores. In other cases the fluorescein did not reappear.

For the free flow test, iodine-131 was the only isotope used. This was again added to the injection hole by means of the perforated breaker tube and washed into the surrounding aquifer by flushing the bore-hole with water.

The observation bore-holes were monitored by the small scintillation detectors as described for the pumped bore work.

Fluorescein was used before the radioisotope was added and on this occasion useful information was obtained.

#### 5. CALIBRATION OF EQUIPMENT

The equipment was calibrated with iodine-131 on return to the A.A.E.C. Research Establishment. The large scintillation heads used to monitor pump output were calibrated by immersing them in a 300 gallon tank filled with iodine solution of known concentration. This condition was close to "infinite volume" and corresponded closely to the conditions of field measurement. To simulate field usage conditions for the calibration of the small diameter probe it was placed in a 2 inch pipe located axially in a 44 gallon drum filled with sand (of voidage approximately 40 per cent.) saturated with an iodine solution of known radioactivity.

The following results were obtained:

Large scintillation head: 3820 counts/sec/ $\mu$ c/gallon  
 1-1/2 inch diameter probe: 56 counts/sec/ $\mu$ c/cubic foot of sand,  
 $= 56 \times 6.25 \times \frac{40}{100}$  counts/sec/ $\mu$ c/gallon of water  
 (assuming 40% porosity),  
 $= 140$  counts/sec/ $\mu$ c/ gallon of water.

## 6. RESULTS

### 6.1 Introduction

The results for each property are presented in the following sections and supplementary notes appear in the appendix. A summary is given in Section 7.

The results of the work with tritium are not given in the report because they only confirm the results obtained with iodine-131. As was expected, the iodine-131 followed the tritium closely and therefore the iodine-131 results needed no correction for adsorption etc. under the particular field conditions.

All iodine readings, whether taken in the bore-holes or in the pump output, were corrected for background and for decay (Kohl et al. 1961) back to the time of injection of radioactivity for the particular experiment.

For the pumped bore tests, the radioactivity readings in the bore-holes were plotted against depth (reduced levels) for various times. The maximum reading at any time (irrespective of the depth at which this maximum occurred) was then plotted against time for each hole monitored.

For each experiment, an isotope balance was made by determining the total radioactivity detected at the pump outlet (integral of count rate/time curve) and comparing this with the amount of iodine-131 added to the injection bore. The accuracy of this method depends mainly on the accuracy with which the flow is known or measured but also on the calibration accuracy and counting geometry etc. of the equipment. Flow was measured, as required, by a crude fluorescein tracer method, or, in one instance, by a V-notch weir.

### 6.2 Results for the Jordan Property (Location plan - Figure 5)

The pump was started at 10.00 p.m. on 15th December 1963. The flow rate (fluorescein measurement) was 29,800 gallons/hour. 1 curie \* of tritiated water and 28.5 millicuries of iodine-131 was added to No. 1 bore at 7.00 a.m. on 16th December 1963.

The monitoring holes (holes 2 and 3) were blocked, hence water levels in the holes were meaningless and did not allow water table or draw-down figures to be obtained directly. However, this information was available indirectly, as shown hereunder:

The count rate at the pump outlet is plotted against time in Figure 12. Using the relationship of Halevy and Nir (1962):

$$(\text{Distance travelled})^2 = \frac{\text{Pump rate} \times \text{time to mid-point of half-peak}}{\pi \times \text{porosity} \times \text{aquifer thickness}}$$

we have for a pump rate of 29,800 gal/hr, aquifer thickness 20 feet (determined from drilling and logging data), time 15 h 12 min, and distance 60 ft:

$$\text{porosity} = 32\%$$

Therefore, at a distance r from the pump,

$$\text{the velocity} = \frac{29,800}{2 \pi r \times 20 \times 6.25 \times 0.32} = \frac{118}{r} \text{ ft/hr} \dots\dots\dots \text{Equation (1)}$$

\* The curie is defined as  $3.7 \times 10^{10}$  disintegrations/second

in which the value 118 represents a constant K of dimensions ft<sup>2</sup>/hr.

In Figure 25 the velocities predicted by using this function are compared with the observed velocities at the points indicated in Table 1.

If it is assumed that the velocity is proportional to the reciprocal of the distance from the pump, the interval velocity V<sub>i</sub> measured between two holes a distance r<sub>1</sub> and r<sub>2</sub> from the pump is represented by:

$$V_i = \frac{1}{r_1 - r_2} \int_{r_2}^{r_1} \frac{K}{r} dr$$

$$= \frac{K}{r_1 - r_2} \ln \frac{r_1}{r_2}$$

A value for K was determined for the interval velocities between the dosing hole and hole 2, between hole 2 and hole 3, and between the dosing hole and hole 3. (The conditions of flow in the vicinity of the pump preclude the use of this method near the pump). The calculated values of K are shown in Table 1.

**TABLE 1**

**VALUES OF K FOR DIFFERENT DEPTHS ( JORDAN TEST)**

Interval	Interval Distance (ft)	Velocity (ft/hour)	Depth (ft)	K (ft <sup>2</sup> /hr)	Key on Fig 25	Remarks
Bore 1 to Bore 2	10	2.2	26 ft 8 in - 27 ft	121	(a)	) Velocities from Table 2
		1.38	26 ft 4 in - 26 ft	76	(b)	
		1.09	26 ft	60	(c)	
		0.95	25 ft 8 in	54	(d)	
Bore 1 to Bore 3	30	3.10		134	(e)	
		2.75		119	(f)	
Bore 2 to Bore 3	20	3.8		161	(g)	1st peak to 1st peak

Figure 23 (constructed from Figures 7 and 8) shows a series of curves obtained by plotting the count rate at constant depths in hole 2 against time. If the aquifer was uniform, and the tracer started at a point source in space and time, all curves should be unimodal and have their maximum at the same time. If the tracer was inserted over a period or at intervals of a few minutes the curves could have a broad peak, or a number of peaks, but they would all reach a maximum at the same time. In this case the tracer was inserted and washed into the aquifer over a period of a few minutes. In Figure 23 there are at least four peaks at different times at different depths (see Table 2), suggesting that the velocity of flow in the aquifer varies with depth.

**TABLE 2**

**RESULTS FOR JORDAN HOLE NO. 2 (10 ft from dosing hole)**

Time of Peak	Depth of Peak Maximum	Elapsed Time Since Dosing	Apparent Velocity Source to Peak
11.30	26 ft 8 in - 27 ft	4 hr 30 min	2.2 ft/hr
14.15	26 ft 4 in - 26 ft	7 hr 15 min	1.38 ft/hr
16.10	26 ft	9 hr 10 min	1.09 ft/hr
17.30	25 ft 8 in	10 hr 30 min	0.95 ft/hr

Figure 24 (constructed from Figure 10) for the 3rd hole at Jordan's is similar to Figure 23. It shows only two distinct peaks, one at about 16 hr 45 min representing a velocity of 3.10 ft/hr between holes 1 and 3 and the other at 17 hr 50 min representing a velocity of 2.75 ft/hr between holes 1 and 3. There were no readings between 17 hr 50 min and 21 hr 00 min, so it is possible that some peaks may have been missed. The widths of the peaks are smaller than for hole 2; this is because hole 3 is 30 ft from the pumping bore while hole 2 is 50 ft from the pumping bore. As the velocity of flow is proportional to the reciprocal of the distance from the pump (except at small distances from the pump) the velocity at hole 3 will be 1.67 times as great as the velocity at hole 2. This may be expressed by the equation  $V = \frac{K}{r}$ , where K has the dimensions ft<sup>2</sup>/hr.

Equation 1 shows that, for the pump rate given, the mean expected value of K is 118. The values of K that can be determined from observations show reasonable agreement with the value 118. Variations in the porosity of the aquifer could affect the value of K, as also could variations in permeability.

The depth of the greatest count rate for holes 2 and 3 is plotted against time in Figure 26 (from Figures 7, 8, and 10). The slopes of the first parts of the curves are sufficiently similar for correlation of the two curves to obtain a velocity and gradient for various stream lines between the two holes. This enables the permeability to be calculated from the relationship:

$$\text{Permeability} = \frac{\text{Area of cross section of flow} \times \text{velocity of flow}}{\text{gradient of flow}} \dots \dots \dots \text{Equation (2)}$$

For a cross section of 1 ft<sup>2</sup> and a porosity of 32 per cent. we have:

$$\text{Permeability} = \frac{0.32 \times \text{velocity of flow}}{\text{gradient of flow}}$$

Table 3 shows the calculated values of permeability for points correlated in Figure 26.

**TABLE 3**

**CALCULATED VALUES OF PERMEABILITY (JORDAN TEST)**

No of Point of Curve	Level Hole 2	Level Hole 3	Velocity 2-3 (ft/hr)	Gradient 2-3 (ft/ft)	Permeability (ft <sup>3</sup> /hr per 1 ft/ft)
1	26 ft 7¼ in	26 ft 10 in	4.44	0.014	102
2	26 ft 7 in	26 ft 9¾ in	5.11	0.014	117
3	26 ft 3½ in	26 ft 7½ in	5.00	0.017	94
4	26 ft 2¾ in	26 ft 7 in	5.25	0.018	93
5	26 ft 2 in	26 ft 6 in	4.70	0.017	89
			Mean	0.016	99

Since under conditions of similar gradient the velocity of flow will depend on the permeability of the aquifer, and the measured gradients are of the same order of magnitude (see Table 3) it should be possible to estimate the permeability from the velocity at points where only the velocity can be measured. Figure 27 shows permeability plotted against velocity for a constant gradient, where the velocity used is the average velocity measured between the dosing hole and hole 2.

By taking the velocity at points on the hole 2 curve (Figure 26) the values of permeability for these points can be read off Figure 27. These are given in Table 4, together with those values previously calculated (see Table 3).

**TABLE 4**  
**COMPARISON OF CALCULATED PERMEABILITIES AND VALUES**  
**OBTAINED FROM FIGURE 27**

No of Point on Fig. 26	Calculated Permeability (from Table 3) (ft <sup>3</sup> /hour per 1 ft/ft)	Velocity 1- 2 (ft/hour)	Permeability from Fig. 27 (ft <sup>3</sup> /hour per 1 ft/ft)
1	102	2.76	136
2	117	2.17	108
3	94	1.85	92
4	93	1.62	81
5	89	1.54	76
6		1.31	66
7		1.25	62
8		1.11	56
9		0.97	49
10		0.93	46
11		0.71	35
		Mean	73

These values of permeability are at best only estimates, but they should certainly be correct in order of magnitude.

Hence if the aquifer is 20 ft thick, and the gradient between holes 2 and 3 is taken as 0.016, being the gradient half way between them, that is, 40 ft from the hole, the expected flow rate will be:

$$73 \times 0.016 \times 2 \pi \times 40 \times 20 \times 6.25 \text{ g.p.h.} = 36,800 \text{ gal/hr.}$$

This value is higher than the observed flow of 29,800 gal/hr; however, the value 73 for the permeability is based on the only data available for gradient, which are for the high permeability part of the aquifer.

### 6.3 Results for the John Ahern Property (Location plan - Figure 6)

The pump was started at 4.00 a.m. on 13th December 1963. The flow rate (fluorescein measurement) was 32,400 gallons/hour. 1 curie of tritiated water and approximately 160 mc of iodine-131 were added to No. 1 bore at 7.00 a.m. on 13th December 1963.

Because the bore-holes were blocked, water levels could not be measured directly, and direct information on draw-down etc. could not be obtained.

The level of maximum reading at holes 4 and 5 is plotted against time in Figure 28 (from Figures 13, 14, 15, and 17). The solid lines represent periods of fairly regular reading and the broken lines represent times during which readings were widely separated. Owing to the inadequate number of readings taken, it is not possible to treat the permeability calculation with the same detail as for the Jordan test. However, a mean gradient of 10.5 inches in 20 feet was determined from Figure 28, and two velocities were determined from Figures 16 and 18, one being 1.8 ft/hour and one 3.3 ft/hour. The 1.8 ft/hour value is a peak to peak velocity while the velocity of 3.3 ft/hour is a velocity based on the first arrival at each hole. As the gradient is determined from the early part of the arrival, it is probable that the higher value is the better one.

Using the method of Halevy and Nir (1962), as for the Jordan case, the porosity was calculated to be 50 per cent. for a flow-rate of 32,400 gal/hr, time from tracer insertion to peak 22 hr 16 min (Figure 19), distance of pump from dosing hole 60 ft, and aquifer thickness about 20 ft (from drilling and gamma logs).

This porosity is too high. For it to be nearer to the expected value the thickness of the aquifer would have to be greater, say 30 ft, which would bring the porosity down to 34 per cent. The information on the thickness of the aquifer was obtained solely from the holes used in the experiment. It is possible that the aquifer is thicker in directions from the pump other than the one in which the dosing hole lies.

For the permeability calculation (Equation 2), the value 34 per cent. for the porosity was used, giving a value 25.6 ft<sup>3</sup>/hour for a velocity of 3.3 ft/hr and a value 14.1 ft<sup>3</sup>/hour for a velocity of 1.8 ft/hr. Because insufficient data were obtained these values can be taken only as estimates.

#### 6.4 Results for the Joe Ahern Property (Location plan - Figure 3)

Pumping started at 4.00 a.m. on 12th December 1963. The pumping rate was 44,000 gal/hr. (V-notch weir measurement). 1 curie of tritiated water and approximately 40 mc of iodine-131 were added to No. 1 bore at 10.00 a.m. on the 12th December 1963.

From drilling information the thickness of the aquifer was believed to be 20 ft. Using this figure a porosity of 107 per cent. was calculated by the method of Halevy and Nir (1962).

This impossibly high value of porosity suggests that the path followed by the water was not directly towards the pump, but could have been through a relatively high permeability channel in the aquifer. This would be consistent with the fact that no activity was detected in the monitoring holes which were on a direct line between the dosing hole and the pump.

#### 6.5 Results for the Fowler Property (Location plan - Figure 4)

The pump was running from 13th December, 1963. The flow rate was 50,000 - 55,000 gal/hr. (fluorescein test). 1 curie of tritiated water and approximately 33 mc of iodine-131 were added to the injection bore at 6.30 a.m. on 14th December, 1963.

From Figure 21 the time to reach the mid-point of the half peak is 7 hours 54 minutes, and the time to peak is 7 hours 10 minutes. Using the method of Halevy and Nir (1962), and an aquifer thickness of 15 feet, the porosity is 35 per cent. for peak time and 39 per cent. for the mid-point of half peaks. These values of porosity are high for a good aquifer.

#### NOTE

All the calculations for the above four properties were made on the assumption that the flow of water in all cases took place in a confined aquifer whose thickness was small compared to the distance from the dosing spear to the pump. The permeability calculations were based on formulae given by Todd (1959). The assumptions were most nearly valid for the Jordan property where the aquifer lies between clay layers. At the John Ahern property, and the Fowler property, the top of the aquifer is probably unconfined.

### 6.6 Results for the Hoey Property (Free Flow Test) (Location plan - Figure 2)

Fluorescein was added to the injection hole at 4.15 p.m. on 9th December 1963. No fluorescein was detected in the sampling holes during the afternoon of 10th December (~24 hours), but fluorescein was detected in quantity in hole 6 when samples were taken at 10.30 a.m. on 11th December (~42 hours).

Approximately 42 mc iodine-131 was added to the Hoey injection bore at 4.30 p.m. on 11th December. No radioactivity was detected in sampling holes at 8.30 a.m. on 13th December (~40 hours).

Slight radioactivity was detected in hole 6 when it was monitored at 3.15 p.m. on 14th December (~71 hours).

Hence, because radioactivity was not detected at 40 hours and fluorescein was detected at 42 hours, the time of travel of the water was taken as 41 hours. The rate of flow over five feet was therefore 1.5 inch/hour in the direction of A6 (that is 15° magnetic). (See Figure 2).

Although this was primarily a free flow test, pumping was started at approximately 8 a.m. on 15th December in an attempt to ascertain the fate of the radioactivity.

The pumping unit consisted of three pumps and three spears, but only one of the three spears was in the aquifer used for injection.

In this test, the injection hole became blocked some time after injection. It was cleared on 15th December at 3 p.m. by pouring water down the pipe. The small peak in the pump outlet curve (Figure 22) could be due to the radioactivity already in the soil before the injection hole became blocked. The large peak would then be due to the radioactivity passing through after the injection hole was cleared.

With these assumptions it is possible to use the information provided by Figure 22 to give an independent check of the rate and direction of the water flow under free flow conditions.

If, at 8 a.m. on 15th December, the first body of radioactivity was  $x$  feet from the pump and the second body was at the dosing hole 60 ft from the pump, and the dosing hole was cleared at 3 p.m. on 15th December, then we have the two equations:

$$\begin{aligned} 60 &= A \sqrt{20} \\ x &= A \sqrt{10.5} \end{aligned}$$

where  $A$  is a function of porosity, flow rate, and aquifer thickness; 20 hours is the time taken for the large amount of radioactivity to reach the pump after the injection hole was cleared, and 10.5 hours is the time taken for the small amount of radioactivity to reach the pump after pumping commenced.  $x$  is therefore 44 ft, that is, this method indicates that the small body of radioactivity was situated 44 ft away from the pump when the latter was started. However, the other method shows that at the time the pump was started (8 a.m. on 15th December), the small amount of radioactivity had travelled 11 ft in the direction of A6 (that is, 87½ hours at 1.5 inch/hour) and was then about 58 ft from the pump.

Hence there is a discrepancy of about 14 ft in the position of the small amount of radioactivity when the pump was started as determined by the two methods.

If the small amount of radioactivity was at this latter point (44 ft from the pump) when the pump started, it would have travelled 17.5 ft in 87½ hours, that is, 2.4 inches/hour on a bearing of 68° magnetic.

It is probable that the true rate and direction of flow lie between the two values obtained by the different methods, that is, 1.5 inch/hour - on a bearing of 15° magnetic and 2.4 inches/hour - on a bearing of 68° magnetic.

These directions are consistent with results of other geophysical investigations in this area (Wiebenga et al. unpublished).

## 7. CONCLUSIONS

The results of the experiment are shown in summary form in Table 5.

TABLE 5  
SUMMARY OF RESULTS

### Jordan Property

Porosity = 32 per cent.

Permeability range 136 to 35, mean about 73, ft<sup>3</sup>/hour for gradient 1 ft/ft.

### John Ahern Property

Permeability range 14.1 to 25.6 ft<sup>3</sup>/hour for gradient 1 ft/ft.

Porosity unknown

### Joe Ahern Property

No porosity or permeability determined.

Estimated aquifer thickness from data approximately 60 ft.

### Fowler Property

Porosity between 35 and 39 per cent.

Permeability unknown.

### Hoey Property

Velocity 1.5 - 2.4 inch/hour.

Direction 15 - 68° magnetic.

Although the results of this experiment are incomplete, they do indicate that it is possible to obtain quantitative information on porosity and permeability of aquifers by the use of radioactive tracers, particularly iodine-131 and tritium, which were shown to be very satisfactory for an experiment of this type. Also, using the Halevy and Nir (1962) technique, the approximate thickness of an aquifer can be determined if a reasonable estimate for the effective porosity can be made.

If the recommendations given below are followed in future experiments, the results should be more complete and more accurate.

## 8. RECOMMENDATIONS

The main weaknesses of this experiment were:

- (1) The dosing spears were not sufficiently open to allow the tracer to move freely into the aquifer. This could be prevented by better development of the dosing spears.
- (2) No draw-down data for observation spears were available to compute gradients. The best solution to this problem would be to have two holes at each point, one open to allow measurement of draw-down, and one closed to allow measurement of radioactivity in a profile through the aquifer. More holes, dispersed on a line at right-angles to the direction

of flow, would also be desirable where deviation of water flow is expected (for example, the Joe Ahern and Fowler properties).

- (3) Because several of these experiments were being run concurrently, it was impossible to obtain sufficient data in all cases. It is essential that in future experiments readings should be taken at least every half hour in all observation holes while radioactivity is present in them. In order to obtain a more detailed profile of the hole it is desirable that a continuous log be taken of the hole, using a probe geared to a depth-count rate meter and recorder.

## 9. SAFETY NOTE

A concentration of iodine-131 in the pumped bore discharges, corresponding to the maximum permissible drinking water tolerance ( $3 \times 10^{-6}$   $\mu$ c/ml) under Queensland regulations gives a count rate of about 50 counts/sec under the conditions of these experiments.

Although concentrations up to several hundred times as high as this figure could be expected in theory (Fry, A.A.E.C. unpublished), the pump discharge graphs show that in no case did the maximum concentration exceed 20 times this figure.

The iodine-131 concentration of the discharged water was greater than the drinking water tolerance for only about two days. As water discharged from these bores is used only for irrigation, these figures are entirely acceptable.

Other safety aspects of this project have been discussed in detail by Fry (A.A.E.C. unpublished).

## 10. REFERENCES

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- Todd, D.K. (1959) - Groundwater Hydrology. John Wiley, New York.
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## APPENDIX 1

### SUPPLEMENTARY NOTES ON RESULTS

#### JORDAN PROPERTY

##### Hole 2 (Figures 7 - 9)

Maximum reading initially at 26 ft 8 in, then gradually moved up to 26 ft.

Maximum count rate (10,800 counts/sec) occurred at 2.30 p.m. on 16/12/63.

$$\begin{aligned}\text{Maximum concentration} &= \frac{10,800}{140} \\ &= \underline{72 \mu\text{c/gallon.}}\end{aligned}$$

##### Hole 3 (Figures 10 and 11)

Maximum reading between 26 ft 5 in and 26 ft 9 in.

Maximum count rate 3,250 counts/sec. at 4.45 p.m.

$$\begin{aligned}\text{Maximum concentration} &= \frac{3,250}{140} \\ &= \underline{23.2 \mu\text{c/gallon}}\end{aligned}$$

##### Hole 4 (Pump outlet) (Figure 12)

Maximum count rate (340 counts/sec) at 10.30 p.m. 16/12/63.

$$\begin{aligned}\text{Maximum concentration} &= \frac{34}{3820} \\ &= 0.089 \mu\text{c/gallon}\end{aligned}$$

$$\text{Isotope balance} = 87\%$$

#### JOHN AHERN PROPERTY

##### Hole 4 (Figures 13 - 16)

Maximum readings occurred at approximately 57 ft 2 in.

Maximum count rate (7,750 counts/sec) at 5.00 p.m. on 13/12/63.

$$\begin{aligned}\text{Maximum concentration} &= \frac{7750}{140} \mu\text{c/gallon} \\ &= \underline{55.4 \mu\text{c/gallon}}\end{aligned}$$

##### Hole 5 (Figures 17 and 18)

No readings were taken between 9.45 p.m. 13/12/63 and 10.00 a.m. 14/12/63. Hence the peak of the maximum count rate versus time curve was not determined. However, the curve shape was estimated by extrapolation.

### JOHN AHERN PROPERTY

No explanation is apparent for the dips in some of the activity/depth curves.

Maximum count rate (350 counts/sec) at 4.00 a.m. 14/12/63 (estimated).

$$\begin{aligned}\text{Maximum concentration} &= \frac{350}{140} \text{ } \mu\text{c/gallon} \\ &= \underline{2.5 \text{ } \mu\text{c/gallon}}\end{aligned}$$

#### Pump outlet (Figure 19)

Activity appeared in the pump outlet almost at the same time as in hole 5, but was much more dilute.

Maximum count rate (850 counts/sec) at 6.00 a.m. 14/12/63.

$$\begin{aligned}\text{Maximum concentration} &= \frac{850}{3820} \text{ } \mu\text{c/gallon} \\ &= \underline{0.22 \text{ } \mu\text{c/gallon}}\end{aligned}$$

No activity was detected at any stage in holes 2 and 3 indicating that the flow was primarily towards the pumped output.

Isotope balance = 100%.

### FOWLER PROPERTY

No activity was found in the monitoring holes at any time.

#### Pump outlet (Figure 21)

Maximum count rate (655 counts/sec) at 1.45 p.m. 14/12/63, that is only 7¼ hours after addition of activity.

$$\begin{aligned}\text{Maximum concentration} &= \frac{655}{3820} \text{ } \mu\text{c/gallon} \\ &= 0.17 \text{ } \mu\text{c/gallon}\end{aligned}$$

Isotope balance = 115%

### JOE AHERN PROPERTY

No activity was detected in the monitoring holes at any time. Pump outlet (Figure 20).

Maximum count rate (750 counts/sec) at 8.30 p.m. 13/12/63, that is 34½ hours after addition of the activity.

$$\begin{aligned}\text{Maximum concentration} &= \frac{750}{3820} \text{ } \mu\text{c/gallon} \\ &= 0.20 \text{ } \mu\text{c/gallon}\end{aligned}$$

Isotope balance = 249%

This very high figure is difficult to explain. It could possibly be due to some contamination in the scintillation head, thus giving the very long tail seen in this pump output curve.



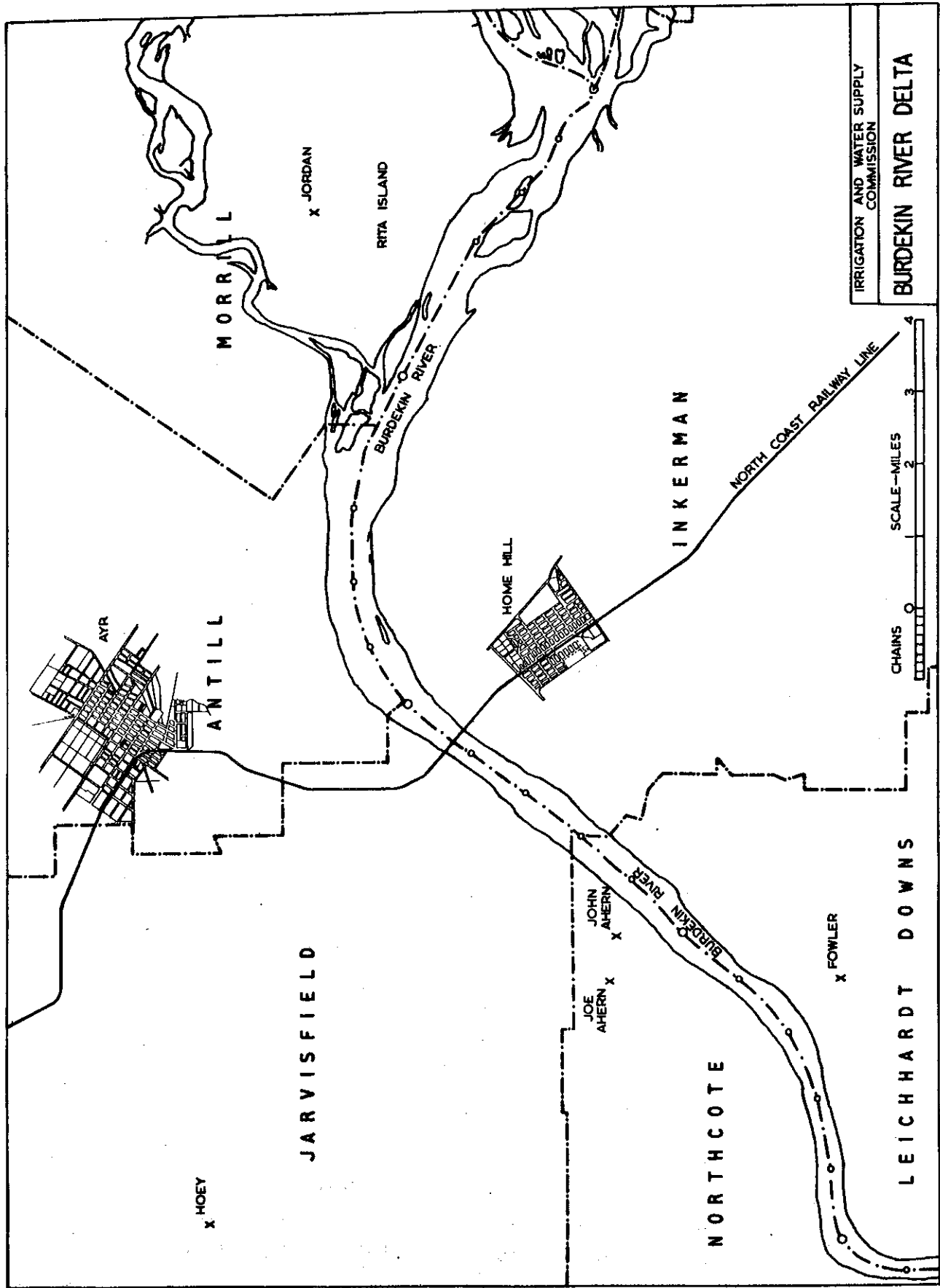
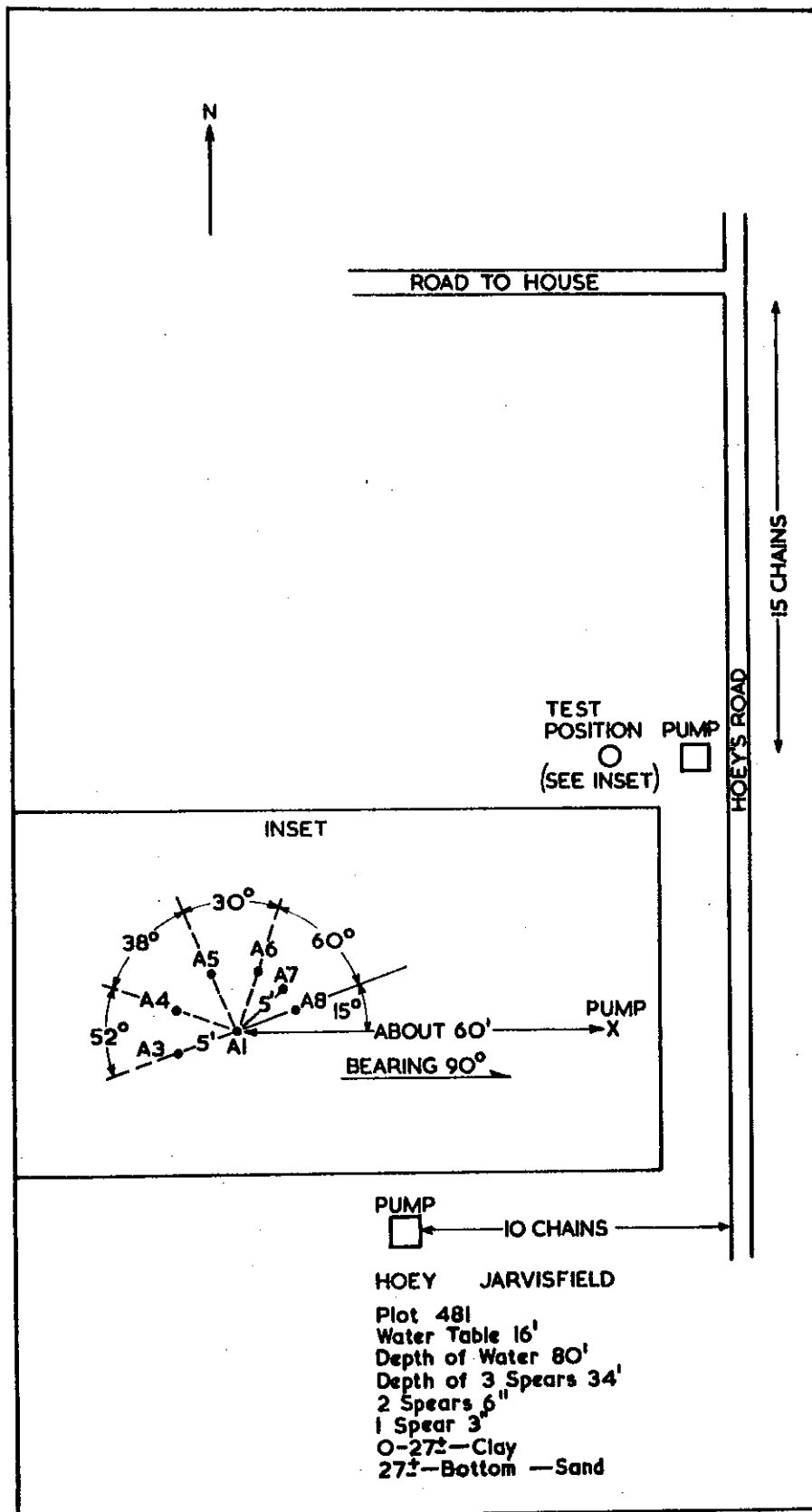
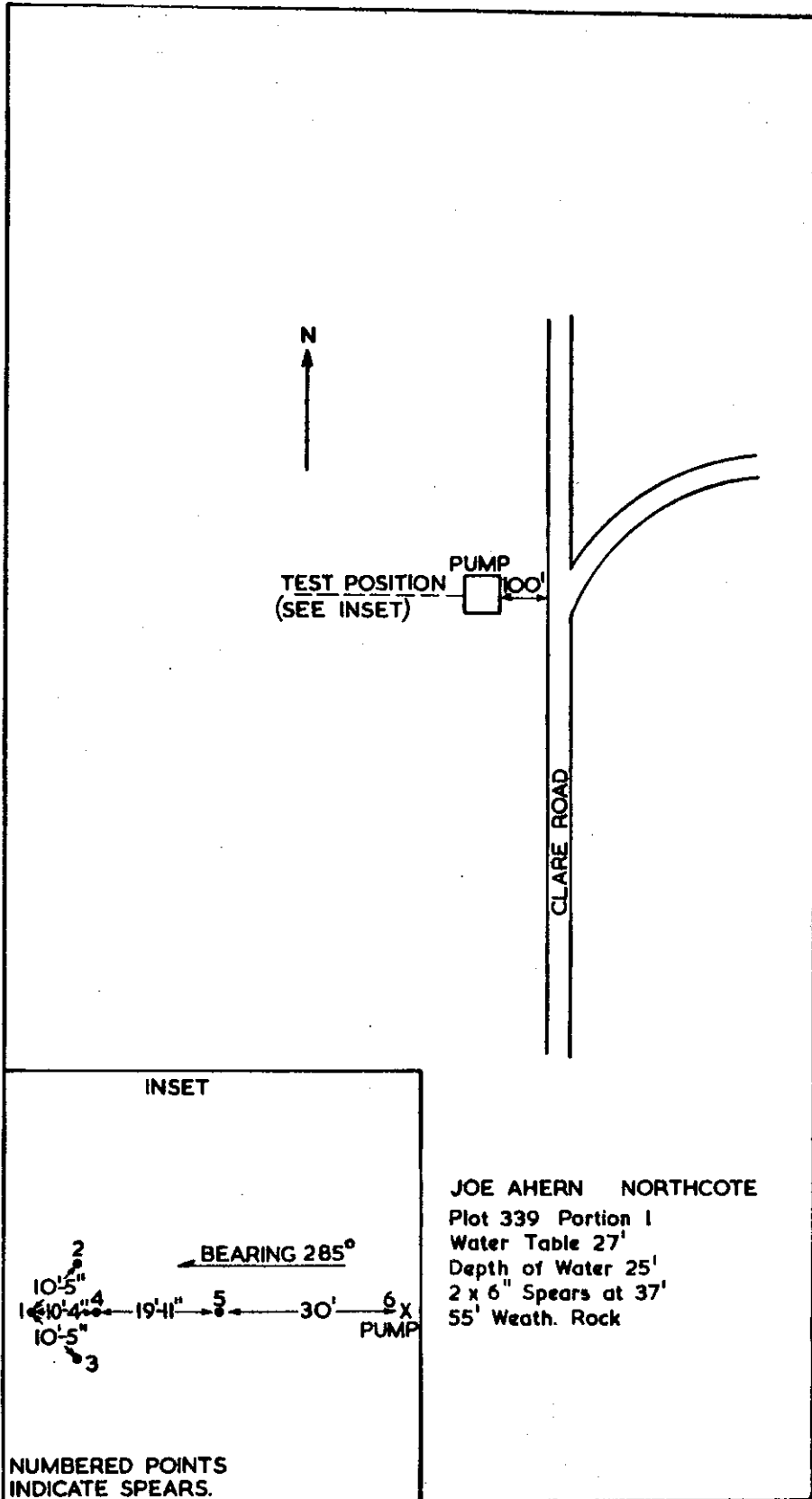


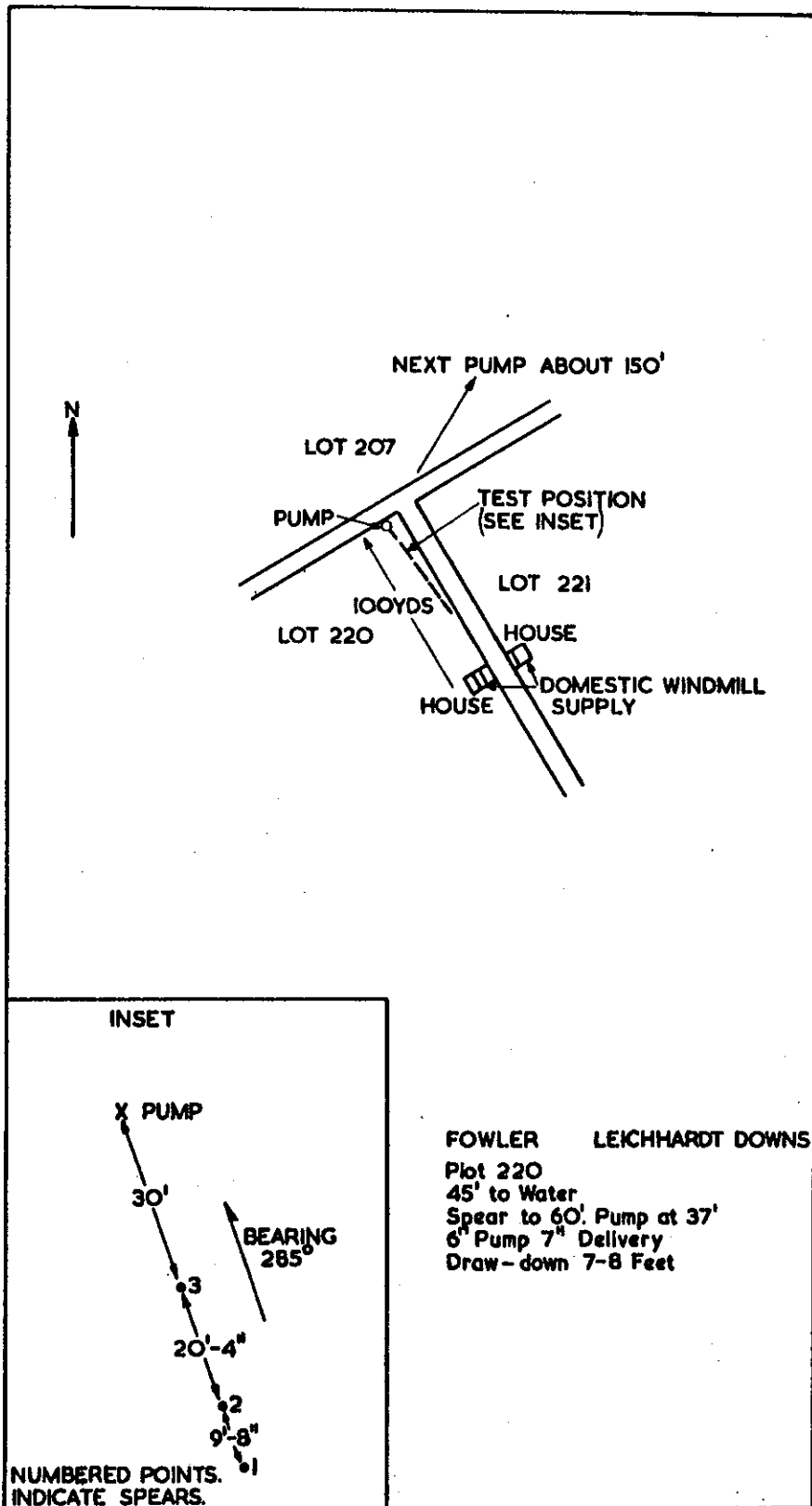
FIGURE 1. LOCATION OF PROPERTIES—BURDEKIN RIVER DELTA (FROM I. & W.S.C. PLAN L17433)



**FIGURE 2. HOEY PROPERTY (FREE FLOW TEST)  
 LOCATION PLAN**



**FIGURE 3. JOE AHERN PROPERTY (PUMPED BORE TEST)-LOCATION PLAN**



**FIGURE 4. FOWLER PROPERTY (PUMPED BORE TEST) LOCATION PLAN**

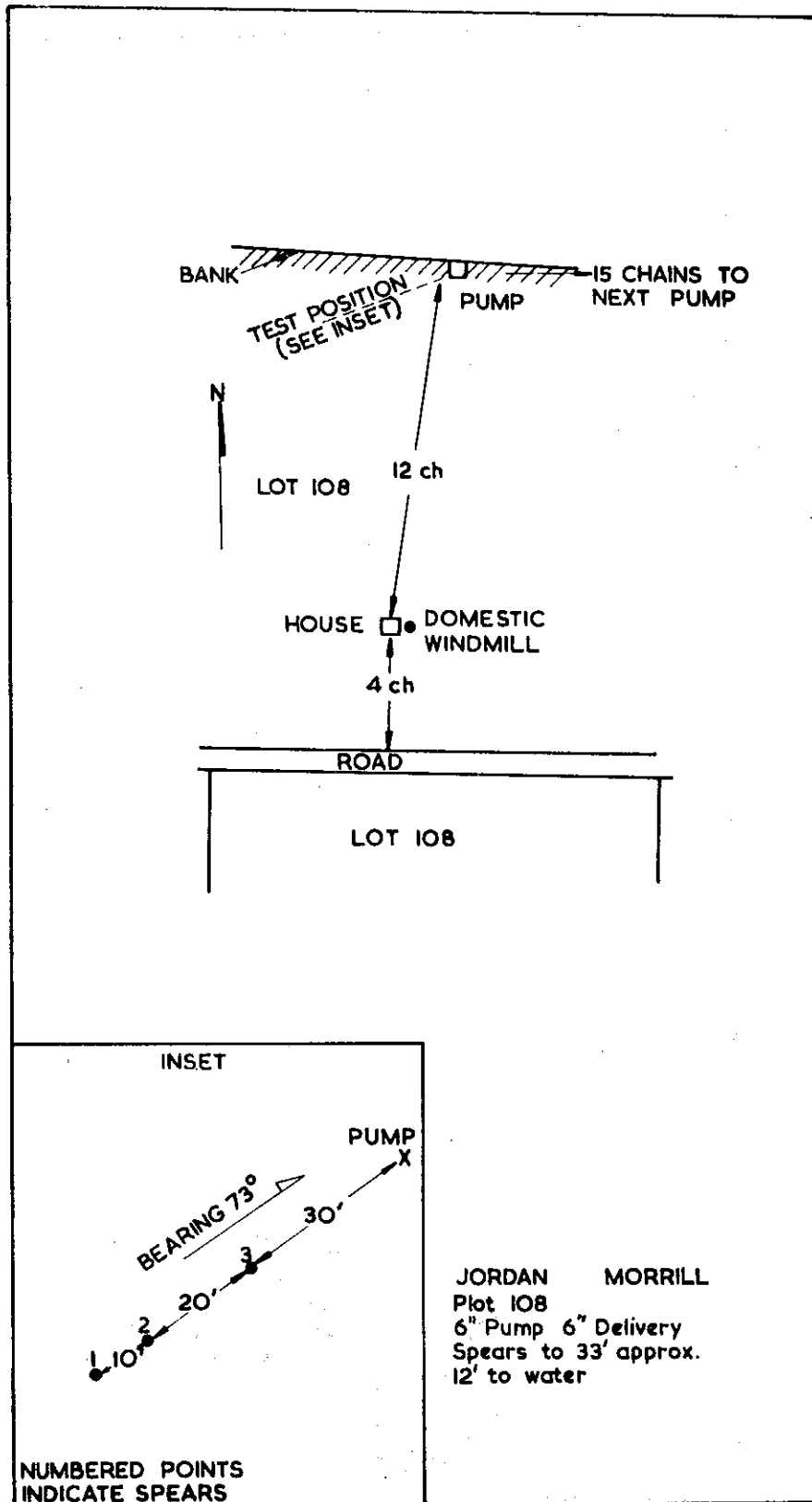


FIGURE 5. JORDAN PROPERTY (PUMPED BORE TEST)  
LOCATION PLAN

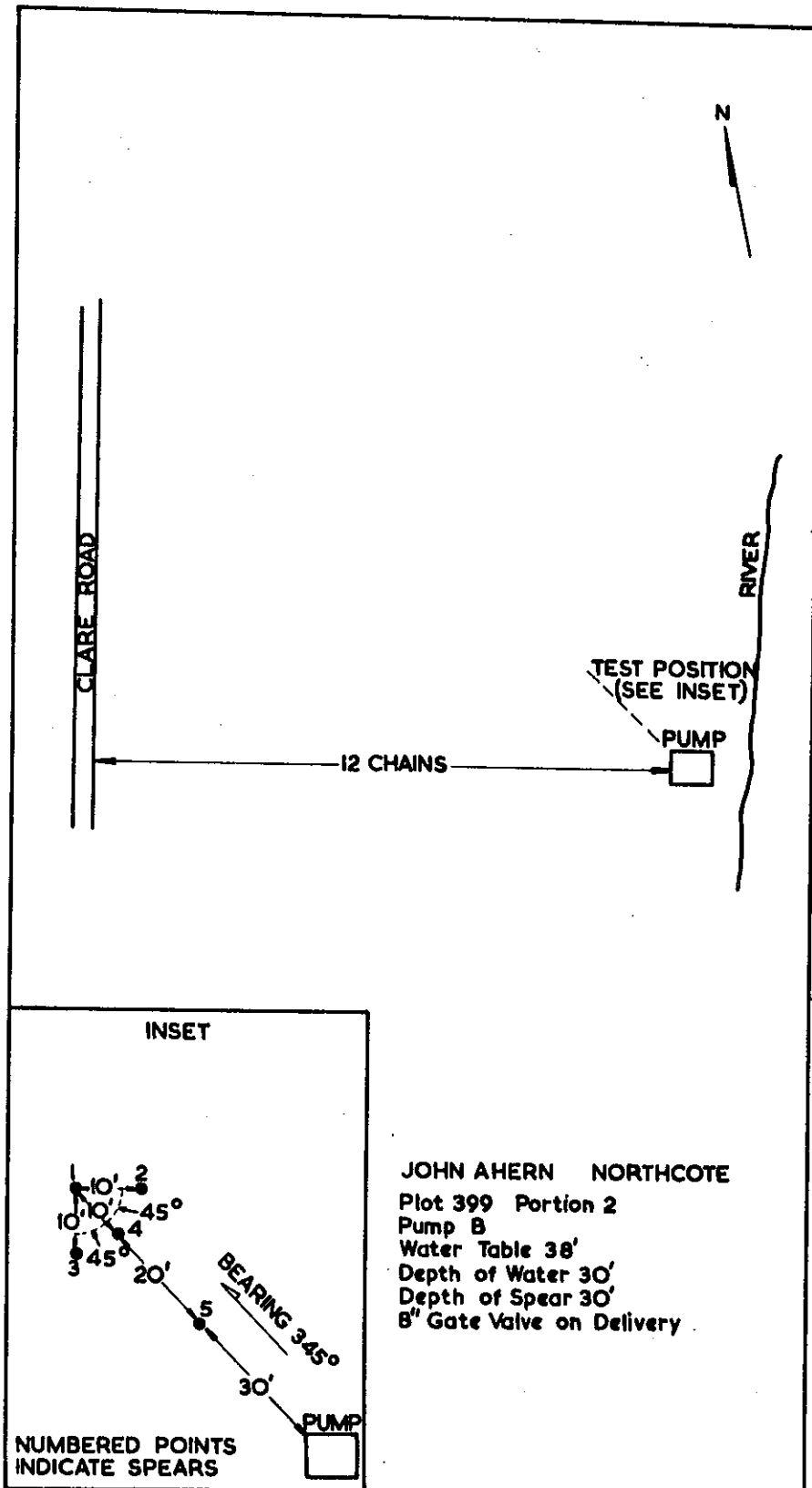


FIGURE 6 JOHN AHERN PROPERTY (PUMPED BORE TEST)—LOCATION PLAN

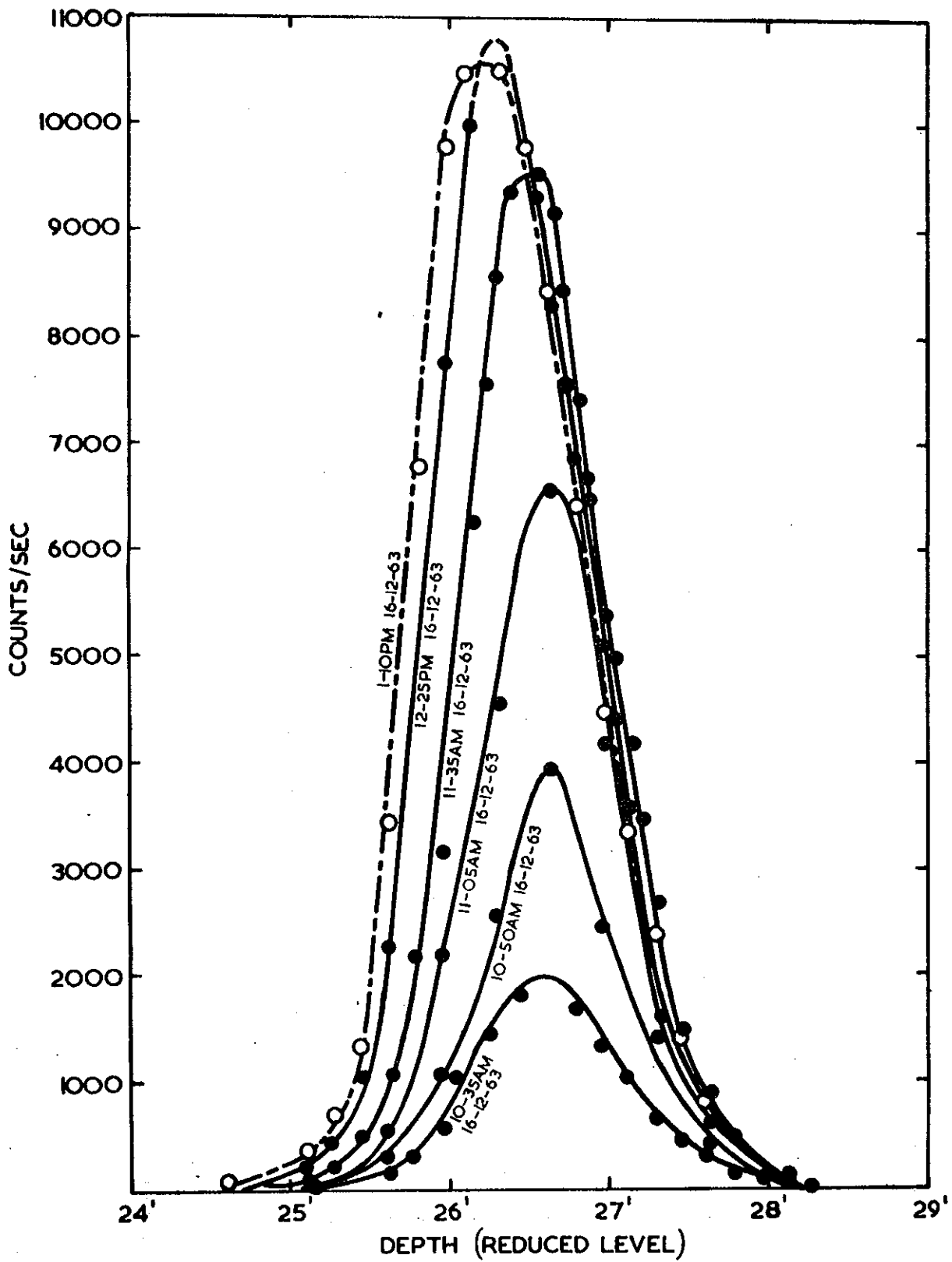


FIGURE 7. JORDAN No. 2 HOLE-PROFILE (SHEET I)

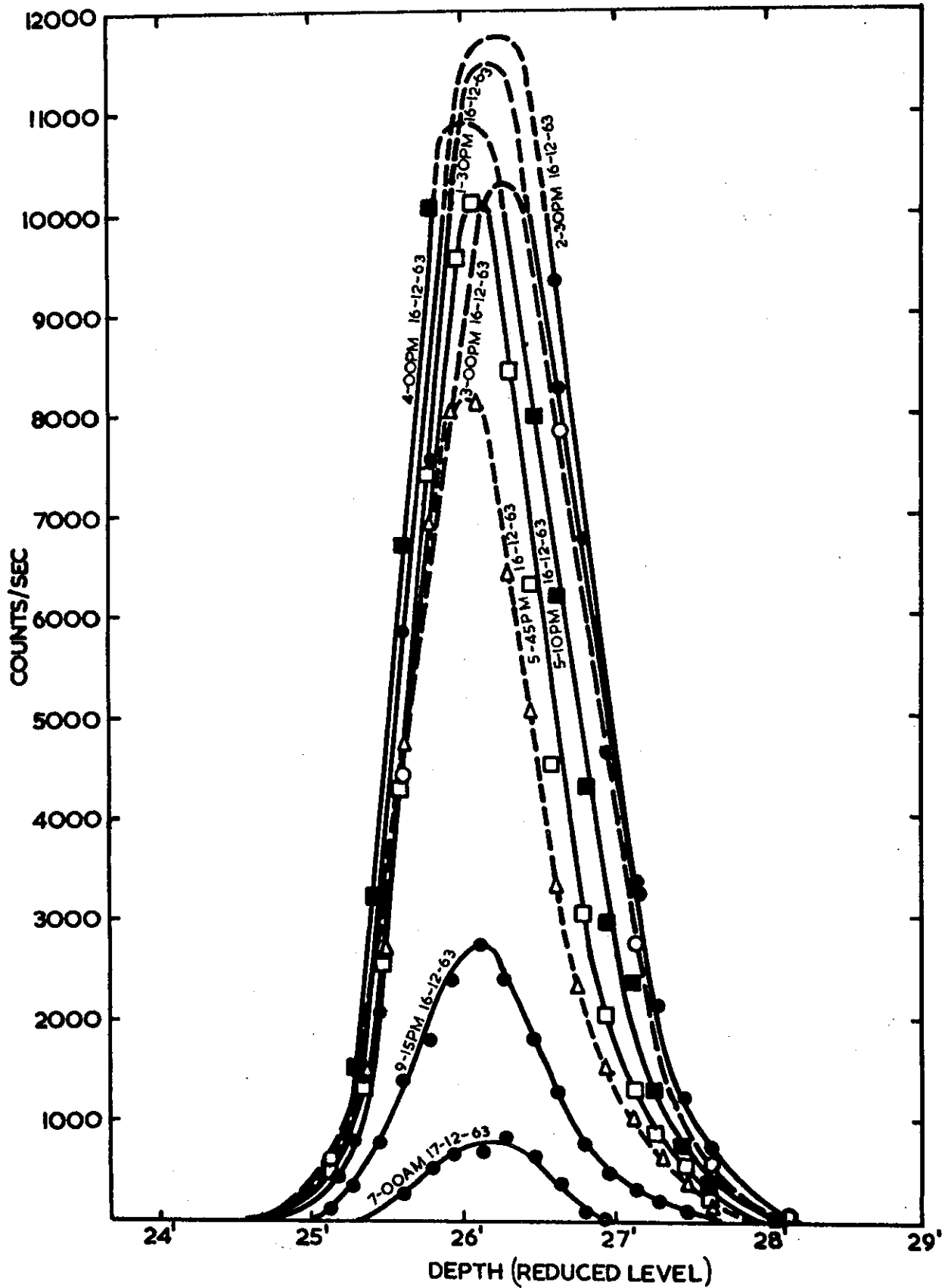


FIGURE 8. JORDAN No. 2 HOLE - PROFILE (SHEET 2)

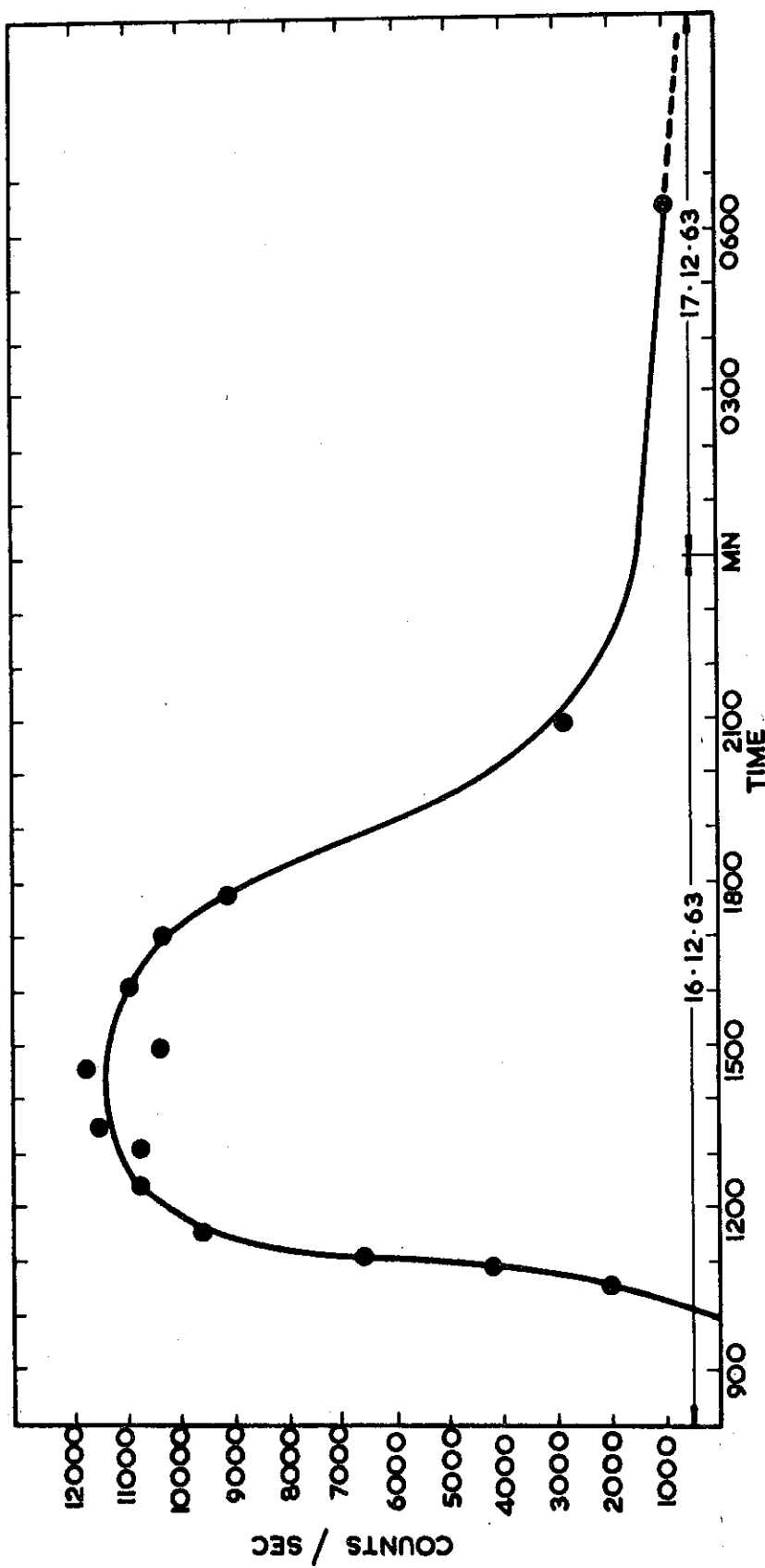


FIGURE 9. JORDAN No 2 HOLE — MAXIMUM COUNT-RATE V. TIME

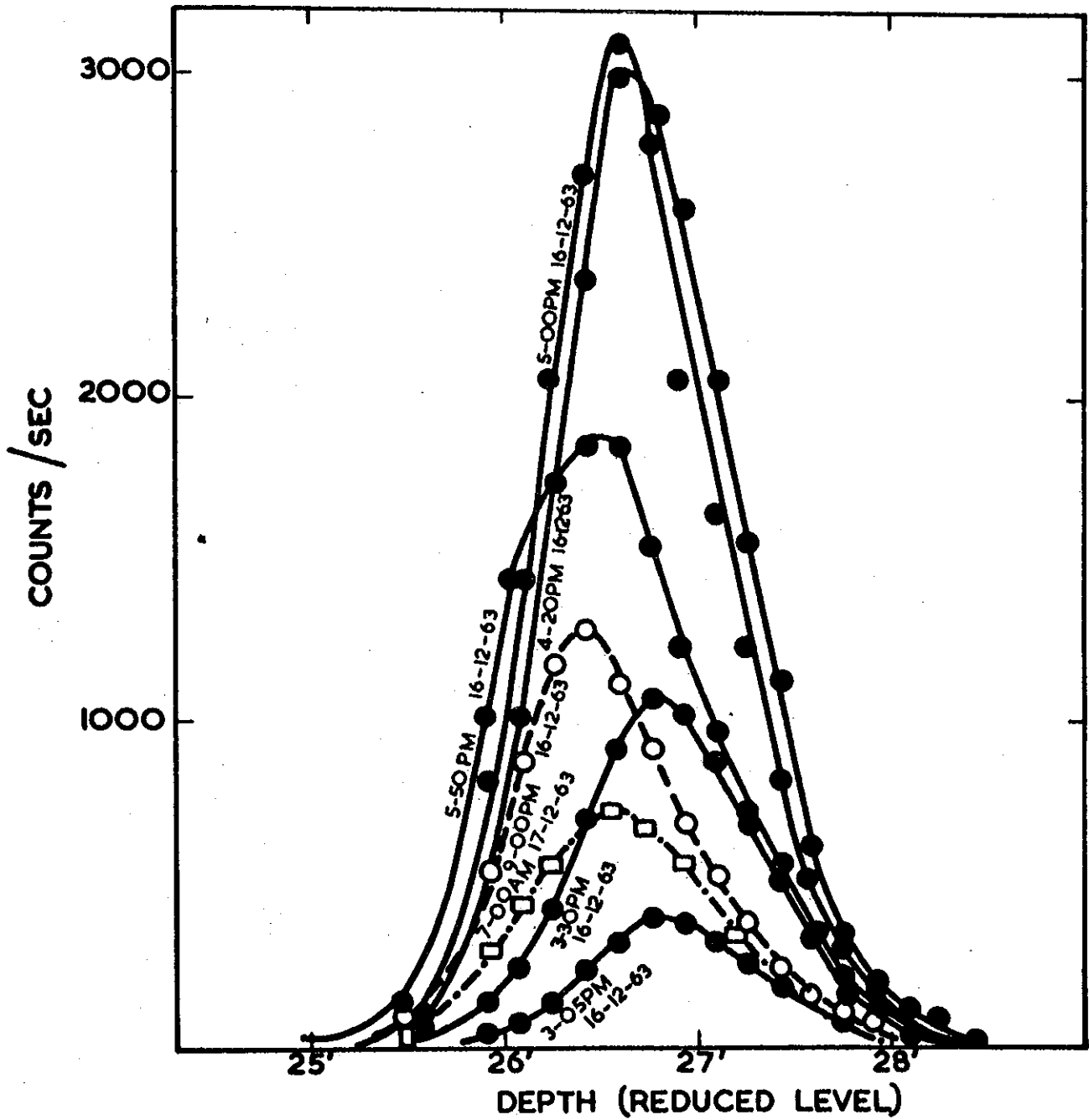


FIGURE 10 JORDAN No 3 HOLE—PROFILE

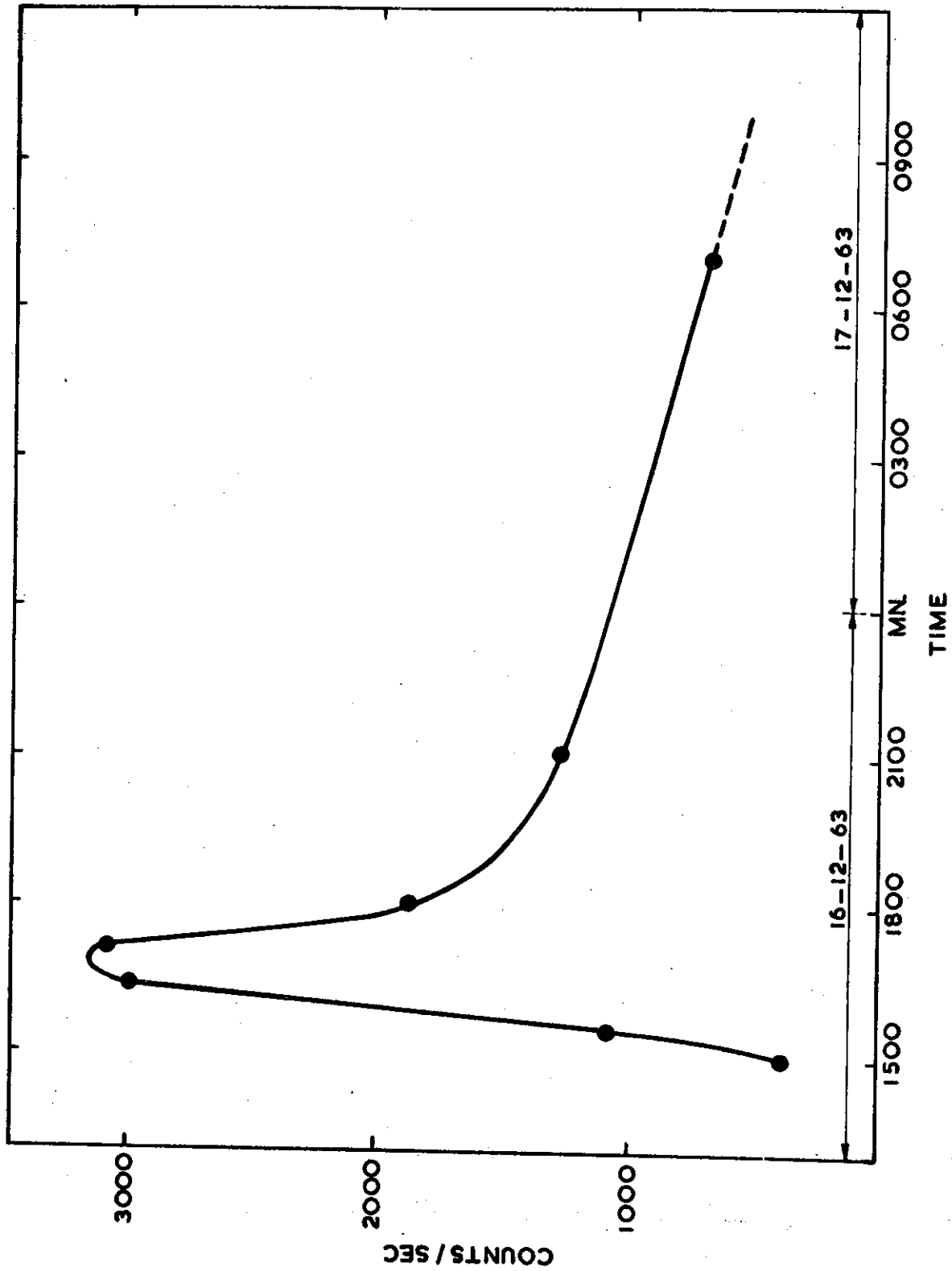


FIGURE II. JORDAN No. 3 HOLE - MAXIMUM COUNT-RATE  
V. TIME

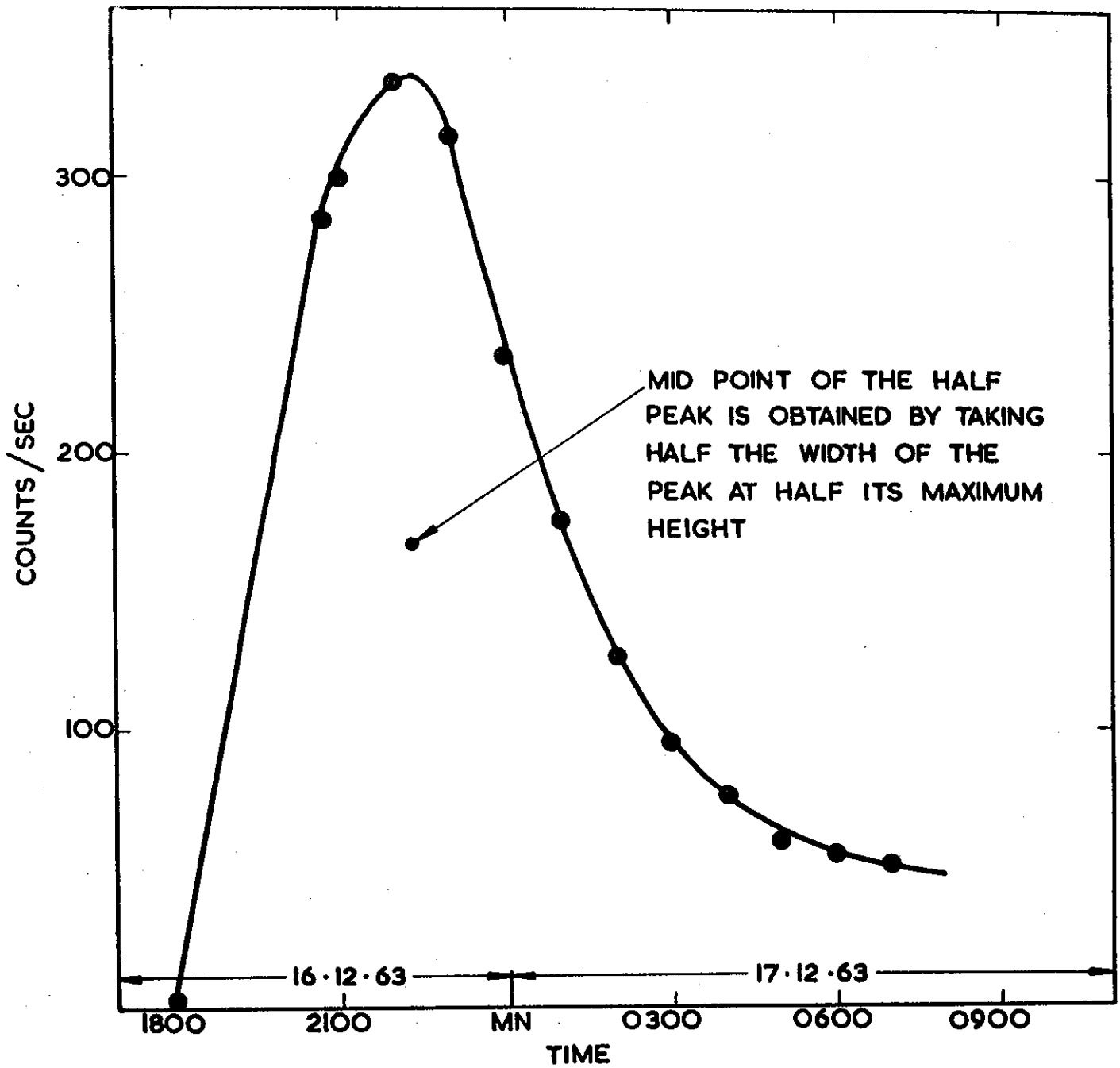


FIGURE 12. JORDAN No 4 HOLE—PUMP OUTLET—  
MAXIMUM COUNT-RATE V. TIME

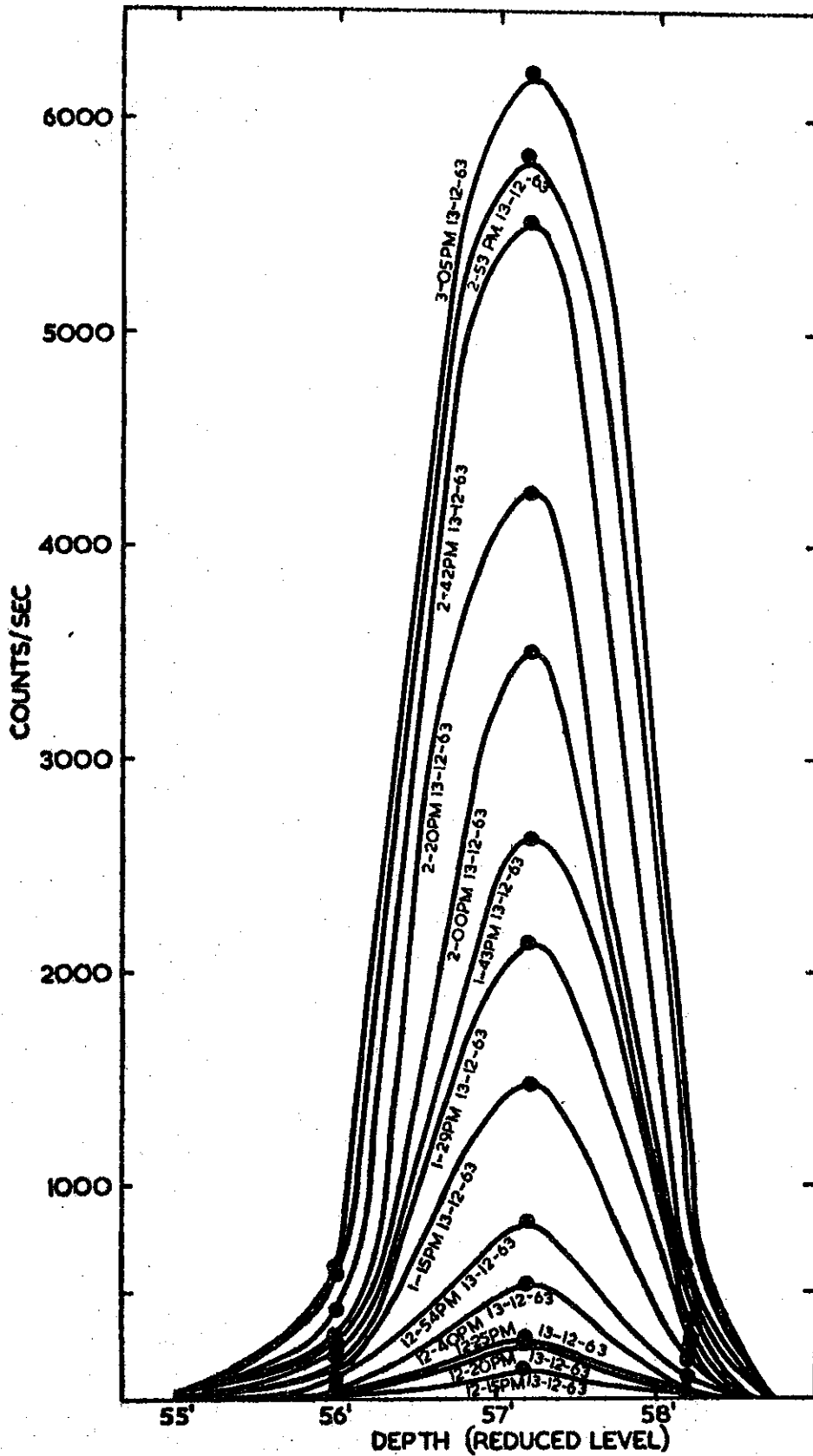


FIGURE 13. JOHN AHERN No 4 HOLE-PROFILE  
(SHEET I)

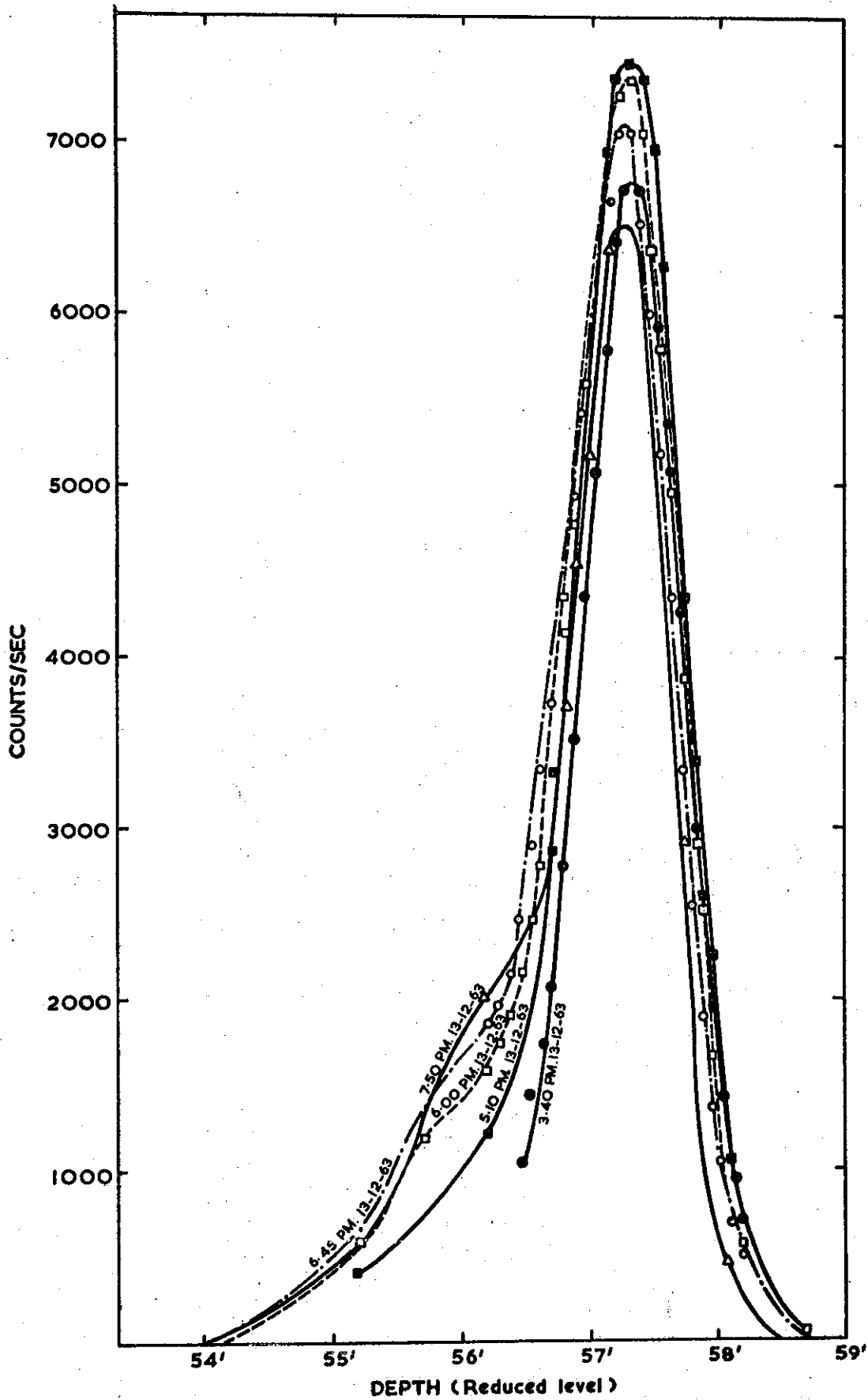
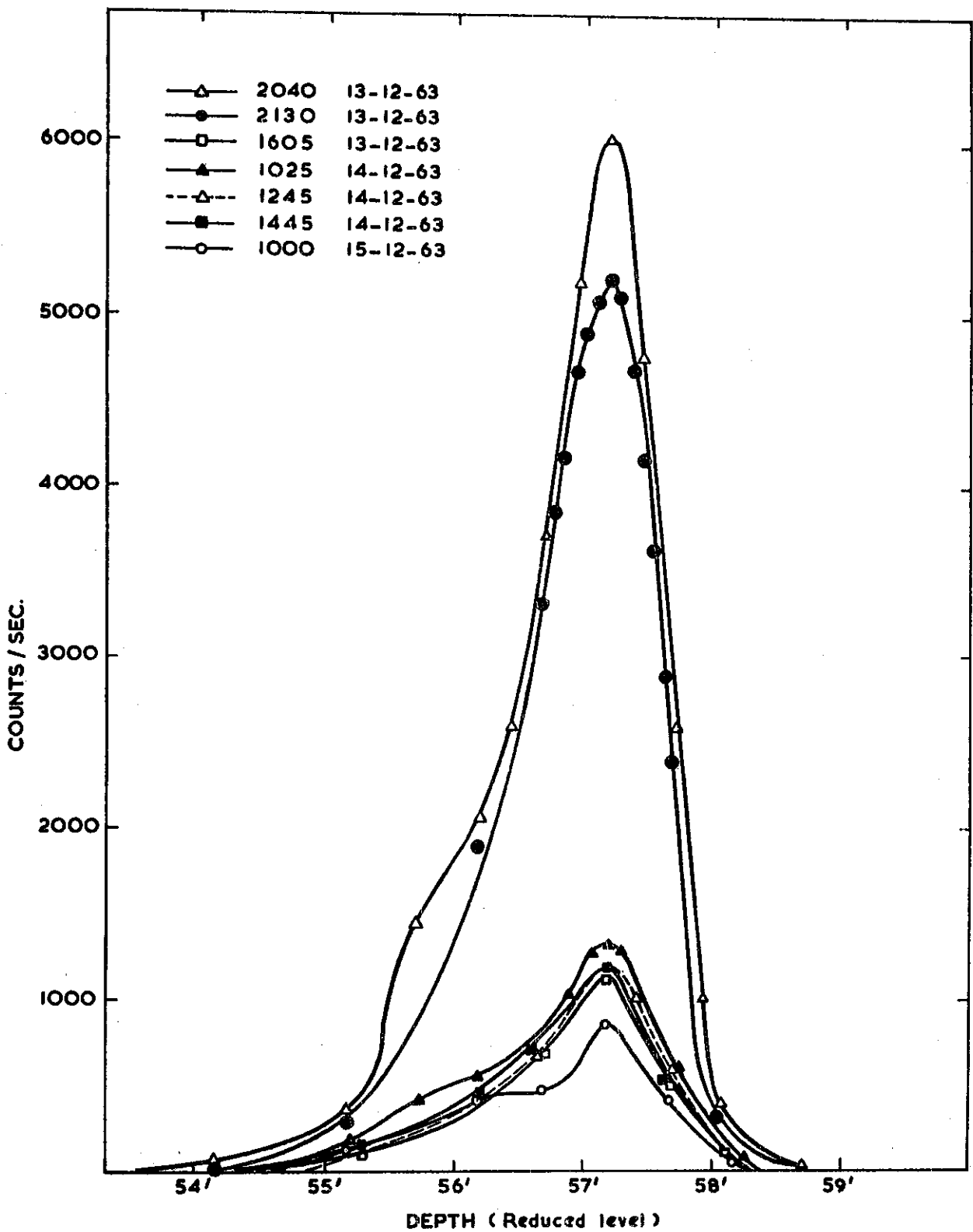


FIGURE 14. JOHN AHERN No. 4 HOLE PROFILE (SHEET 2)



**FIGURE 15. JOHN AHERN No. 4 HOLE - PROFILE  
( SHEET 3 )**

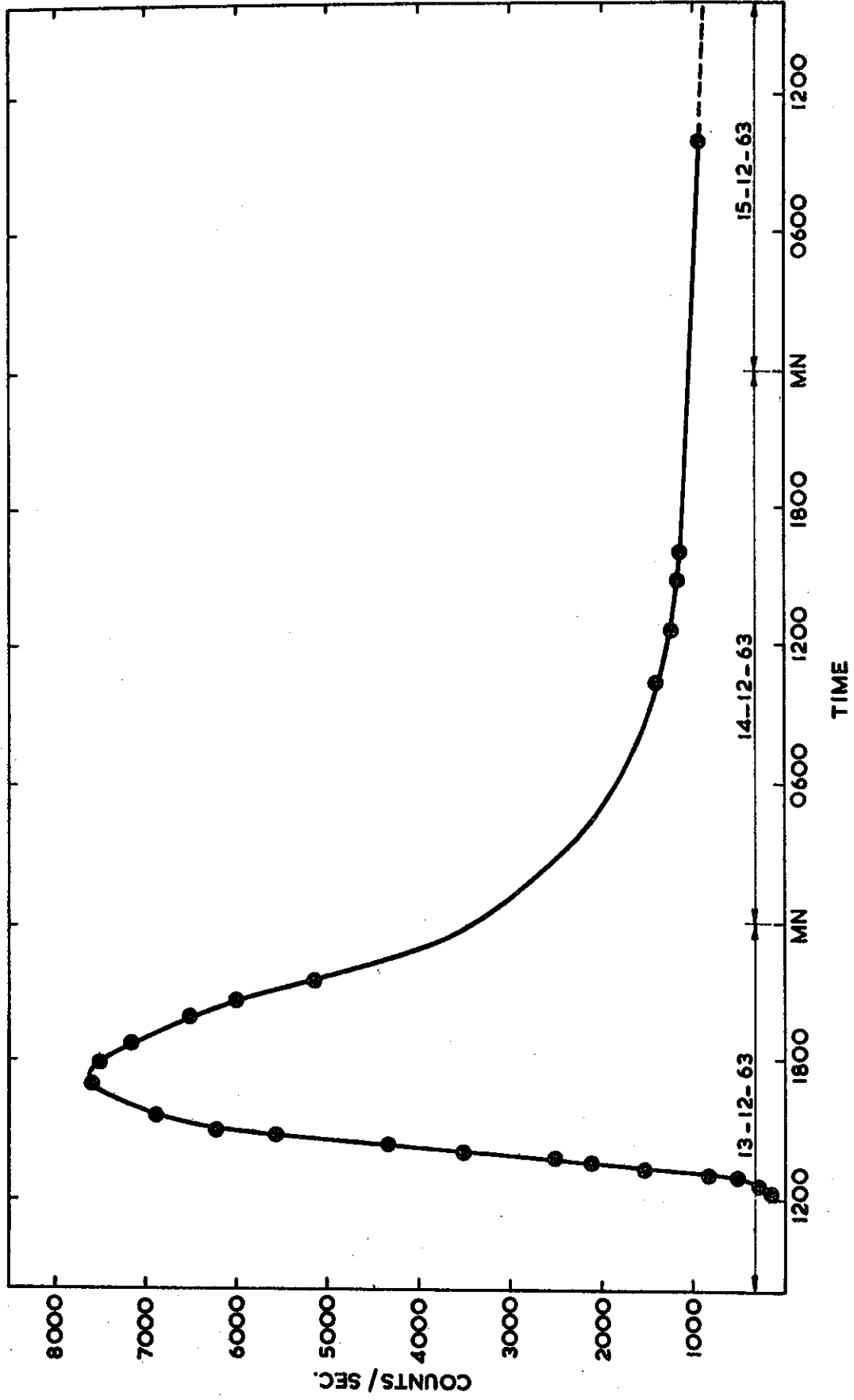


FIGURE 16. JOHN AHERN No. 4 HOLE—MAXIMUM COUNT RATE V. TIME

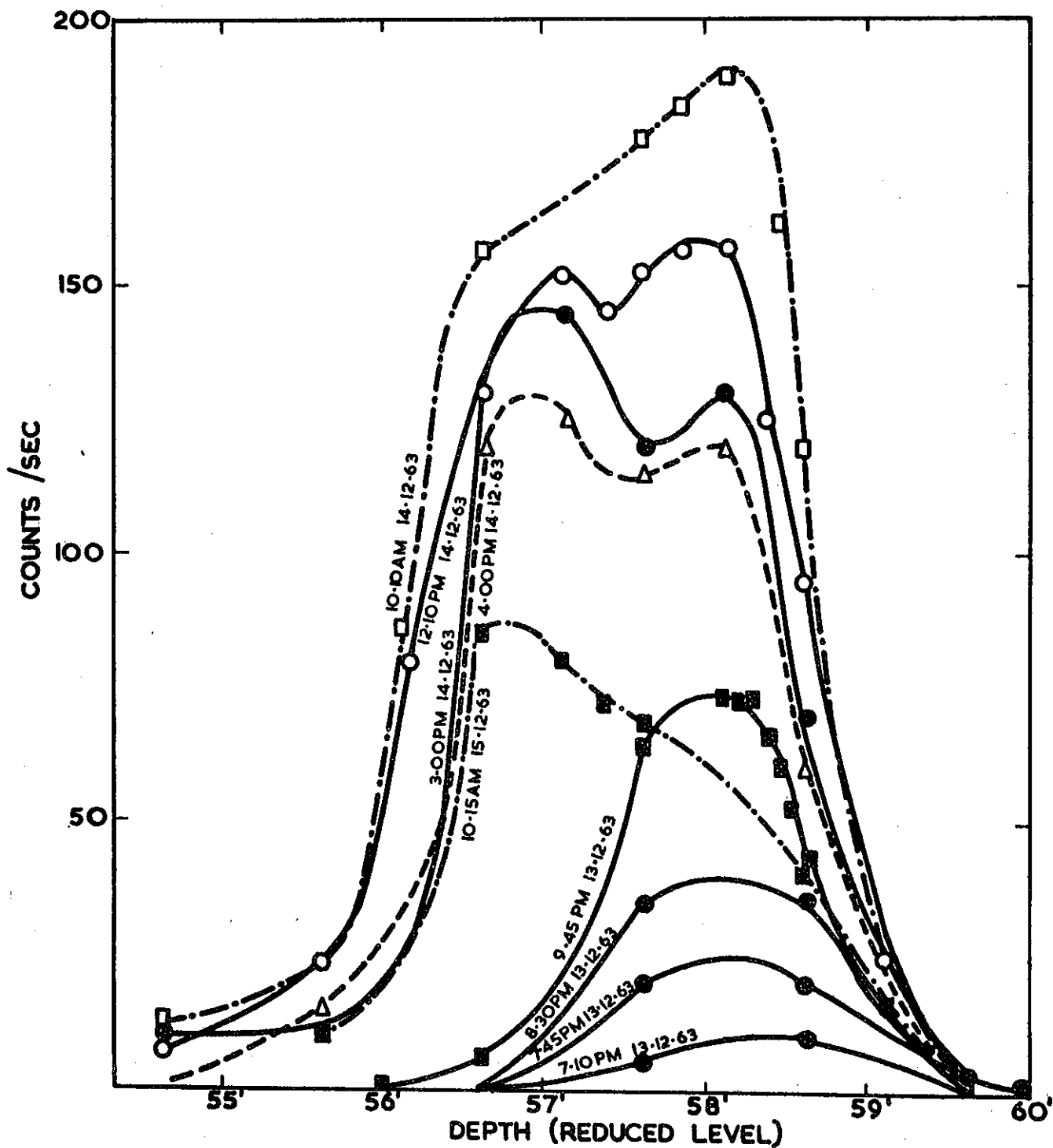


FIGURE 17. JOHN AHERN HOLE No 5 — PROFILE

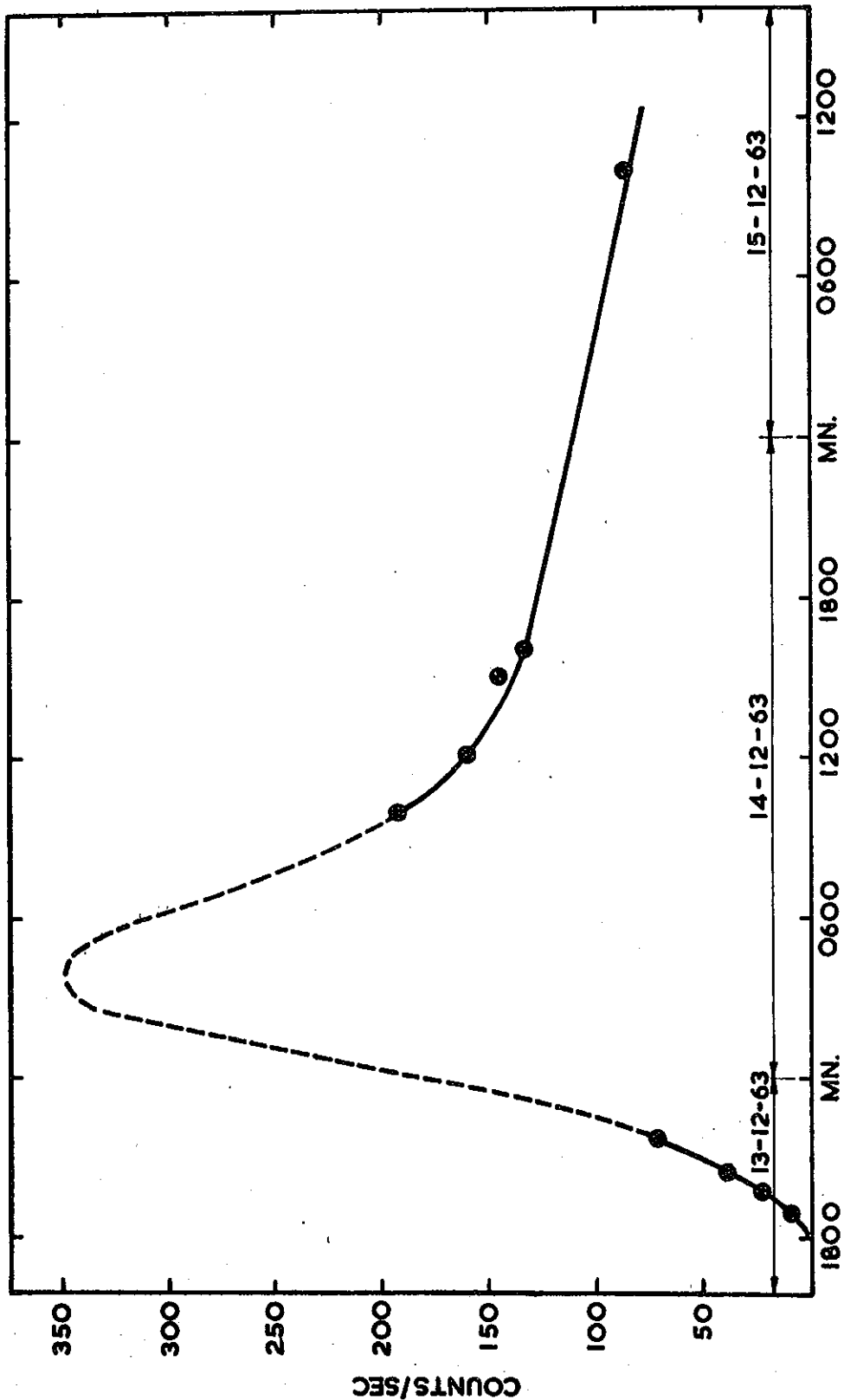


FIGURE 18. JOHN AHERN No. 5 HOLE --  
 MAXIMUM COUNT-RATE V. TIME

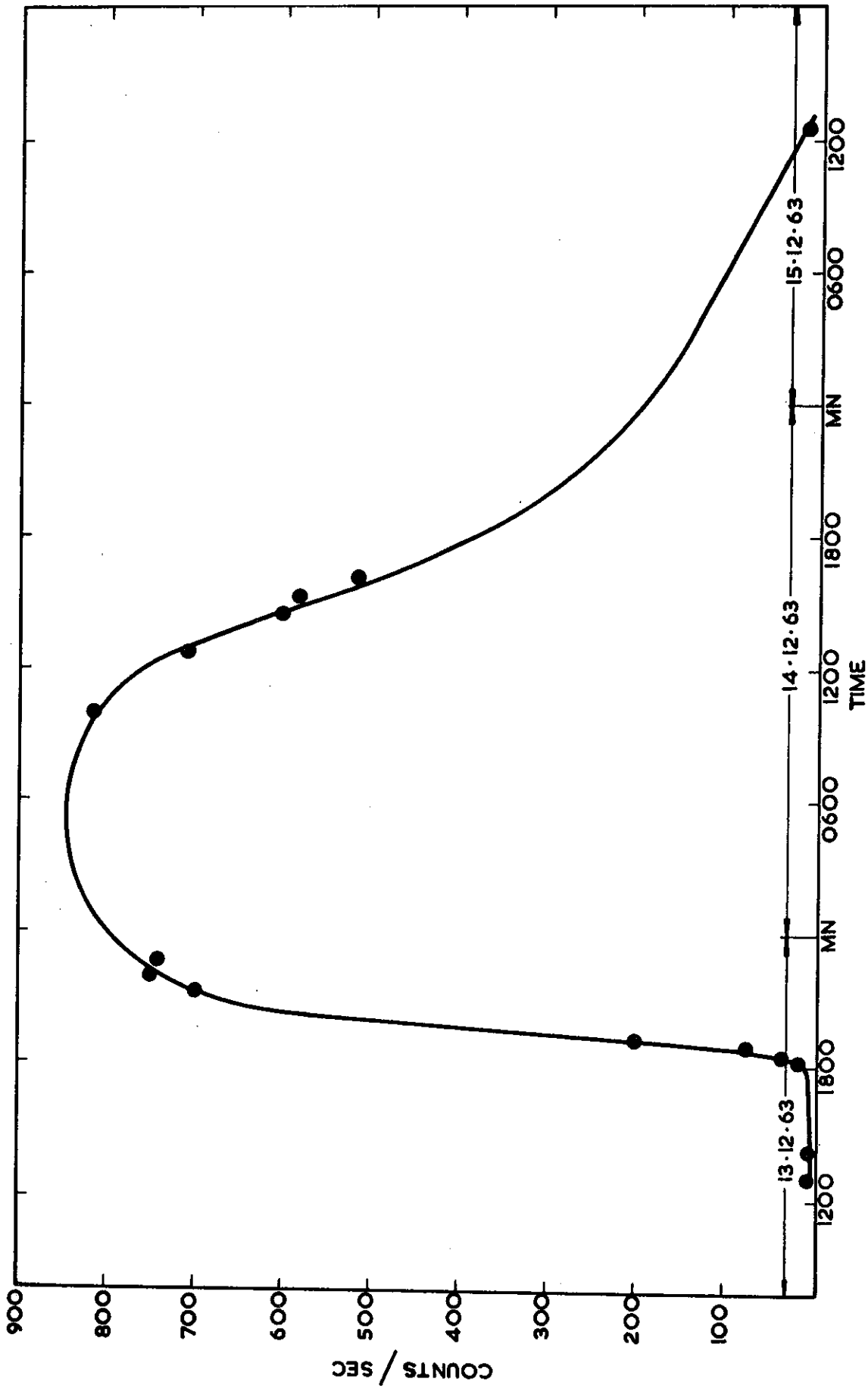


FIGURE 19. JOHN AHERN — PUMP OUTLET — MAXIMUM COUNT-RATE V. TIME

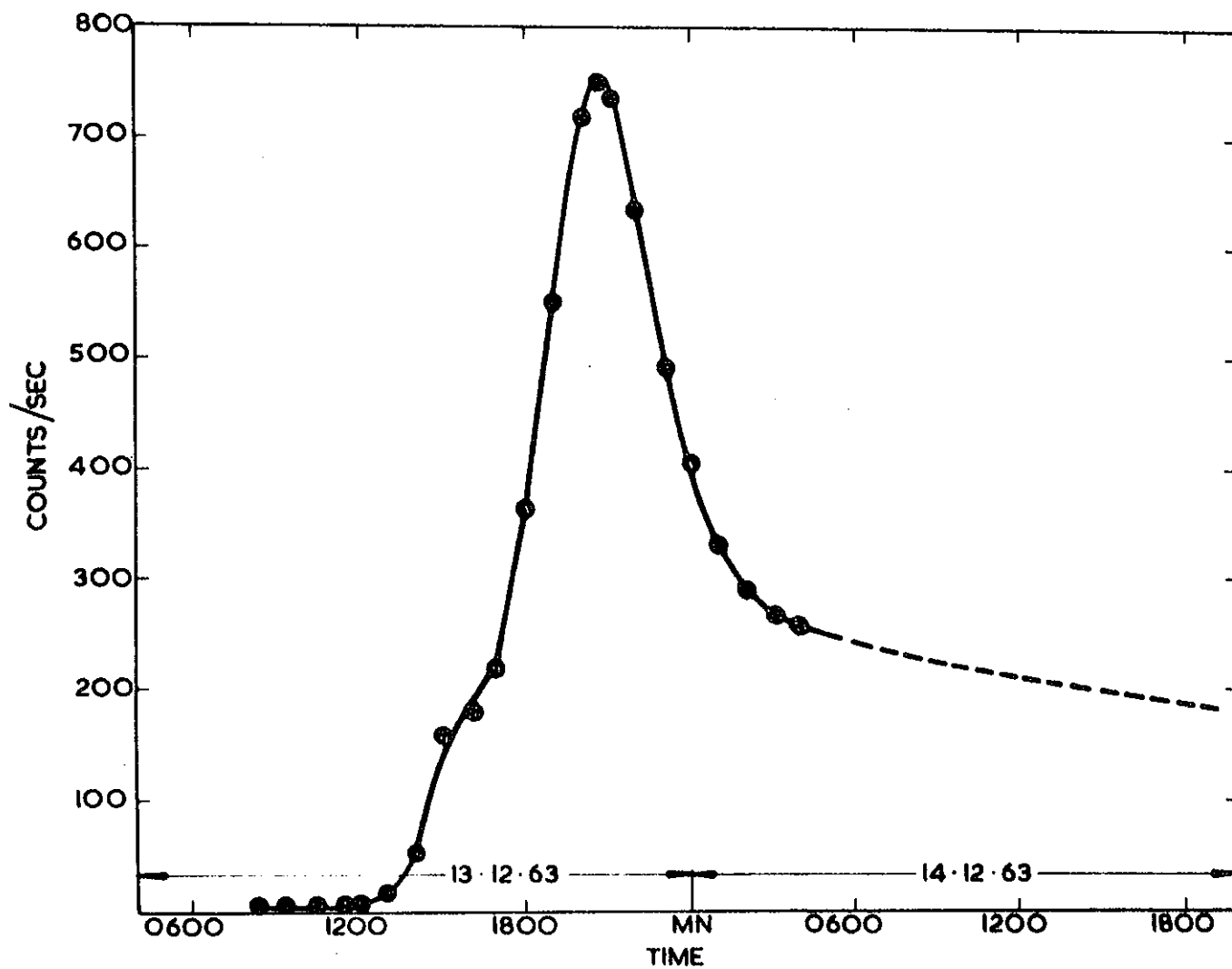


FIGURE 20. JOE AHERN—PUMP OUTLET—  
MAXIMUM COUNT-RATE V. TIME

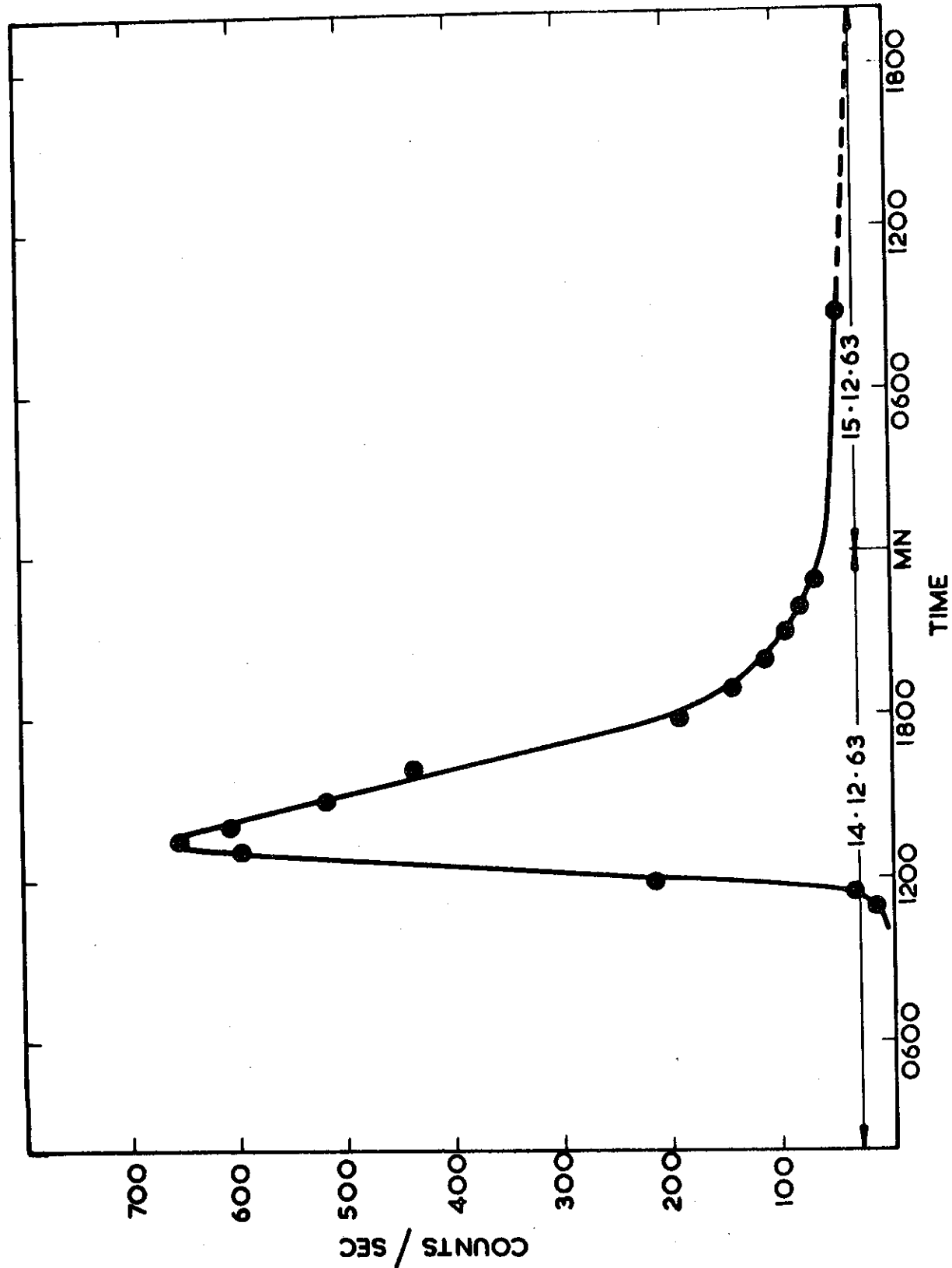


FIGURE 21. FOWLER - PUMP OUTLET  
 MAXIMUM COUNT - RATE V. TIME

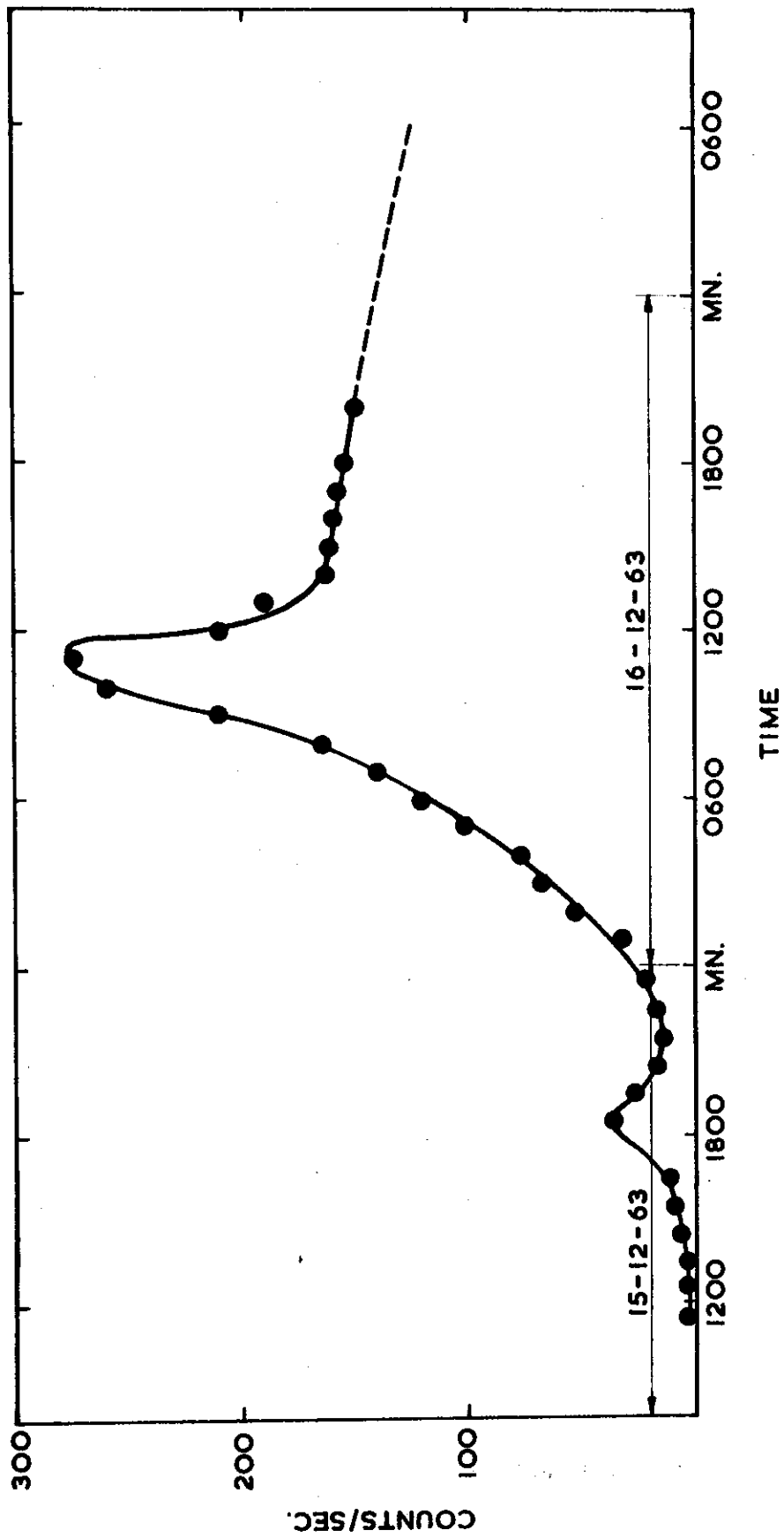


FIGURE 22. HOEY - PUMP OUTLET - MAXIMUM COUNT - RATE V. TIME

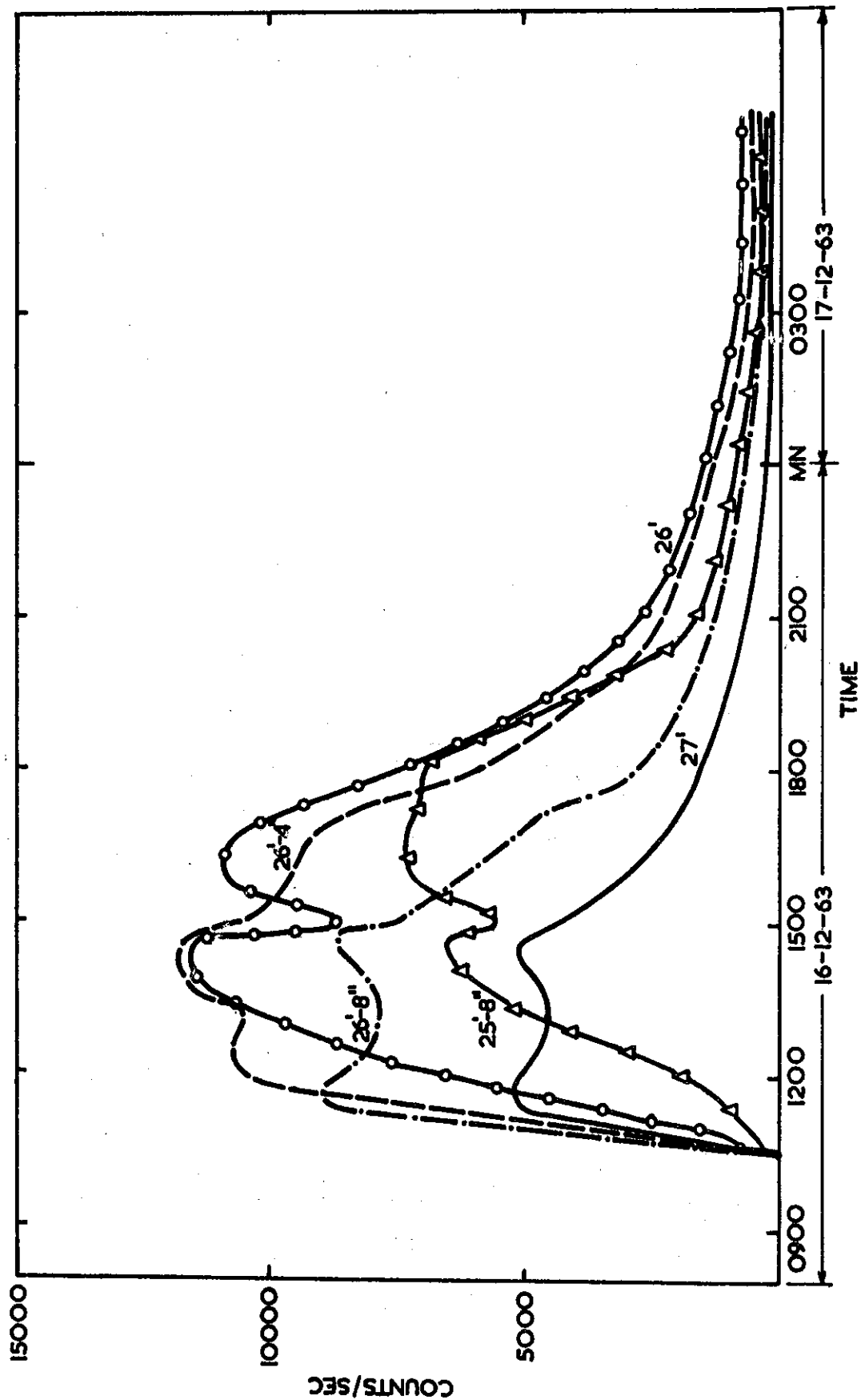


FIGURE 23. JORDAN No. 2 HOLE - COUNT RATE V. TIME AT CONSTANT DEPTHS

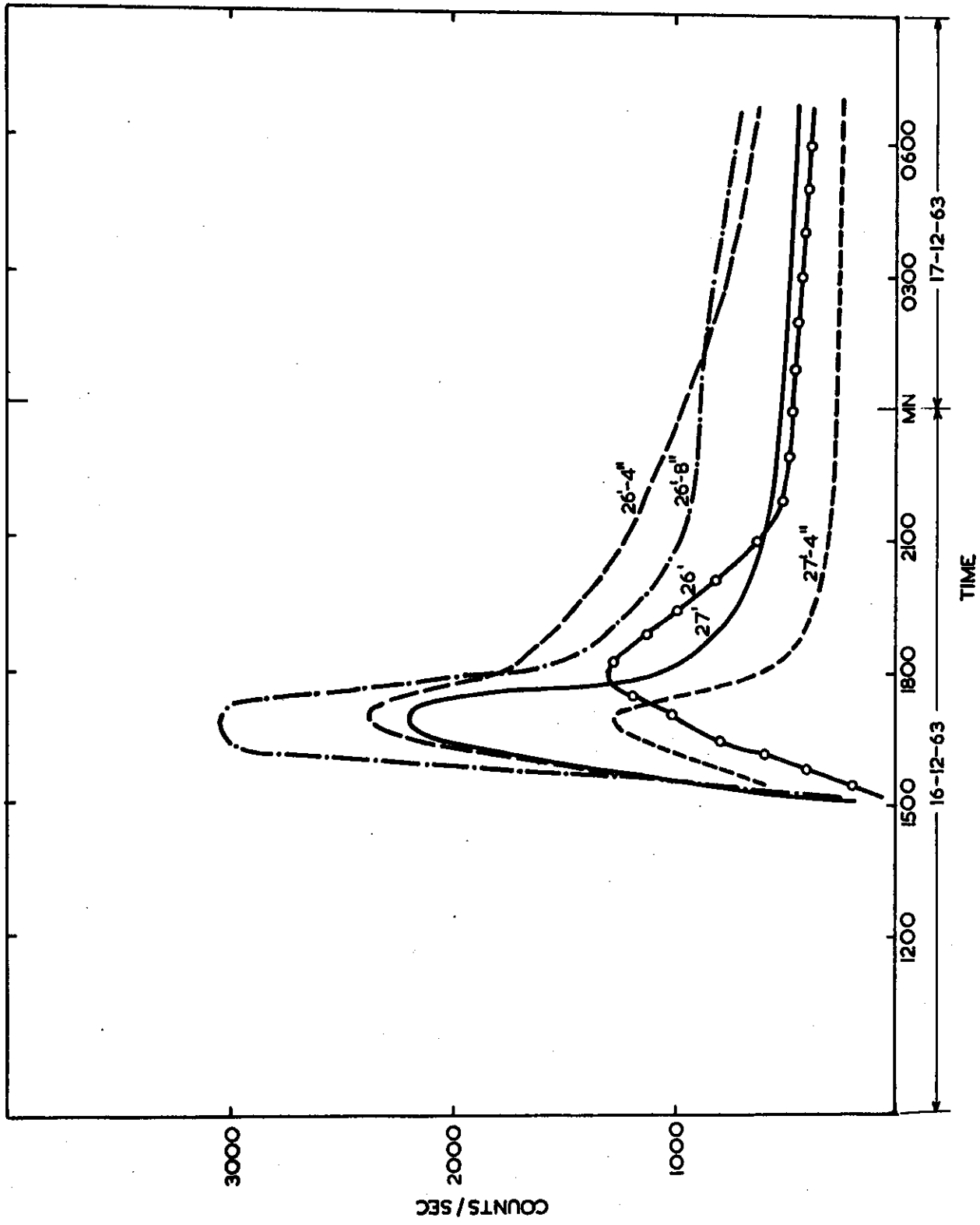


FIGURE 24. JORDAN No. 3 HOLE.-COUNT RATE V. TIME AT CONSTANT DEPTHS

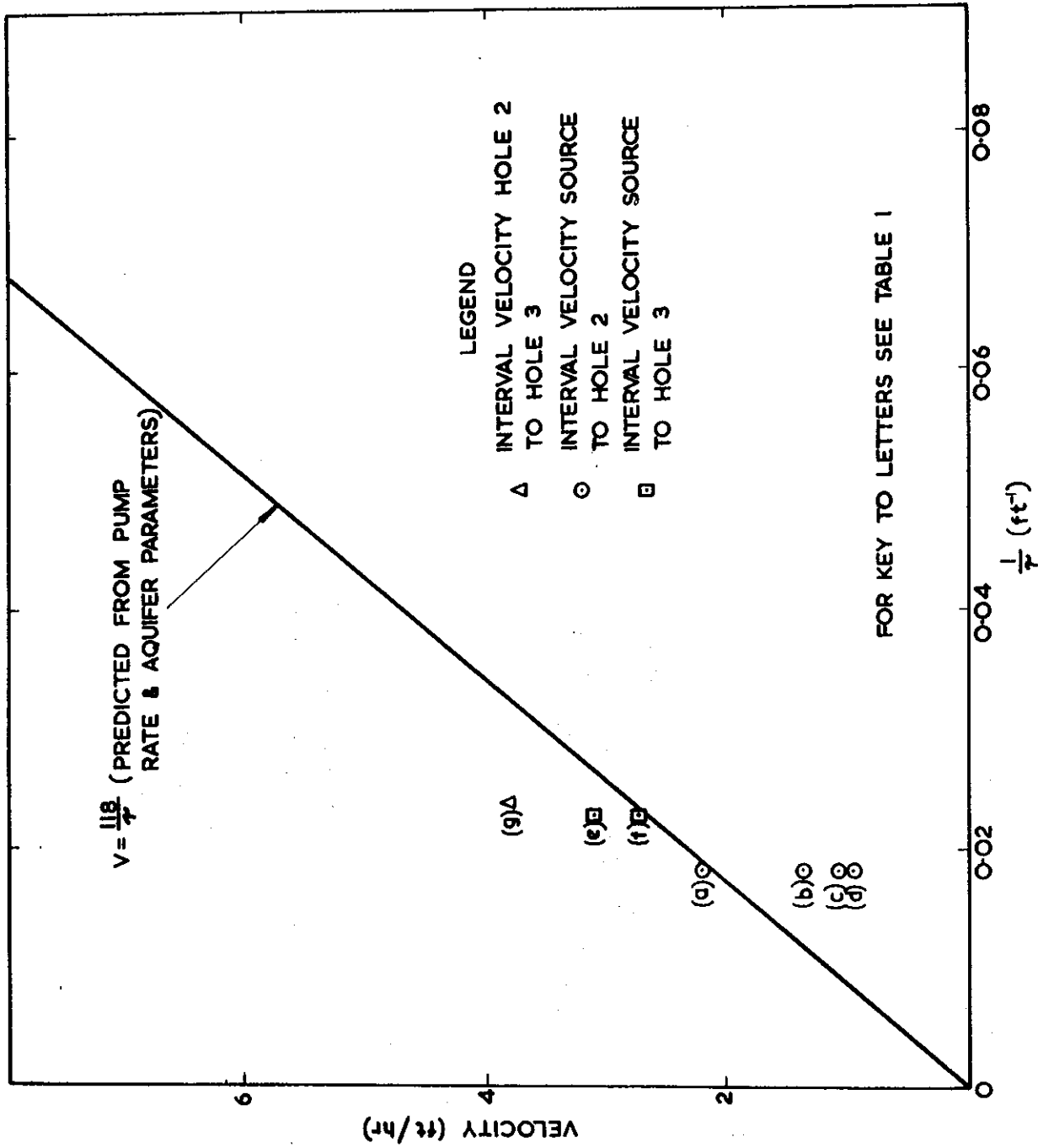


FIGURE 25. JORDAN — PREDICTED AND OBSERVED VELOCITIES

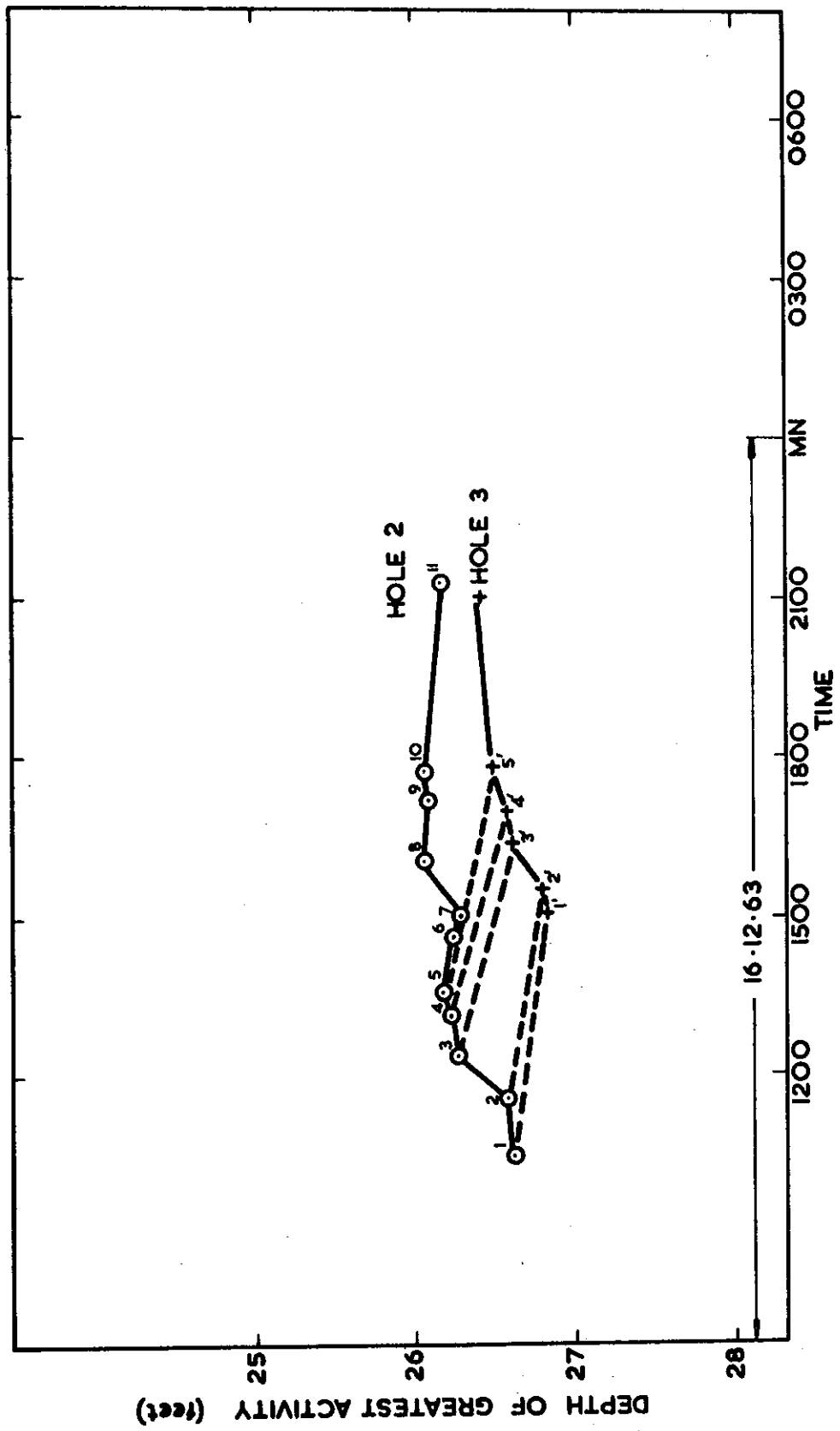


FIGURE 26. JORDAN HOLES Nos. 2 AND 3  
DEPTH OF GREATEST ACTIVITY V. TIME

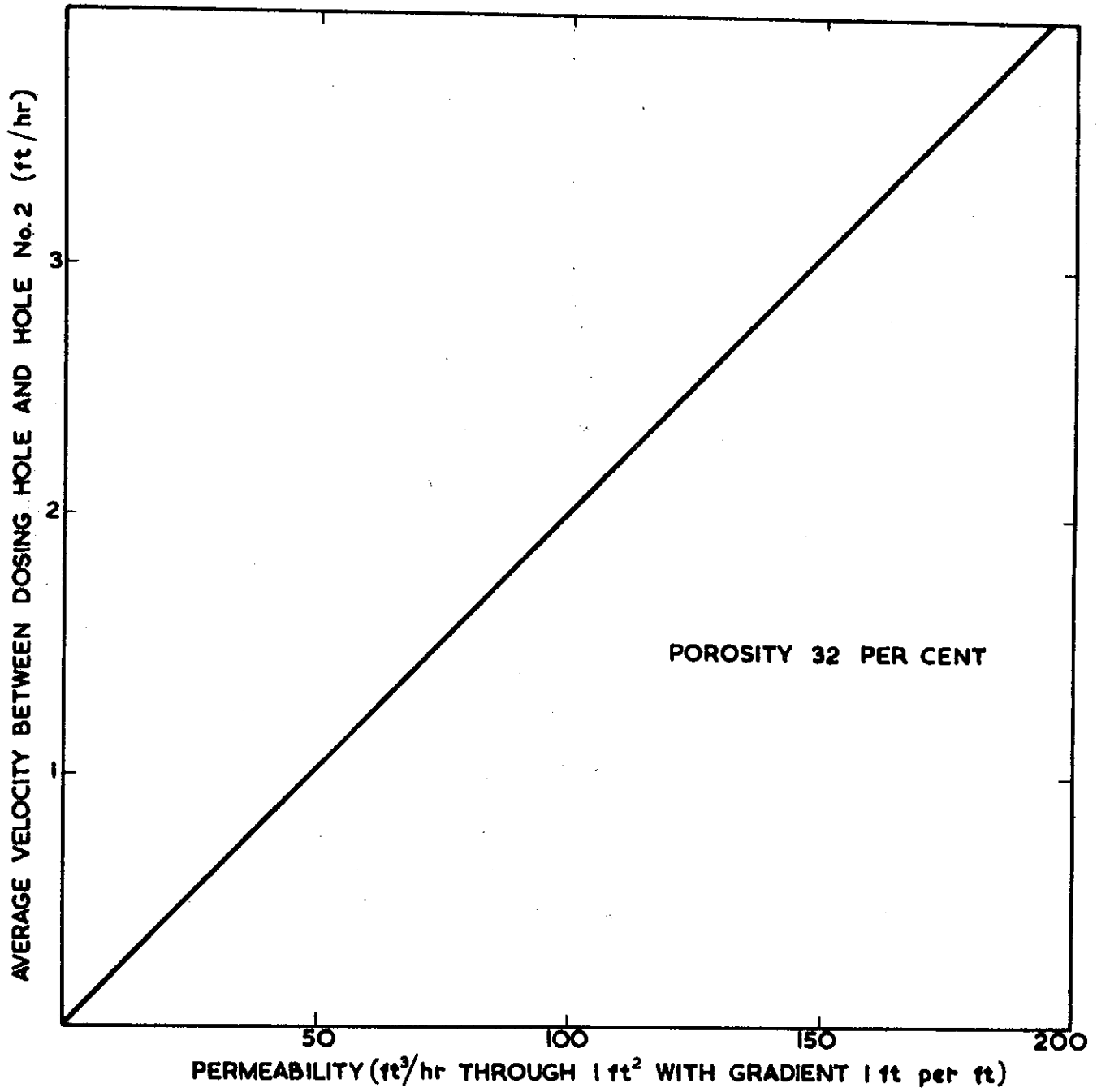


FIGURE 27. JORDAN—PERMEABILITY V. VELOCITY FOR CONSTANT GRADIENT

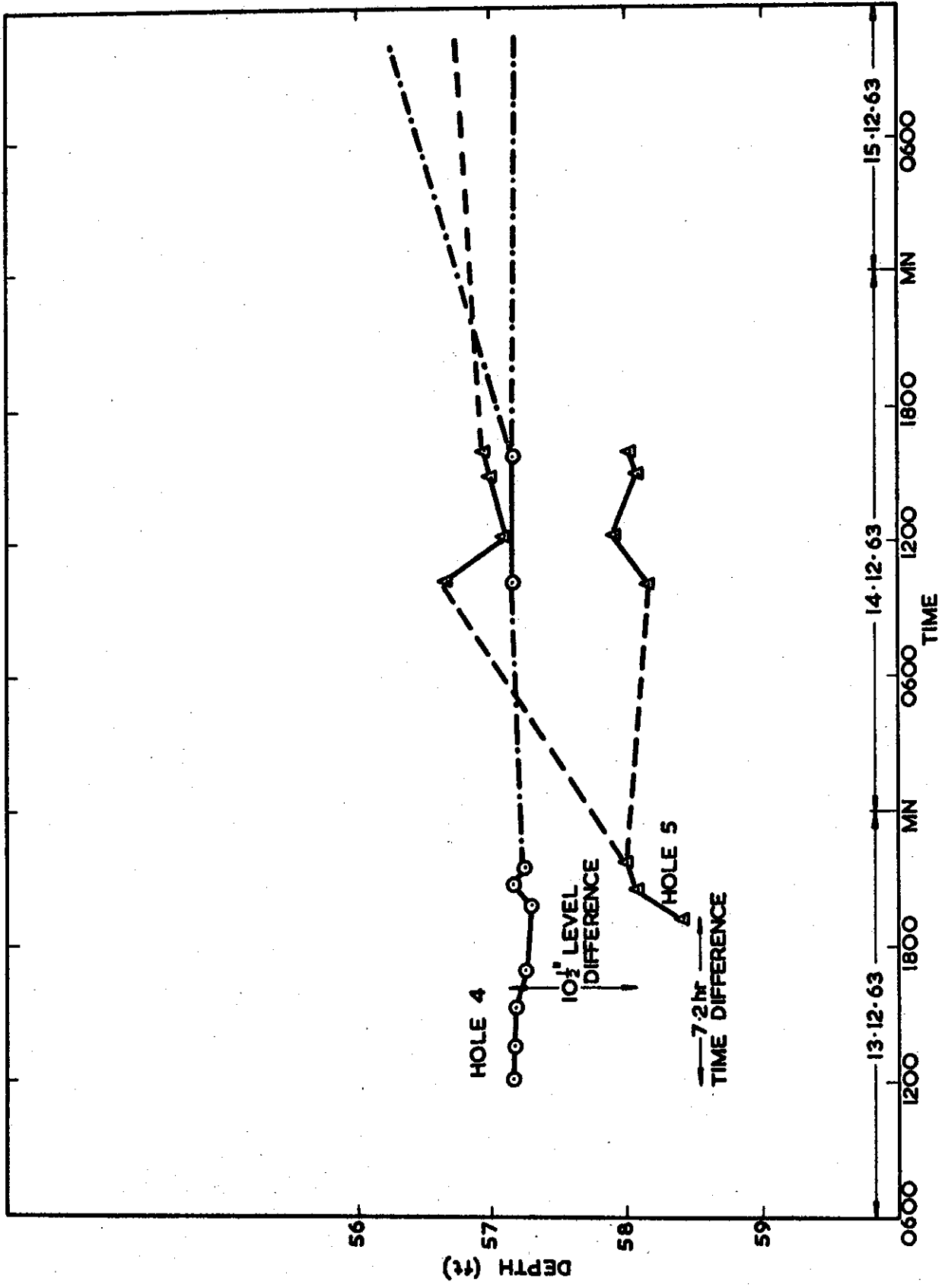


FIGURE 28. JOHN AHERN HOLES Nos 4 AND 5— DEPTH OF GREATEST ACTIVITY V. TIME