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AN EXPERIMENTAL CONTINUOUS-INDICATION PLUGGING METER FOR IMPURITY MONITORING IN LIQUID ALKALI METALS

D. F. DAVIDSON and P. F. ROACH
Reactor Engineering Laboratory
Risley

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THE REACTOR GROUP
HQ, Risley, Warrington, Lancs

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by

D. F. Davidson and P. F. Roach

SUMMARY

Plugging meters, although non-specific, are useful for detecting changes in the gross impurity level of liquid alkali metals. For the coolant circuits of a fast reactor, automatic as opposed to manual measurement of the plugging temperature is required. The Report describes the development of an experimental automatic instrument, designed to have a fast response and display a continuous record of plugging temperatures.

The liquid metal supply to the instrument flows from zero differential pressure sampling points on the external system and circulation is maintained by using a separate pump. With this design, the flow emerging from the cooler has two alternative routes, one through the orifice and one by-passing it. The by-pass flow is guided near the orifice and aids rapid unplugging. Under automatic control, the orifice is partially blocked with impurities. The temperature of the liquid metal near the orifice is adjusted to keep orifice flow a fixed fraction of its unplugged flow (i.e. at the saturation value). This temperature is measured and indicated.

The instrument has operated in sodium over a range of saturation temperatures from 250 °C, where the temperature swings were ± 1 degC, down to 125 °C (<7 p.p.m. for a sodium/oxygen system) where the temperature swings were ±5 degC.

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CONTENTS

INTRODUCTION

1. Sodium or sodium-potassium (NaK) alloy is used as the coolant in existing and proposed "fast" nuclear reactor systems. The presence of impurities, particularly oxygen, increases the rate of corrosion of materials with which it comes into contact. Further, by precipitating out of solution in the form of solids in relatively cool regions, they can restrict or block narrow passages in the coolant circuits.

2. Plugging meters have been used for some years by Batutis (1958) to estimate the impurity content (mainly oxygen) of sodium and NaK alloys. Their principle depends on determining the temperature at which oxide particles begin to precipitate or re-dissolve, i.e. the saturation temperature. The equivalent oxide concentration may then be deduced from the solubility/temperature relationship (Fig. 1). Although these instruments have been commonly called "oxometers" they cannot differentiate between oxygen and any other impurity that may be precipitating. The eventual indicated plugging temperature will be the highest temperature at which precipitation takes place, regardless of the type of impurity. It is thus non-specific. From a reactor operational point of view, this is not a serious disadvantage if changes in gross impurity level may be detected conveniently and rapidly.

3. Conventional, manually operated instruments give only intermittent checks on the saturation temperature. Ideally, for the coolant circuits of a fast reactor, a continuous measurement is required. The object of the experimental work carried out was to produce a sensitive, stable and fast responding automatic instrument which displayed a continuous record of saturation temperature. Similar work is also in progress in France (Delisle, 1963).

PRINCIPLE OF PLUGGING METER ACTION

4. In the simplest form of plugging meter, the liquid metal is passed through a pipe fitted with a flowmeter, cooler and restriction (or sieve), as shown in Fig. 2. The restriction is downstream of the cooler and the temperature is measured at this point. If the temperature of the liquid metal is gradually reduced by means of the cooler, impurity particles will begin to form below the saturation temperature. The particles are trapped in the restriction and a sharp fall in liquid metal flow due to this plugging action indicates that the saturation temperature has been reached. The temperature indicated at the time when plugging is apparent is lower than the saturation temperature. An "unplugging" run is usually performed to obtain two temperature readings the mean of which is taken as the true saturation temperature. Variations in plugging meter design include notched valves (forming the orifice) which can be manually or mechanically opened, for flushing. These have been described by Parker (1963) and Davis (1959).

5. The drawbacks of the conventional manual instrument observed during experiments by the Authors and by Batutis (1958) and Parker (1963) are:

(a) At low impurity levels the rate of build-up of a plug is very low because of the logarithmic nature of the solubility curve. Very slow cooling rates are thus required, leading to long time intervals between checks.

(b) At high impurity levels the instrument is prone to block completely and is then difficult to unblock.

(c) The rig conditions of flow and temperature must be held steady during a plugging run.

(d) The difference between 'plug' and 'unplug' temperatures (sometimes as much as 50 degC) is not satisfactorily resolved by taking an average because of the non-linear solubility curve and the differing rates of precipitation and solution.

6. If a stable partial plug of impurity is maintained in the orifice by manual or automatic control of temperature, some of these defects are overcome. The instrument reads saturation temperature continuously instead of intermittently and the plug and unplug temperatures may be said to coincide.

7. The conventional instrument, unfortunately, has an inherently unstable characteristic which makes control in the partially plugged state very difficult. This instability arises from the fact that heat input depends on liquid metal flow, which varies with the degree of orifice plug. Orifice temperature is the result of a balance of heat input and cooling and therefore an effect analogous to positive feedback is present.

8. The experimental instrument design improves the characteristics to enable automatic control to be achieved and also overcomes the other shortcomings of the older model.

DESCRIPTION OF THE EXPERIMENTAL INSTRUMENT

9. The complete arrangement, which is the subject of a patent application by Roach and Davidson (1965) is shown diagrammatically in Fig. 3. It will be seen that part of the total liquid metal flow feeding the instrument by-passes the orifice and rejoins the orifice flow via the valve V2. This arrangement, when fed with a constant flow, allows plugging to proceed without changing the liquid metal flow through the cooler. The feedback effect mentioned in para. 7 is virtually eliminated, making the system as a whole more amenable to automatic control.

10. When operating under automatic control, the orifice is maintained in a partially plugged state which restricts the orifice flow to a chosen reference value. Departure of the measured orifice flow from the reference value is sensed by the control unit which adjusts the flow of cooling air. The temperature of the orifice is changed to cause either further blocking or unblocking, whichever is required to bring the orifice flow back to the reference value. Thus, the liquid metal temperature near the orifice varies about the saturation temperature as the servo seeks to keep the orifice flow at the reference value.

11. By arranging the orifice and by-pass flows to run co-axially, as shown, the problem of unplugging a completely blocked orifice is overcome. The by-pass flow scours the orifice area as it passes through the instrument. The temperature of the orifice, even when completely plugged with impurities, can be raised rapidly and the overall response of the instrument is quickened.

12. Finally, to avoid the effect of varying rig flow conditions, the instrument is fed from zero differential pressure sampling points and a separate pump is used to maintain liquid metal circulation.

13. Information on the pump is given in Appendix I.

DESIGN DETAILS

THE BY-PASS COAXIAL SYSTEM

14. Referring to Fig. 3, an approximately constant liquid metal flow through the instrument is obtained if the fluid resistance of the source is large compared with that of the orifice and by-pass passages. This condition is obtained in practice by feeding the instrument from a high-pressure source (the pump) and limiting the flow by adjustment of the valve V1. This valve therefore forms the predominant flow restriction and in practice absorbs about 90% of the pump pressure.

15. Orifice flow variations due to plugging are largest when orifice and by-pass flow values are comparable. For this reason, and to make the initial setting up procedure simple, the valve V2 is adjusted to give equal unplugged-orifice and by-pass flows. To avoid precipitate blocking the by-pass line, the temperature of the liquid metal immediately downstream of the orifice is raised by the re-heater.

16. The plugging orifices, twelve in all, are formed by notching the outside edge of the orifice plate, which itself is a close fit in the bore of the outer supporting tube (Fig. 3). By this means, the orifices are located against the outside wall of the co-axial pipe arrangement where the cooling takes place and where the temperature is measured. The counterflow cooler creates a falling temperature gradient in the direction

of liquid metal flow. The last copper cooling fin actually forms the end-plate of the cooler box, defining accurately the coolest point for location of the orifice.

17. The total liquid metal flow through the instrument was set at an optimum value of 0·3 gal/min. With this value of total flow, the plugged orifice flow is about 0·1 gal/min. To measure small variations in this already rather small orifice flow, a sensitive permanent magnet e.m. flowmeter was used, consisting of a flattened section of ¼ in. nominal bore pipe and a high flux magnet.

18. Figure 4 shows the plugging meter mounted inside a hotbox. Two coolers (shown lagged) were used because components were readily available.

AUTOMATIC CONTROL

19. As the system to be controlled contains a number of time-dependent factors, the design of the control mechanism is essentially a compromise between the requirements of stability, and response time. The guiding principle used was to reduce the value of system lags wherever it was possible.

20. Two main sources of lag, common to any design of plugging meter are:

(a) thermal lags in the cooler

(b) the time required to build up a finite amount of precipitate.

21. The thermal lag is a function of the ratio of the thermal mass to the rate of heat supply to that mass. Any attempt to economise in rates of heat supply or removal increases the thermal lag. A counterflow heat economiser was not used in the design for this reason.

22. The cooler was designed to operate from a compressed air supply of about 50 lb/in^2. Copper fins, brazed to the outside of the pipe carrying the liquid metal, form a labyrinth of passageways through which the counterflow of cooling air is forced. This form of cooler has a fast response and a well defined temperature gradient; both features are desirable.

23. The control unit used is a standard commercial instrument and comprises three main sections. These are:

(a) A self-balancing potentiometer which measures and indicates orifice flow.

(b) Transmitting slidewire and reference point assembly.

(c) 3-term controller, providing means of adjusting proportional, rate and reset terms.

The electrical output from the controller is converted to a pneumatic signal, amplified and fed to the compressed air regulator.

THE PUMPING SYSTEM

24. The plugging meter was first tested without a separate pump to circulate the liquid metal. The instrument was connected at points "A" in Fig. 3, directly across the main rig pumps. Changes in rig temperature and pressure resulted in temporary errors in indicated saturation temperature; the majority of the disturbances were due to changes in rig pressure only.

25. Three methods of reducing the effect of changing rig pressure were possible. These were:

(a) Flow stabilisation

(b) Flow ratio measurement

(c) A separate circulating pump.

26. Stabilising the flow to the instrument is complicated, requiring a servo loop. Control would only be effective over a limited range.

27. With the flow ratio system, measurements of both orifice and total flow are taken and the instrument controls to a fixed ratio of orifice to total flow. This system has a fundamental failing since it does not compensate for the change in heat balance that accompanies a flow change. This unbalance causes a temporary error in the indicated saturation temperature which lasts until equilibrium is re-established.

28. The use of a separate circulating pump was considered better in principle and this method was adopted. The supply of liquid metal to the instrument must come from zero differential pressure sampling points on the main rig. This can be done simply as shown in Fig. 3. The arrangement also allows operation of the plugging meter with the main rig pumps switched off.

29. A small permanent magnet conduction pump was used. The simple theory for deducing the pressure developed by such a pump at zero flow is given in Appendix I. The design and setting up procedure is also given. The pump itself is shown in Fig. 5.

30. It will be seen that liquid metal from the main (Fig. 3) passes through a filter before reaching the pump. The filter was added to reduce the possibility of insoluble matter being trapped by the partially opened valves or orifice.

EXPERIMENTAL WORK

31. The instrument was tested in R.E.L. on the 1 in. general purpose test loop which holds about 100 lb of sodium. The plugging meter was tested initially without a separate circulating pump and the disturbing effects of varying rig conditions, particularly pressure, were immediately evident.

32. Simple electrical modifications were made to allow a flow ratio system to be briefly examined. The results showed an improvement in the stability of the saturation temperature reading (but temporary errors in the indication still occurred when rig conditions were changed). With stable rig conditions, however, saturation temperatures as low as 125 °C could be read to within ± 5 degC.

33. With the separately pumped system, as shown in Fig. 3, the instrument was unaffected by rig pressure changes and the saturation temperature reading remained undisturbed when the main rig pumps were switched off. The following tests and observations apply to this system only.

34. The reduction in orifice flow caused by partial plugging is expressed as a percentage of the unplugged flow. The percentage plug is varied by adjustment of the reference point assembly on the control unit. The instrument was operated with 10%, 50% and 75%-plugged orifice flows without marked variations in performance.

35. After about 70 hours of continuous running, occasional temperature transients occurred on the saturation temperature record. These were found to be due to parts of the oxide plug breaking away from the orifice. It was also found that vibration of the plugging meter pipework could break away the oxide. The trouble is thought to be due to relative movement of the orifice plate which was not made a good enough fit in the bore of the containing outer tube (see Fig. 3).

36. During instrument start-up it is desirable that the temperature in the region of the orifice is lowered below the saturation temperature as far as possible in order to form the partial plug quickly. The re-heater must then be capable of raising the temperature of the by-pass flow above the saturation temperature if blocking of the by-pass valve is to be avoided. This difficulty was experienced when starting up the experimental plugging meter and the re-heat power had to be increased.

37. Two prolonged runs of about seven days each were recorded during testing. There was no tendency for the instrument to control at a second higher saturation temperature as found by Delisle (1963), but this may simply be due to his second impurity not existing in a large enough quantity in the test rig used. It is possible, however, for several impurities to be present. If one impurity, 'A', has a higher saturation temperature but a lower precipitation rate than impurity 'B', then the automatic plugging meter initially controls on 'B'. When sufficient precipitate from impurity 'A' has been collected, the instrument then controls on that impurity at the higher saturation temperature. The interpretation of plugging meter readings when several impurities are present is discussed briefly by Smith (1961).

38. Variation in the temperature of the liquid metal supply to any type of plugging meter upsets the indication. With the automatic instrument, the disturbance is temporary. Steady temperature drifts at rates less than 5 degC/h are not detectable on the saturation temperature trace. Faster changes, however, will show up, particularly at low saturation temperatures where instrument response is slowest. Fortunately, rapid changes in temperature are not expected to occur at the liquid metal sampling points of a fast reactor. With multi-purpose test loops, however, separate temperature stabilisation of the input liquid metal flow would be worthwhile.

39. Examples of the type of saturation temperature records obtainable are shown in Fig. 6 (a, b). The lower half of Fig. 6(a) shows a period at the beginning of a rig clean-up run. The upper half of the graph shows the position four days later; the reduction in saturation temperature can be seen.

40. Fig. 6(b) shows a fairly rapid change in saturation temperature from 170°C to 193°C. Initially the cold trap was used to clean the liquid metal and it was then isolated to allow rig conditions to stabilise. After a few days, it was put back into circuit but at a higher temperature than the rig saturation temperature. The impurity content, and hence saturation level of the whole rig, was raised to a new value in about 1 hour, as shown.

41. The smoothness of the saturation temperature record could be varied by altering the "proportional band" setting on the controller unit. A smoother trace is obtained at the expense of a longer recovery time when the system is disturbed. In general, the best results were obtained with zero "rate time", the minimum of "reset action" and the narrowest possible "proportional band" setting.

OVERALL ACCURACY

42. The instrument accuracy is affected by:

(a) Errors in the measurement of orifice temperature arising from the position of the thermocouple and the method of attachment (estimated to be less than 1 degC)

(b) Errors in the thermocouple itself (up to ± 3 degC)

(c) Errors in the operator's assessment of the average value of the saturation temperature trace from cycling around the controlled value.

43. Considering the errors in (c) above, over the saturation temperature range 125-250°C the maximum temperature swing, with steady rig conditions, did not exceed 10 degC. The largest swing of ± 5 degC occurred at a saturation temperature of 125°C, where the impurity level for oxygen in sodium is less than 7 p.p.m. and the servo control is least stable. This allows estimation of the impurity content to about 1 p.p.m. (Claxton, 1965). As the impurity level rises, the saturation temperature trace becomes smoother, and at 250°C the temperature stability allows it to be read to better than ± 1 degC. At 250°C the impurity level is about 50 p.p.m. and the actual value can be estimated to within 2 p.p.m.

CONCLUSIONS

44. A successful continuous-reading plugging meter has been demonstrated, monitoring the saturation temperature of sodium over the range 125°C to 280°C. The coaxial by-pass system used eliminates the undesirable control characteristics of the conventional straight-through arrangement. Satisfactory automatic control in the partially plugged state is obtained even at low impurity levels where the time to accumulate a finite amount of precipitate is longest.

45. The largest cyclic variations in the saturation temperature trace were ± 5 degC at 125°C. Under stable rig conditions, the indicated saturation temperature could be read to within 2 degC at 125°C and 1 degC at 280°C.

46. A separate pump ensures a constant liquid metal flow through the instrument regardless of rig conditions; it also allows static systems to be sampled.

47. With both the conventional and automatic plugging meter, changes in liquid metal supply temperature vary the orifice temperature. These variations show up on the automatic instrument as transient changes in indicated saturation temperatures. The effect of sudden gross temperature changes can be reduced by external temperature stabilisation of the sample flow.

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APPENDIX I

Calculation of stalled pressure developed by a permanent-magnet d.c. conduction pump

The force on a conductor carrying a current I amp, perpendicular to a magnetic field of B gauss is given by

$$f = BI \times 10^{-1} \text{ dyne per cm length}$$

$$\simeq BI \times 10^{-4} \text{ g per cm length (since } 981 \simeq 10^{3}\text{)}.$$

The length here is the width of the duct between the electrodes (W cm).

Hence

$$f = WBI \times 10^{-4} \text{ g}$$

This force acts on the area of the duct (dW, where d is its depth).

$$\therefore \text{ Pressure} = \frac{f}{dW}$$

$$= \frac{BI}{d} \times 10^{-4} \text{ g/cm}^2$$

$$= \frac{BI}{d} \times \frac{10^{-4}}{70} \text{ lb/in}^2$$

This is an approximation for a square duct, assuming that a uniform magnetic field is covering all the current paths, and neglecting pipe currents.

The pressure drop across the orifice and by-pass passages in parallel was estimated at less than 0·5 lb/in² at the required 0·3 gal/min flow. Since with the by-pass system most of the applied pressure is absorbed by the valve V1 (Fig. 3), a pump developing 4 to 5 lb/in² was considered necessary.

Description of the pump assembly

A schematic diagram of the pump assembly and power supply is shown in Fig. 7. To ensure that sufficient pressure was developed, two pumps in series were used; one current supply passes through both pumps.

Setting the correct working pressure

To obtain the correct pump pressure, first the series valve V1 (Fig. 3) was opened wide. The flow through the instrument was then set to 0·3 gal/min with the by-pass and orifice flows equal. The current through the pumps was measured and found to be 15 amp. It was then increased to 150 amp, thereby increasing the pump pressure tenfold. The series valve V1 was partly closed to re-establish a flow of 0·3 gal/min; the valve therefore absorbed most of the pump pressure, as required.

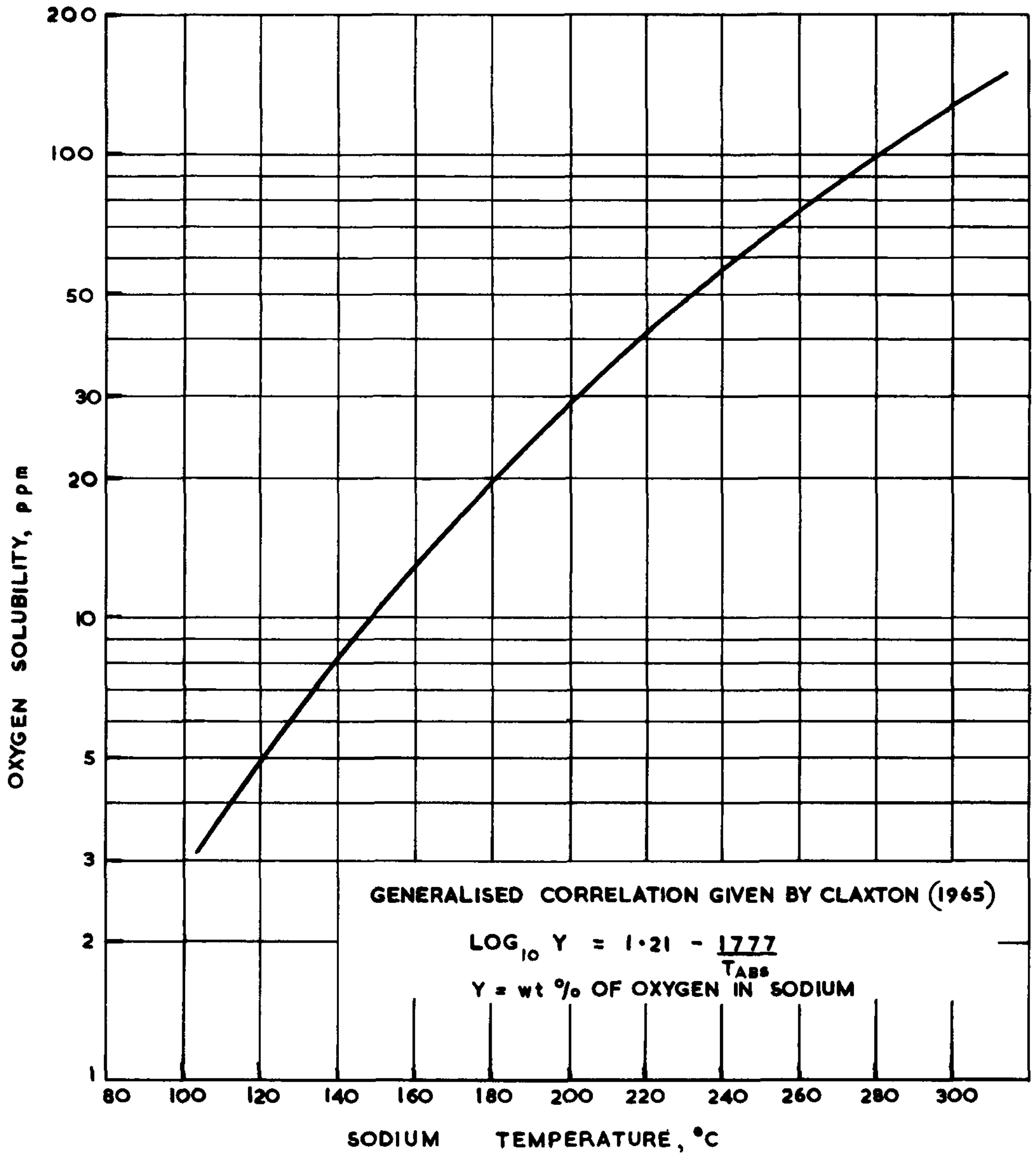

FIG. 1 OXYGEN SOLUBILITY IN SODIUM VERSUS TEMPERATURE

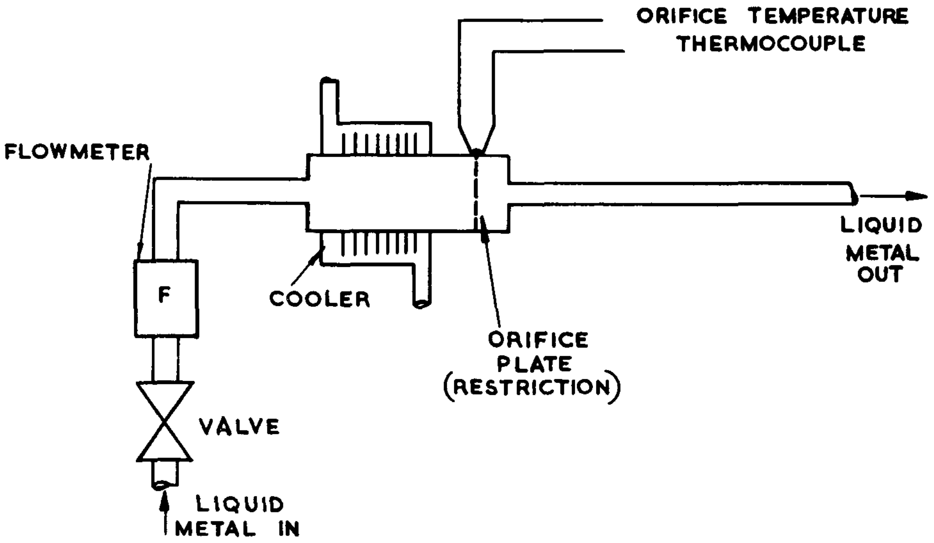

FIG. 2 PLUGGING METER - SCHEMATIC DIAGRAM

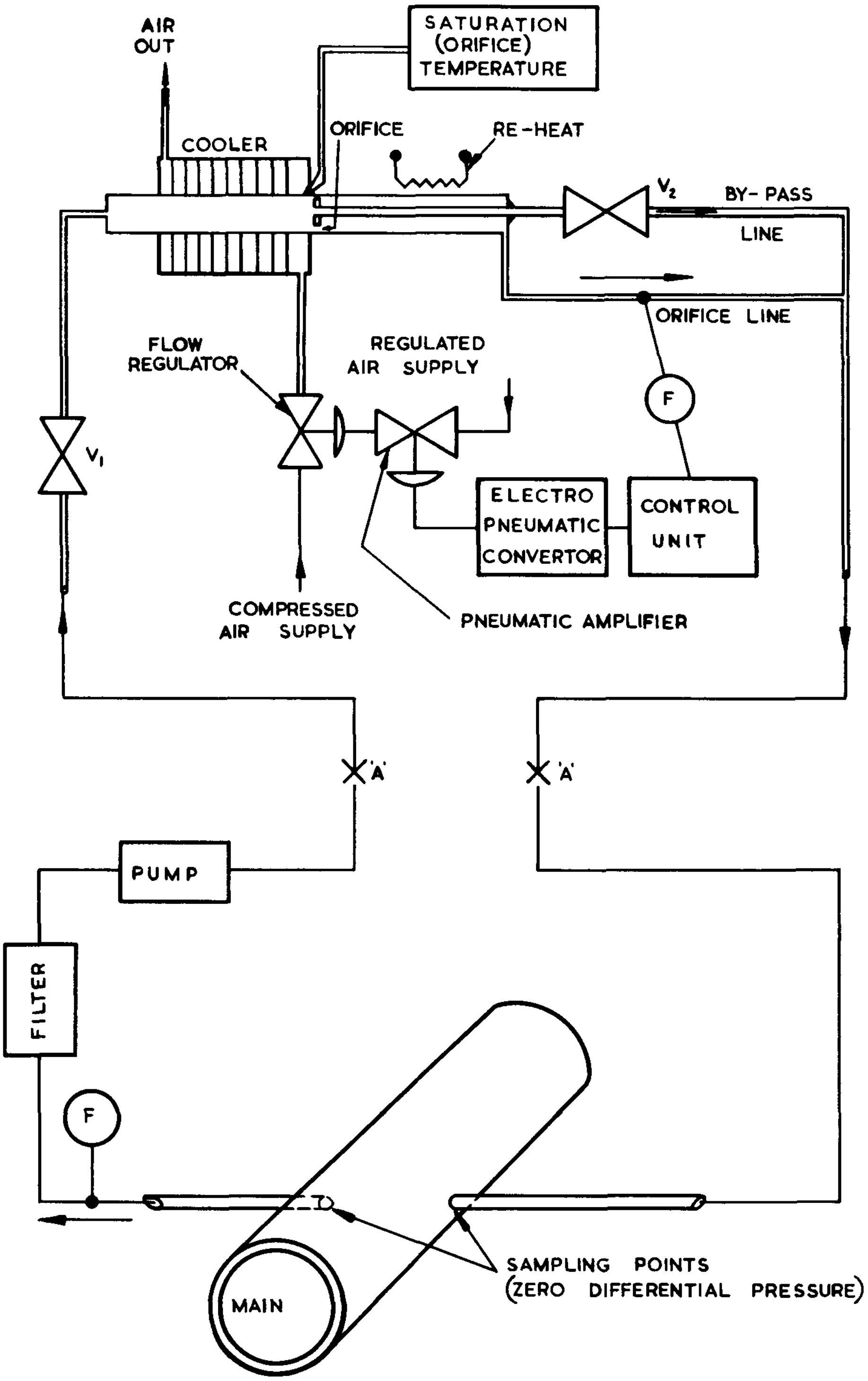

FIG. 3 AUTOMATIC PLUGGING METER AND SEPARATE CIRCULATING PUMP

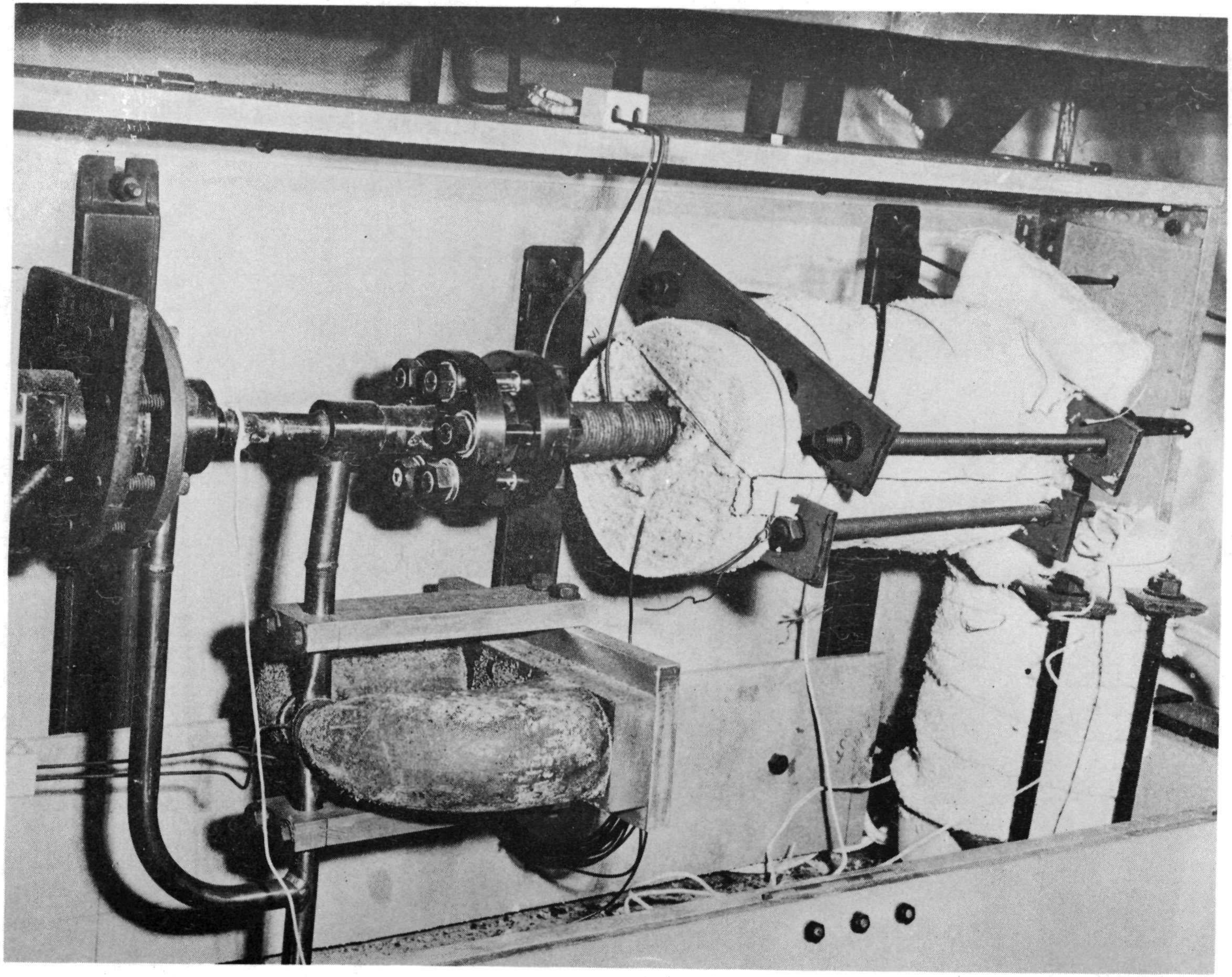

Fig. 4. Plugging meter mounted inside a hotbox

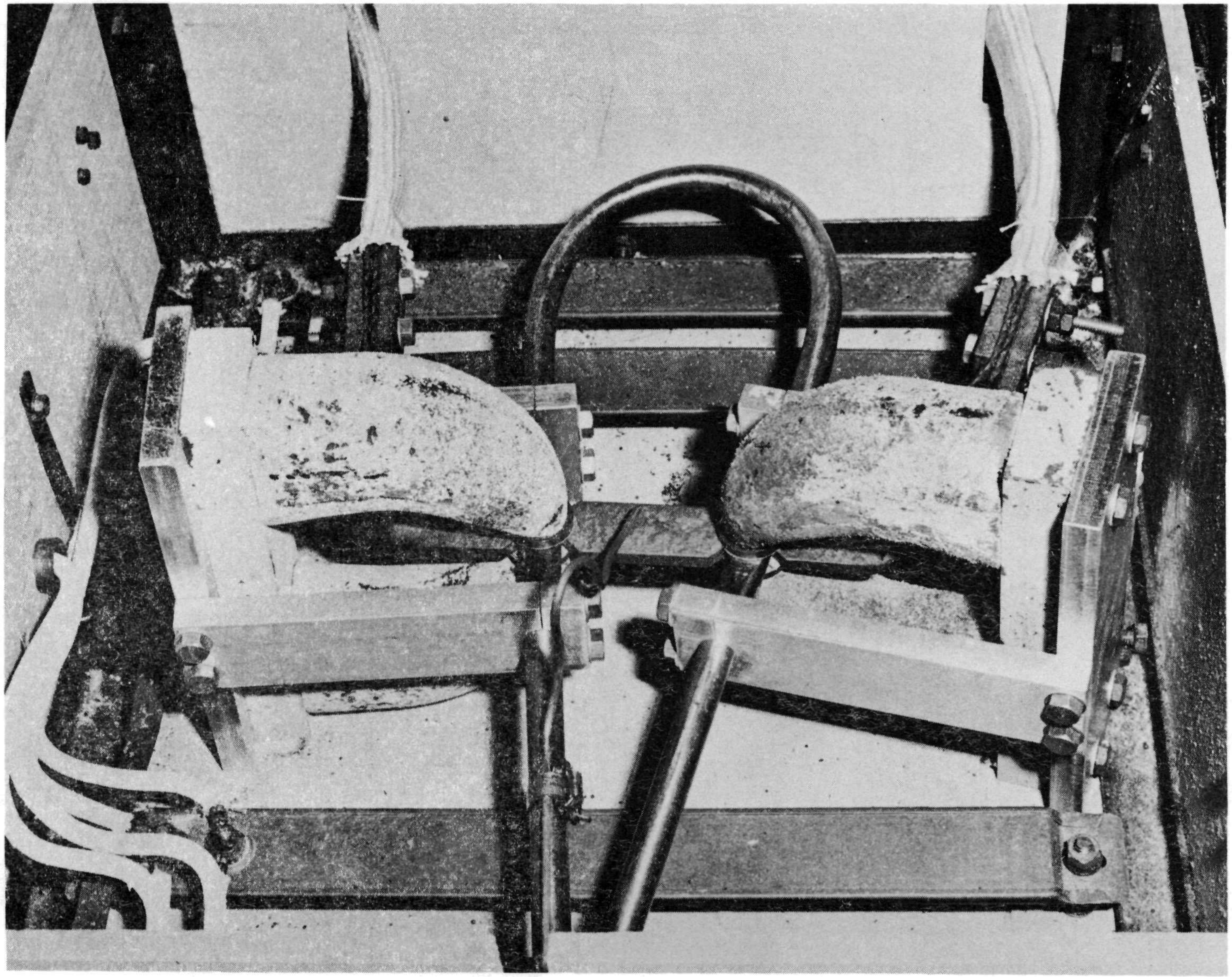

Fig. 5. Two-stage permanent magnet conduction pump

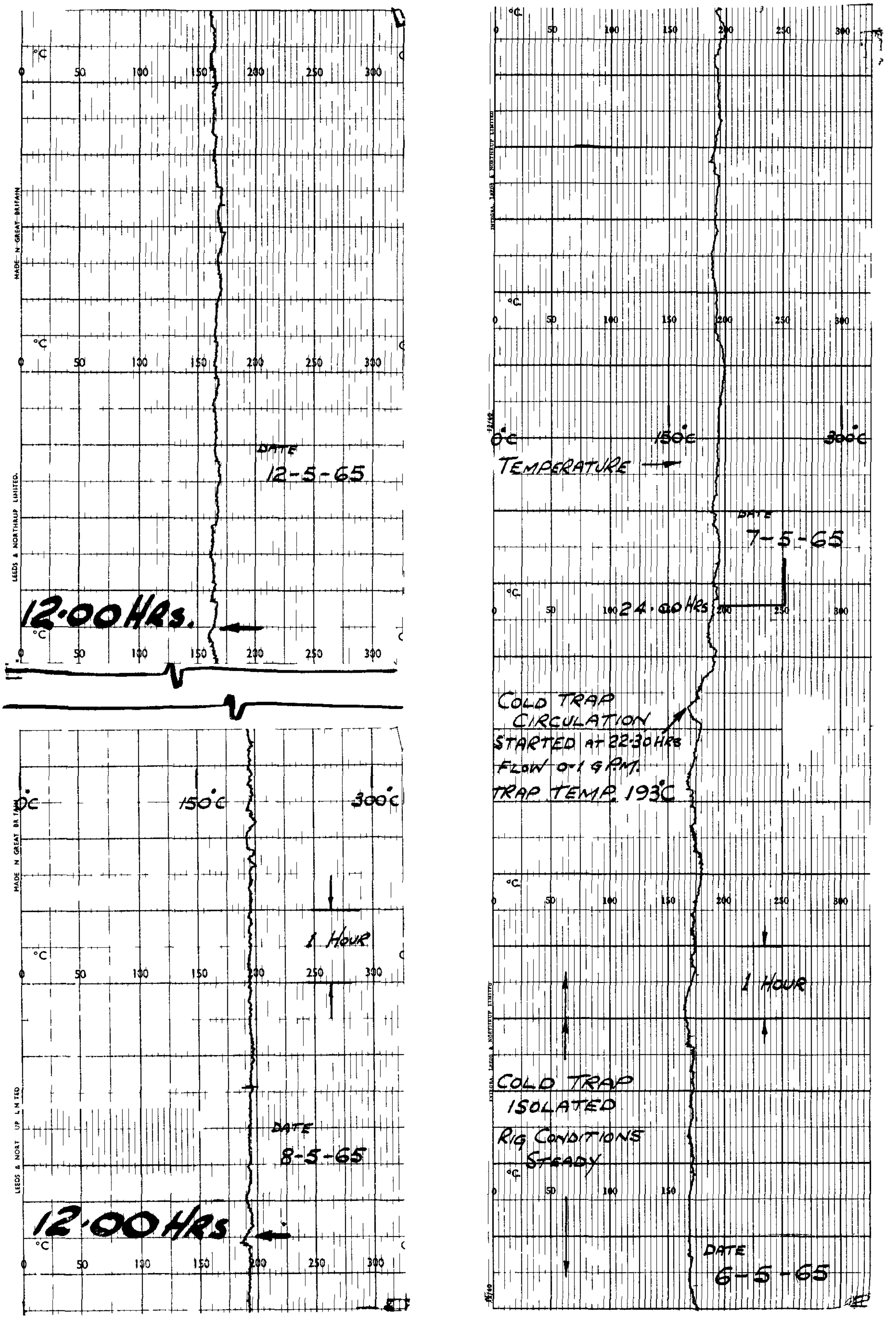

Fig. 6(a). Monitoring the rig clean-up progress

Fig. 6(b). Following an increase in impurity level

Fig. 6. Examples of saturation temperature records

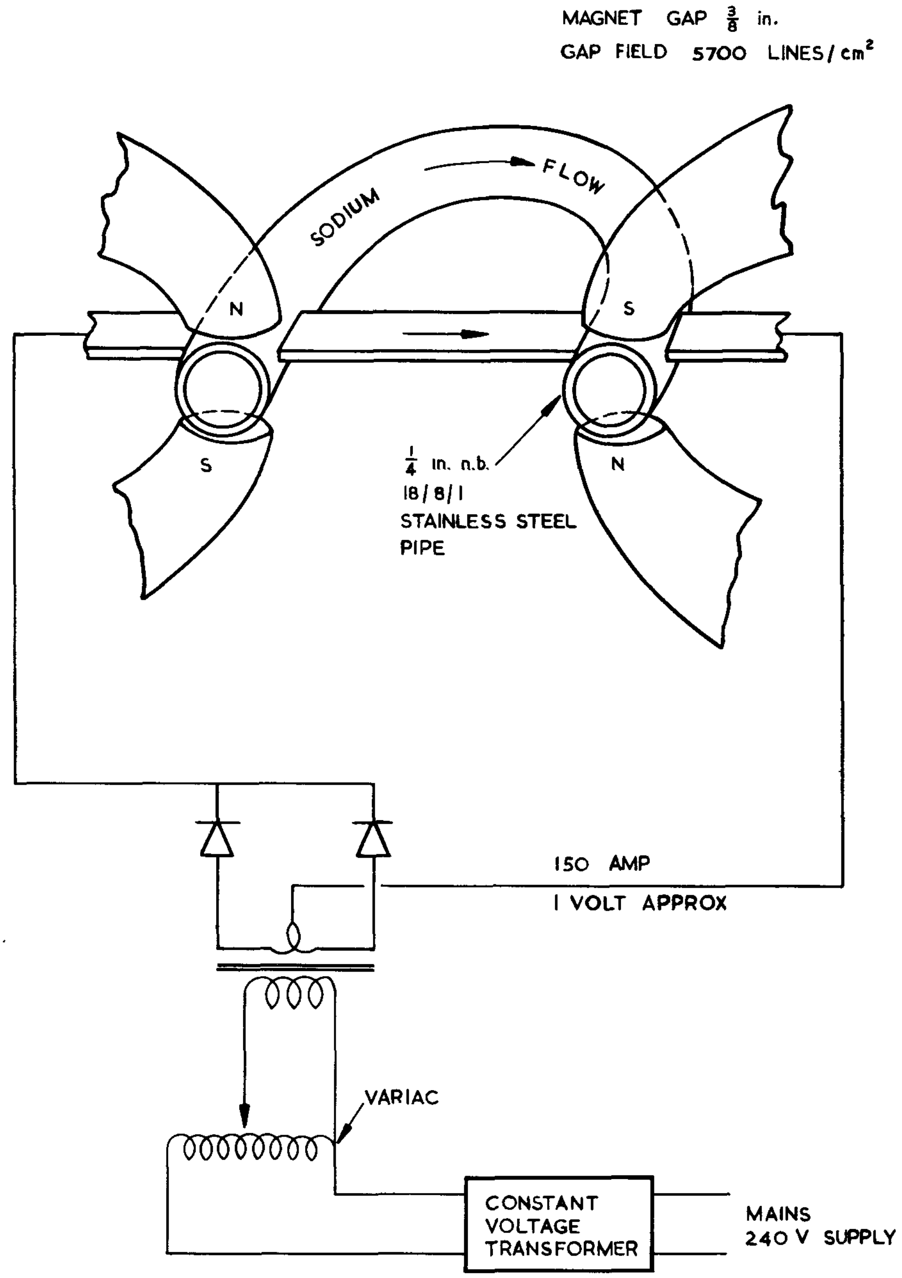

FIG. 7 PERMANENT MAGNET CONDUCTION PUMP AND SUPPLY CIRCUIT