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LUCAS HEIGHTS

STUDIES OF URANIUM–SODIUM SUSPENSIONS

PART 2

HYDRODYNAMIC, METALLURGICAL, AND MECHANICAL EFFECTS: GENERAL CONCLUSIONS

by

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FOREWORD

This report describes part of the work carried out at the Lucas Heights Research Establishment on a liquid metal fuel reactor based on a dispersion of fissile material in sodium.

Research at Lucas Heights on the liquid metal system ceased in 1959. As this is therefore a complete report of discontinued work, a considerable amount of detailed description and discussion is presented, over and above that nomal to a report on part only of a continuing project.

K. F. ALDER,

ACTING DIRECTOR.

17. 5. 61.

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ABSTRACT

Hydrodynamic behaviour of a 0.76 atomic per cent. uranium in sodium suspension has been explored for velocities up to 8.3 ft/sec. and temperatures up to 625°C. The influence of velocity and temperature on suspension behaviour is described. Mechanical and metallurgical effects associated with circulation of the suspension in an austenitic stainless steel loop in contact with beryllium are listed. The behaviour of the suspension is explained in terms of hindered settling theory. A reactor loop model illustrating possible use of the uranium–sodium suspension as a reactor fuel/coolant is presented and recommendations for further work are given.

CONTENTS

(Continued)

1. INTRODUCTION

In Part 1 (Bett et al., 1961) the design, construction, commissioning, and operation of a small uranium–sodium pumped loop system is described to the point where a complete stable suspension was obtained.

In Part 2 which follows, experimental results of an investigation into the hydrodynamic, metallurgical, and mechanical effects of the circulation of the suspension are presented and discussed.

2. HYDRODYNAMIC EFFECTS

2.1 Influence of Velocity on Homogeneity of Suspension

Initial studies by Alder and Bett (unpublished) had indicated that fluid velocity would have important effects on suspension behaviour, being a convenient means of transmitting energy to the suspended particles and thus maintaining suspension. The effects of velocity on suspension were therefore studied. Bulk flow velocity, which is the overall velocity of the circulating fluid irrespective of localised secondary velocities, was measured by an electromagnetic flowmeter, and steps in the derivation of velocity from the flowmeter e.m.f. are listed in Appendix 1. The corrected flowmeter readings were not absolute values but were considered to be sufficiently accurate to be within the limits of significance of other related measurements. Absolute velocities were not measured as the installation of pressure tapping points would have involved much expense, increase in the loop size, and interfuptions to the smooth internal contours of the loop.

2.1.1 Decrease in Velocity

The velocity was decreased in steps to test whether uranium, deposited from suspension by a reduction in velocity, could be resuspended by an increase in velocity. A radiograph of the bottom and top half circles or "limbs" of the loop was taken at each step. It was found that uranium deposited first on the bottom surface of the top limb, at a bulk flow velocity of approximately 4.8 ft/sec. Deposition was accelerated in the top limb by a decrease in velocity but could not be obtained in the bottom limb except by stopping flow.

Deposition at constant velocity in the top limb commenced as a fine layer increasing in depth from just before the vent tank on the up flow side to approximately half way round the curve on the down flow side of the loop. The fine layer was then gradually built upon until ripples appeared. At this stage some preferential erosion appeared to occur and the pattern of deposition became discontinuous.

At lower rates of deposition, smooth general deposition and erosion continued; at higher rates large block deposits of uranium powder were built up which were either gradually smoothed down or rapidly eroded as single masses. When this occurred the flowmeter reading would drop suddenly to recover slowly. In any case, the form of the deposit was a series of "dunes" changing continually and progressively while the amount of deposit progressively increased around the upper limb.

Radiographs taken at approximately 30 minute intervals are shown in Figure 1. The radiographic techniques used are described in Appendix 2. The radiographs illustrate progressive alteration in the shape of the "dune" deposit. (See also Cairns and Lawther in AAEC/E37, 1958). The final amount of the deposit varied with the bulk flow velocity, being greater for lower velocities. Because of its high density, uranium would be expected to deposit on the bottom limb of the loop. The explanation for the unexpected deposition on the lower surface of the top limb of the loop is taken from Goldstein (1938) and is as follows:

"The faster moving fluid at the middle is moving outwards, pushing the fluid in the boundary layer at the outer wall to the top and bottom walls toward the inner wall. Thus fresh liquid is being brought continuously into the neighbourhood of the outer wall and then forced round toward the inner wall, being continually retarded. There is thus an accumulation of retarded fluid at the inner wall".

Conditions can thus exist in the region of retarded fluid flow at the inner wall for particles to settle out from suspension. In the lower limb, the particles settling out in the retarded flow region fall by gravity into the faster flowing liquid and are kept in suspension. In the upper limb, particles settling out in the retarded flow region fall directly to the inner wall of the curved tube. Cairns' and Lawther's results in AAEC/E38 (1958) support this explanation.

Because of the continuous exchange of fluid between the regions of main and retarded flow, uranium particles would be exchanged between the two regions and smaller particles, deposited under non-equilibrium fluctuations in flow, could be eventually re-suspended.

In this way the largest uranium particles would eventually collect in a bed on the lower surface of the top limb, smaller particles remaining in suspension, assuming that the bulk flow velocity was not increased during their period of collection. By very slowly reducing the bulk flow velocity, a progressive variation of particle sizes of powder would be obtained in the bed deposited on the lower surface of the top limb; the slower the rate of velocity reduction, the slower the deposition, and closer the sizing. By definite stepwise reduction in velocity, a series of strata containing definite size ranges would be obtained. More rapid reduction in velocity would cause more random distribution of particle sizes in the deposited beds until the limit of an instantaneous cessation of flow was reached, in which case a random distribution of particle sizes would be obtained, except that allowance must be made for (a) the degree of randomness of the suspension and (b) the momentum of particles at the instant of velocity cessation.

Deposition in the lower loop limb would commence when the bulk flow velocity was insufficient to suspend the largest uranium particle then in suspension. Because of the then much lower secondary flow velocity in the upper limb, deposition of these particles would occur in the upper limb except where the rate of velocity reduction was sufficiently rapid to allow them to be carried past the top limb. In practice, this rate of velocity reduction was of the order of that obtained by switching off the pump.

Once the equilibrium deposit had formed it would not be affected, except by the slight forward drag of the retarded flow, provided that the bulk flow velocity was not altered. In both upper and lower limbs the deposit would be isolated by a boundary layer of low velocity, while the deposit in the upper limb would be further isolated from the effects of the main flow by the region of secondary flow. The hypothetical case of equilibrium, where the extent of the deposit so constricted the flow area available that the velocity at the constriction was raised to the suspension velocity, was not encountered, as the amount of deposit was never large enough. However, it is likely that a mechanism of this type helped to prevent the excessive formation of nodular or uneven deposits.

Radiographs of the vent tank indicated that deposition of uranium occurred on the sloping shoulders of the vent tank at all velocities, but more rapidly at higher velocities. This uranium could be resuspended by vibrating the vent tank walls thereby presumably disturbing the boundary velocity layers and hence the uranium. To obviate the necessity for continued vibration of the vent tank, the sodium level was lowered into the tube connecting the loop to the vent tank. It was expected that no uranium would deposit on the vertical walls of the tube and that uranium deposited in low velocity areas would fall back into the main stream and be suspended there. However, radiographs of the tube (Figure 2) showed the formation of uranium deposits in an approximately spiral fashion in the absence of vibration. Vibration of the tube quickly dispersed the deposits and was consequently applied at all times when the deposition was not being studied.

The deposition of uranium in the vertical tube connecting the loop to the vent tank can be explained by adapting the explanation already given for the deposition in the curved limbs of the loop. Thus, referring to Figure 3 which gives a schematic illustration of the proposed explanation, part of the main flow of the loop was diverted into the vertical tube under the influence of centrifugal force. On entering this tube it had a nett velocity compounded of radial and forward components, which thus forced the stream onto the tube wall where it travelled upward. No evidence was available as to whether the main stream had any rotational component of velocity and hence whether the diverted stream entered the vertical tube with a third (rotational) velocity component. However, the tube was displaced approximately 5 degrees from the plane of the loop effectively imposing a rotational component of velocity on the diverted stream.

Frictional forces between the entering diverted stream and the sodium in the vertical tube would then cause the diverted stream to induce circular flow of the sodium in the vent tank, dissipating the energy of the diverted stream and giving rise to a vortex in the tube. The extent to which this proposed cycle would come into operation in the vertical tube depends on two factors, (a) bulk flow velocity, and (b) height of fluid in the vertical tube.

If the bulk velocity is low, the energy of the diverted stream will be low, its penetration into the vertical tube small, and vortex formation may not occur.

If the height of fluid in the vertical tube is sufficient the energy of the diverted stream may not be great enough to cause vortex formation because of the frictional losses involved.

The asymmetric vertical motion of the diverted stream would introduce a vertical component into the induced circular flow causing a resultant rising spiral flow. The return flow from the tube would then be downwards through the centre of the vortex, returning to the sides of the main stream. All sizes of powder in suspension in the main stream would be able to enter the vertical tube, but the largest particles would tend to deposit as soon as the diverted flow velocity was sufficiently decelerated by friction and change of direction. These particles would probably fall back into the loop before being incorporated into the spiral flow. Smaller particles would continue suspended into the spiral flow region where they would be deposited by centrifuging, or they might be carried through with the outflow stream. The particles deposited by centrifuging would tend to fall back under gravity into the moving stream where they would be subject again to its action.

The fluid immediately adjacent to the diverted stream will be affected in a similar way and an area of induced secondary flow will be associated with the negative pressure edge of the diverted flow. Deposition of uranium powder in these areas of secondary flow would give rise to a linear type of deposit outlining the path of the decaying diverted stream.

At high bulk flow velocities in the loop, more uranium would enter the vertical tube than at low velocities (a) because of more powder in suspension and (b) because of greater centrifugal effect. The higher bulk flow velocities would cause higher spiral velocities and thus more deposition of powder by centrifuging. Thus, it was found that deposition of uranium in the vent tank was more rapid and extensive at higher fluid velocities.

The effect of vibrating the tube would be (a) to dislodge deposited particles from the walls of the tube and (b) to disturb the velocity pattern in the tube, thereby interfering with re-deposition and allowing more opportunity for the uranium to re-enter the loop.

The radiographs in Figure 1 show the main deposit and a very fine continuous deposit or concentrate on the tube walls. Other radiographs show that this fine deposit was present fairly uniformly over the entire inner surface of the loop. It is thought to have been associated with the low-velocity boundary layers of fluid at the tube walls. A continuous velocity gradient existed from the tube walls to the region of maximum flow and uranium particles consequently entered the layers of low velocity where those particles not able to be suspended would deposit. In low velocity layers on the upper surfaces of the loop tube, deposited particles would fall back into the main flow and be re-suspended. Suspended particles would remain in exchange between the boundary layer and the main stream but for each velocity in the boundary layer it is likely, considering the relatively steady conditions obtaining, that a particular size of particle collected in a fluidised condition. By this means, a thickening of the boundary layer might be envisaged as particles of a given size gradually found their place in an appropriate fluidised bed.

This in fact did happen, especially on the lower surfaces of the loop tube, but was limited in extent by the fact that, due to the velocity gradient existing in the boundary layer, the thickness of the boundary layer was proportional inter alia to the square root of the kinematic viscosity of the fluid in it, the kinematic viscosity being proportional to the solids content of the fluid. The velocity gradient in the layer thus caused a less than proportional increase in layer thickness with increase

in solid concentration. Limiting solid concentration then limited the layer thickness. Because the boundary layer deposit is, in fact, in continuous motion, it would be better described as a concentrate.

2.1.2 Increase of Velocity

The bulk flow velocity was increased in steps from various ground states, radiographic and radiometric techniques being used to estimate the state of suspension. The patterns of suspension from upper and lower limbs with increasing velocity were investigated and the time necessary to obtain complete suspension from complete deposition was measured.

Details of radiometric techniques are contained in Appendix 3 but, in brief, the method consisted of counting a collimated beam of radiation from the natural uranium in the loop using a lead shielded sodium iodide crystal counter mounted nine inches above the centre line of the flowmeter magnet. Comparison of the counts recorded with the amount of uranium in suspension as measured by radiographic techniques indicated that the counting method might be relied on as indication of the amount of uranium in suspension at the point of counting. Due to the experimental difficulties the counting method was not used as an absolute method of measuring uranium concentration.

Deposition in the bottom limb could only be obtained by abrupt cessation of the bulk flow in a condition of partial or complete suspension as explained in Section 2.1.1. Pickup velocity of uranium in the bottom limb was measured by gradually increasing the bulk flow velocity while counting at the position above the flowmeter.

The results recorded at a loop temperature of 400°C are shown in Figure 4. Figure 5 shows radiographs taken during the period of suspension. Pickup from the bottom limb commenced at a bulk flow velocity of approximately 3 ft/sec and continued until completed at approximately 3.9 ft/sec (c.f. Cairns AAEC/E38, 1958). Pickup commenced mainly on the downflow side but partly on the upflow side and was accompanied by some deposition on the upflow side and in the upper limb. The pattern of pickup appeared to be irregular, small islands of powder remaining rather than a smooth even layer. This could probably be due to the random distribution of particle size in the deposit because, on contact with increasing velocity, suspension and therefore removal of powder occurred more readily in some areas than others, leading to channelling and more powerful erosion in the channels, plus a degree of protection to the top and rear of the islands due to aerofoil flow in the fluid. Suspension of larger particles in the channels could be followed by deposition of these particles in the low velocity areas behind islands.

Steady increase in bulk flow velocity caused further suspension and erosion as larger particles were suspended until, finally, complete suspension was achieved.

Pickup from the top limb is described more fully in Section 2.2, but it should be noted that as with pickup behaviour from the bottom limb, pickup occurred over a wider velocity range. Thus at 400° C, pickup from the top limb commenced at a bulk flow velocity of approximately 3 ft/sec, but was not complete until approximately 4.6 ft/sec. The pattern of pickup was essentially the same as that described for the bottom limb with the difference that in the top limb, the velocity actually causing pickup was the secondary or induced velocity. As a result, the bulk flow velocity for complete suspension in the top limb was higher than the corresponding figure for the bottom limb, the difference being that between bulk flow and secondary velocities.

During suspension from the top limb, sudden small drops in the flowmeter reading were noticed, similar to those noticed during deposition. The flowmeter reading would then either slowly return to its original value when the vent tank was not vibrated, or would return relatively quickly to a value below its original value when the vent tank was vibrated.

Radiographic examination showed that the initial drop in flow was associated with the absorption into the flow stream of an "island" of powder from the down-flow side of the top limb. Addition of powder to the loop had been accompanied by a drop in flowmeter reading from which it

was concluded that the power necessary to pump a suspension at a given velocity was higher than that necessary to pump sodium at the same velocity; an estimate of the required pumping power is made in Section 4.

A steady return of the flowmeter reading to approximately its original value when the vent tank was not vibrated was found by radiographic examination to be accompanied by steady deposition of powder in the vent tank. The flow was reduced on suspension of powder and then slowly increased as this powder was deposited from suspension.

A return of flow to a lower value when the vent tank was vibrated was explained in terms of the extra power required to pump a more concentrated suspension when no deposit was formed in the vent tank. In view of the initial drop of flow followed by the partial recovery, the process of absorption of the island would appear to give a "slug" of highly concentrated suspension which continued to circulate until it was fully dispersed by turbulent mixing. The drag on the slug caused the bulk flow velocity to be reduced and the velocity increased to normal as the slug became dispersed.

Radiography of the deposit in the top limb showed that during suspension, the eroded dunes appeared to progress steadily in the direction of flow. It is suggested that the reason for this is the same as that already advanced for the similar phenomenon noted in pickup from the bottom limb; that channelling occurred, and velocity variations due to aerofoil flow over the dunes allowed redeposition of larger particles on the downstream side of the dunes, causing the dunes to move downstream while being eroded.

The extent of this movement would be partly governed by the degree of classification in the deposit. Thus in a slowly formed deposit, with relatively closely sized beds, the inhomogeneity of surface particle size distribution necessary for channel formation will be largely absent and even erosion will occur in preference to channelling and island formation. In a rapidly formed deposit, the reverse will occur.

The time to achieve a state of full suspension from a state of complete deposition following a rapid increase in pump power was measured by taking a series of short period radiometric counts commencing at the moment of switching the pump from zero to maximum voltage. Full suspension was achieved in less than 2 seconds, this being the shortest counting time used. For reference full flow was achieved in something less than 0.2 seconds.

2.1.3 Homogeneity of Suspension

Because retarded flow caused deposition in curved pipes, it was reasoned that concentration inhomogeneities might persist into regions of fully suspended flow. To investigate this, a series of radiometric traverses were made at different points around the loop (see Figure 6) at a series of different bulk flow velocities, loop temperature being held constant and the vent tank being vibrated. The traverses were then compared with an ideal distribution of counts across the loop calculated for a uniform suspension. This ideal distribution was derived mathematically as shown in Appendix 4.

The results are shown in Table 1 and the comparisons with the ideal distribution are shown in Figures 7 to 14. The source density (S in Appendix 4) could not be estimated accurately so the counts were graphed as percentages of the maximum count obtained for the traverse; hence the figures indicate trends only.

The graphs show the following effects:-

1. A trend towards higher uranium concentration at the inner wall of the tube at positions 1, 3, 4, and 5 whereas the higher uranium concentration is towards the outer wall at position 2 (immediately below position1).

2. Much higher concentrations of uranium at the tube walls than would be expected from the ideal distribution.

3. Less uranium in suspension at position 5 (downward flow) than at the other positions (upward flow) with the amount of uranium apparently in suspension in the upward flow limb increasing up the limb.

4. More uranium in suspension as suspension velocity increases.

5. The closest approach to the ideal curve is at position No. 5 with low velocities.

6. A traverse in a plane perpendicular to the flow direction and the flow plane showed only the high values near the walls; no trends to left or right were noticed.

An extra effect not shown directly by the graphs is that, at the maximum velocity used, equivalent to 105 pump volts or 8.3 ft/sec, uranium concentration inhomogeneities persisted in the curved limbs. This maximum velocity was not set by pump capacity but by an inability to prevent uranium deposition in the vent tank (an area of relatively low velocities) in spite of vibration.

The trend toward higher concentrations of uranium at the inner tube walls is a result of the secondary velocity effects already referred to in Section 2.1.1. These high concentration layers would contain the larger size fractions of the uranium powder, the smaller fractions remaining in the bulk flow, and would be expected to be in a state of dynamic equilibrium subject to the forces of gravity and the hydrodynamic forces from the movement of the suspension. The effect of gravity on uranium particles in a low velocity area in a near vertical limb, e.g. position 1, would be to cause larger particles to tend to move down the limb against the flow direction in a condition of hindered settling. They would continue to move downwards under gravity (in secondary velocity areas) until they came to a vertical section of the loop when they would be exposed to the full bulk flow velocity and incorporated into the main flow. With the deviation of the main flow to the outside of the loop on entering a curved section of the loop, the particles under discussion would first be swept towards the outer wall of the loop before being redeposited in secondary velocity layers in the curved section. This explains the trend at position 2 and a local circulating stream of larger uranium particles is postulated. This circulating stream would be in a condition of dynamic equilibrium for any bulk flow velocity and this equilibrium would determine the sizes of particles in the stream. Similar local circulating streams could exist at any change of direction in the path of the loop on the upflow side where gravity can act against the flow forces.

The postulate that local circulating streams existed satisfactorily explains (a) how there appeared to be more uranium in suspension at any point as the bulk flow velocity in the loop was increased, and (b) how the uranium in suspension in down-flow areas was less than for upflow areas for a given bulk flow velocity. Thus deposition in secondary areas and resultant circulating streams in the upflow region of the loop would tie up disproportionate amounts of uranium, leaving only very fine material in suspension to be carried through the top limb of the loop and into the downflow region of the loop. An increase in the bulk flow velocity would mean more energy for suspension in the flow stream and less deposition in secondary velocity areas; hence more uranium in suspension in the main flow.

The above explanation is dependent on there being a range of sizes in the uranium powder particles. Kelly (unpublished) has shown that a range of sizes did exist in the powder as used in this experiment: (-3 microns, 2%; $+3-4$ microns, 90%; $+4-9$ microns, 3%. Percentages determined by microscopic count).

Inhomogeneities in uranium distribution caused by changes in fluid flow direction and consequent secondary velocity effects could not be prevented by increase in bulk flow velocity because the displacement of the main flow stream is a function of velocity, and therefore secondary velocities could not be prevented. By using very fine uranium powder and large radius bends the inhomogeneities due to secondary flow would be reduced and would disappear in long straight pipes. However, inhomogeneous distribution due to concentration in boundary layers would remain. No experimental evidence was obtained on the variation of boundary layer uranium concentration but it is considered on theoretical

grounds that the amount of uranium held up in boundary layers would be reduced if very fine uranium powder were used in suspension. Considering the range of sizes of powder used in the experiment "very fine uranium powder" should be taken to mean sub-micron sized powder. The traverse in a plane perpendicular to the flow direction and the plane of the loop shows no asymmetrical trends but only the secondary velocity zone deposit and boundary layer concentrate. This is in agreement with Goldstein's description of the induction of secondary flow.

Thus the overall picture of uranium suspension flow in the loop is a main flow with regions of secondary or retarded velocity at changes in flow direction. Deposition of the larger size fractions of the uranium powder in the retarded flow regions occurred while the smaller size fractions remain suspended in the main flow. Interaction of gravity and hydrodynamic forces in upflow regions caused circulating streams of larger uranium particles to flow downwards in secondary velocity areas and upwards in the main flow. If circulating flows were present, uranium concentration in the upflow regions was higher than in downflow regions. Increase in bulk flow velocity, by increasing hydrodynamic forces operating against gravity in upflow regions caused uranium to be suspended and removed from the circulating streams, thus increasing the concentration of uranium in the main flow.

Inhomogeneities of uranium distribution around the loop were thus due to secondary velocity effects and a range of sizes of uranium particles. Inhomogeneities across the loop were also due to these factors, as well as the effect of boundary flow which caused a concentration of particles in the boundary layer with a consequent thickening of the layer. Increase in bulk flow velocity does improve the homogeneity of distribution, but it is expected on theoretical grounds that closer sizing of uranium powder and the use of very fine sizes would cause a much greater improvement in suspension homogeneity.

Flow in curved uniform conductors would be susceptible to both types of suspension inhomogeneity but flow in straight uniform conductors would be affected only by boundary layer concentration effects. Non-uniformity of conductors would influence suspension homogeneity according to the type of local velocity distribution produced.

2.2 Influence of Temperature on Suspension

The velocity of the sodium required to bring about suspension of deposited uranium particles from the top limb of the loop was determined within the temperature range 300°C to 500°C. The amount of uranium in suspension at each velocity was determined by the radiometric technique already mentioned (Section 2.1.2). When the count rate reached a maximum, radiographs of the loop confirmed that the uranium particles in the loop were fully suspended and circulating in the main fluid stream. The results of these experiments are shown in Figure 16.

The suspension velocity was not markedly affected by temperature within the range studied. However, the random spread of results indicates that factors other than bulk flow velocity and temperature were operative during the experiment. Complete suspension of the particles was indicated by maximum count rates which ranged from 315 to 445 counts per minute. This indicated that the amount of uranium present in the loop and available for suspension was not constant, but varied as the concentration of uranium in the main stream was reduced by the centrifugal ejection of suitably sized particles into the low velocity areas of the vent tank. It is also apparent that, in the range of velocities between 2.5 and 5.0 ft/sec where incipient suspension occurred, the count rates recorded were not directly dependent on a given velocity of flow but varied if that velocity was approached from a higher or lower velocity level; i.e. the particle sizes last deposited on the classified dunes were not resuspended at the same bulk fluid velocity at which deposition occurred. This is due to the low velocity boundary layer present at the surface of the dunes. The particles required greater agitation or higher velocities to overcome the damping effect of this boundary layer and move them into the main stream. At the same time, particles which were resuspended from dunes in the most favourable position upstream from the vent tank were often redeposited on downstream dunes in the top limb as already described, before eventually being suspended in the main flow stream and contributing to the count rate recorded at the detection head.

The variation of maximum count rates (which indicate complete suspension) and the variation of count rate at any given velocity between 2.5 and 5.0 ft/sec were influenced by vibrating the vent tank to disturb the velocity patterns established in it and to prevent deposition of uranium there. Comparison of the curves plotted from results obtained at 375°C, with vibration, and without vibration, indicates that equivalent count rates were recorded at lower velocities when the loop was vibrated, thus confirming the effect of deposition in the vent tank. It was possible to reproduce the results obtained at 375°C with vibration by decreasing or increasing the velocity in steps without deviating from the general curve.

When the temperature was increased from 450°C to 625°C, with the electromagnetic pump setting constant at 80 volts, velocity effects similar to those already noted appeared. The bulk flow velocity increased from 6.85 ft/sec at 450°C to 8.1 ft/sec at 625°C due to changes in density, viscosity, and electrical resistance of the sodium and stainless steel. The count rates gradually decreased as the temperature increased. The low count rate at the flowmeter at 575°C, when the velocity was 7.7 ft/sec, indicated that the majority of the uranium had transferred to the vent tank. Careful vibration of the loop at this temperature caused resuspension of the uranium particles into the main stream and an increase in the count rate.

Abraham, Flotow, and Carlson (1957) reported that uranium dioxide particles could not be suspended in sodium at temperatures above 575°C without using additives and that uranium and calcium additions increased the temperature at which sudden deposition occurred to 600°C. (Tellurium additions made further substantial improvements). No evidence of this "de-wetting" type of behaviour was noted at temperatures up to 625°C.

The percentage of calcium in the loop was estimated to be 1.4 per cent. As the solubility of calcium in sodium is 1.4 per cent. at 365°C, no undissolved calcium, as metal, would be present in the loop above this temperature. The rejection of calcium from solution was found to occur at an average loop temperature of 366°C. The velocity of the dispersion fell abruptly by 0.85 feet per second as the sodium cooled through this temperature. The decrease in flow accompanying the precipitation of calcium, and the consequent increase in nett suspension concentration, is further evidence of the extra power required to pump the suspension compared with that necessary to pump sodium alone.

2.3 Operation of the Analogue Rig

The deposition and resuspension behaviour of tungsten particles in a tungsten-water analogue loop was studied and photographed and used to confirm the behaviour of the uranium particles, inferred from an examination of the radiometric and radiographic data recorded at various positions on the sodium-uranium suspension loop.

The analogue loop was fabricated to the overall dimensions of the experimental loop from one inch nominal diameter polythene tubing and included a centrifugal pump, a one inch nominal diameter vent pipe attached to the top limb and a flow restriction in the vertical upflow side of the loop to simulate the effect of the flowmeter venturi. 70 grams of tungsten powder was added to 1200 grams of water to form a 0.57 atomic per cent. tungsten-water suspension in the loop.

The suspension was circulated at a range of velocities controlled by the voltage applied to the pump motor. The actual velocity of the circulating suspension was not measured but the pump voltage when the particle behaviour was photographed was noted to give an indication of the relative velocity of the main stream, velocity being approximately in direct proportion to pump voltage in the range used.

2.3.1 Observations at Various Pump Voltages

The observations made at the various pump voltage settings are listed below and reference should be made to photographs 1 to 14 in Figures 17 and 18.

Pump setting: 230 volts – A region of high concentration of tungsten particles in the bottom of the top limb upstream from the vent pipe was indicated by slow moving stream lines of tungsten. However, these stream lines were not a deposit. (See photograph 1. See also Cairns and Turner AAEC/E16).

Marked turbulence occurred in the vent pipe. The surface of the fluid in the pipe was revolving in a swirl pattern indicated by the thin moving lines of segregated tungsten particles visible in photograph 2.

Pump setting: 200 volts – Deposition of the largest particles in the loop began in the top limb downstream from the vent pipe. (See photograph 3).

Pump setting: 185 volts – Dunes formed in the top limb and began to increase in depth and to extend downstream. Stream lines appeared in the bottom limb of the loop, indicating a non-uniform distribution of tungsten particles, but no deposition occurred.

Pump setting: 175 volts – The deposits in the top limb extended. A thin line of tungsten upstream from the vent pipe in the curve approaching the top limb merged into more extensive deposits, separated by lengths of clear pipe, under and downstream from the vent pipe. (See photographs 4, 5, and 6. See also Cairns and Lawther AAEC/E37).

Particles deposited in the vertical upflow limb above the flowmeter but before reaching the top limb fell back a short distance and were swept upwards again by the main stream forming a local circulating stream.

There was less turbulence in the vent tank and the surface was calmer but the swirl pattern noted before in the fluid was still present. (See photograph 7).

Pump setting: 160 volts – Deposition in the curve before the top limb had developed into the normal type of dune formation. (See photographs 8 and 9).

Photograph 10 shows the stream lines in the bottom limb of the loop. No deposition had taken place.

Pump setting: 140 volts – Deposition occurred more readily above the flowmeter in the vertical upflow limb before the tungsten particles entered the curved section of the top limb. Some of these particles fell back a short distance while others fell back to the flowmeter restriction before returning to the bulk flow. This deposition and resuspension of the particles resulted in a local circulating stream in the vertical upflow limb in which suitably sized particles were retained so that the concentration increased in this part of the loop. (See photograph 11).

Deposition of tungsten particles began to occur in the bottom limb. (See photograph 12).

Pump setting: 110 volts – The main stream was flowing very slowly (approximately 1 ft/sec) at this pump setting. Less turbulence was seen in the vent pipe but the swirl pattern was still present. The fluid surface was level and two separate layers of different tungsten concentration could be seen in the vent pipe. (See photograph 13).

Tungsten particles deposited and falling back in the vertical upflow limb appeared just above the flowmeter restriction and a line of tungsten particles were carried over into the vertical downflow limb to the top of the pump.

Considerable deposition had occurred in the bottom limb in dunes of similar contour to those formed at higher velocities in the top limb. (See photograph 14).

Pump setting: 180 volts – Increasing the pump voltage to 180 volts resulted in the rapid removal of the deposits from the bottom limb but the deposits in the top limb were still extensive.

2.3.2 Conclusions Drawn from Observation of the Analogue Loop

The following general conclusions can be drawn from observation of the tungsten–water analogue loop:–

(1) Deposition occurred most readily in the top limb.

(2) Centrifugal and gravitational forces combined to concentrate the particles in the vertical upflow limb.

(3) Particles tended to segregate into the vent pipe and become suspended there, thus lowering the concentration of tungsten in the main stream.

(4) Deposition of tungsten was observed in the bottom limb of the analogue loop but radiographs of the bottom limb of the uranium–sodium suspension loop at velocities as low as 0.5 ft/sec did not reveal any evidence of uranium particle deposition.

These conclusions directly substantiate explanations for the following aspects of the behaviour of the uranium–sodium suspension: the mechanism of deposition in the top limb of the loop, the existence of local circulating streams of particles in the upflow limbs, composition inhomogeneities in fully suspended flow, and the mechanism of precipitation in the vent tank. This last one is not substantiated in full as it was not possible to see anything but the outer surfaces once the tungsten powder was suspended. However observation of these surfaces and the water flow during the short interval before suspension, substantiated in general terms the explanation offered in Section 2.1.1 for the uranium–sodium suspension.

Deposition of tungsten was observed in the bottom limb of the analogue loop during relatively rapid reduction of bulk flow velocity, but uranium deposition was not observed in the experimental loop under much lower rates of velocity reduction. This difference in degree was probably due to

(a) the different rates of bulk flow velocity reduction, and

(b) the different size distributions of the two batches of powder under consideration. It was noticeable that the first experiments with the tungsten powder failed to produce many of the desired results as a closely sized batch of powder was used. Substitution of a batch of more random sized powder gave the results described in this section. This substantiates the statement in Section 2.1.3 that the use of closely sized powder would avoid many of the problems of deposition.

Operation of the tungsten–water analogue loop therefore confirmed the explanations of the operation of the uranium–sodium loop.

2.4 Behaviour of the Suspension after Shutdown

The power supply to the loop was cut off suddenly while the loop was operating at 350°C and the suspension was circulating at a velocity of 5.3 ft/sec. The uranium particles were in suspension so that general deposition in all parts of the loop was expected. Figure 19 shows the results of radiographic and radiometric surveys giving the final position of the uranium particles in the loop.

The deposition pattern was as follows:

2.4.1 Vent Tank

Above the tapered section – The uranium shown clinging to the vent tank wall above and on the circumferential weld settled in these positions when the powder was first added to the loop. The rings of uranium on the wall below the weld were deposited from the suspension before sodium was removed to lower the fluid level into the vent pipe. The uranium was held in position by the sodium film remaining on the tank wall.

Tapered section – This section of the vent tank accumulated uranium particles readily because of the range of velocities induced by the tapering inside diameter. The particles deposited were retained where they fell on the slope of the wall and not dislodged unless the loop was vibrated. The particles visible in the radiograph were probably left there during the 625 degree run as little vibration was applied to the loop at this temperature and the expansion of the sodium would have lifted the liquid surface into this region. As before, the deposited particles were retained in situ by the film of sodium remaining on the tank wall when the sodium level was lowered.

Vent pipe – The largest of the uranium particles suspended in the vent pipe when the suspension was circulating at 5.3 ft/sec, dropped into the loop within moments of the pump stoppage. The smaller particles remained on the wall of the vent pipe in the position in which they were retained during operation. This distribution is a result of the interaction of centrifugal and gravitational forces which classified the particles by size (see Section 2.1.1). The larger particles tended to move more readily towards the wall of the pipe but they also settled at a faster rate and fell into more turbulent regions and were lifted upwards again before reaching the low velocity layer near the wall. As the smaller particles settled at a slower rate, they reached the wall higher in the pipe in a position where the velocity pattern favoured deposition.

Retention of these very fine particles in their deposited position on the rapid shutdown would be caused by:

(a) their being deposited in a closely packed bed on the pipe wall, greatly reducing their hindered settling velocity;

(b) cooling of the vent pipe walls by conduction to the air cooled parts of the vent tank which would increase the viscosity of the sodium layer immediately in contact with the walls and containing the deposited uranium; thereby further reducing the hindered settling velocity of the particles;

(c) their free settling velocity being low; and

(d) contraction of sodium in the loop, by lowering the sodium level in the pipe, which would lock the particles in position before much movement had taken place.

2.4.2 Top Limb

The uranium had built up on the bottom of the top limb as a continuous deposit which increased in depth downstream from the vent pipe. This formation is consistent with that to be expected as a result of the rapid deceleration of the suspension to velocities less than the suspension velocity.

Radiographs taken during the operation of the loop indicated that a layer of uranium covered the inside of the tube at all velocities. This buffer layer had decreased in thickness after shutdown as most of the particles had fallen from the wall when the forces operating in the circulating fluid were removed.

2.4.3 Vertical Up–flow and Vertical Down–flow Limbs

The final position of the particles was dictated by gravity and the geometry of the loop. The buffer layer protecting the stainless steel from erosion had stayed in position at certain points but, in general, the particles had fallen away from the inner wall. The welds were outlined with uranium because of slight surface roughness on the inside of the tube. For a similar reason a small defect in the tube above the pump showed clearly in the radiograph.

2.4.4 Flowmeter Venturi

This section of the loop was the first to solidify, as shown by the pipe formed in the sodium below the venturi. This was due to the lack of thermal insulation, the close proximity of the air cooling for the flowmeter magnet and the heat sink effect of the substantial metal supports holding

the flowmeter. The uranium particles deposited during operation because of the increased velocity, turbulence, and the consequent increase in boundary layer thickness, thus had to stay in position for a relatively short time only before freezing in place. Also they were not subjected to any displacing force due to the contracting sodium.

2.4.5 Pump Tube

The contour of the deposit in the pump tube indicated that it was brought about by velocity variations in the fluid. No analysis of the phenomenon can be given without further experimental work but the following factors suggest themselves as being relevant to the problem.

The magnetic field due to the flow of current across the pump duct distorted the field between the magnet poles by introducing a component which increased the resultant field intensity on the entrance and lowered it on the exit. The field intensity also tended to be less at the centre of the duct between the poles of the magnet. The counter e.m.f. developed in the liquid as it moved through the magnetic field is a function of the magnetic flux density between the magnet poles and the velocity of the liquid flow in the duct. Therefore, the current density in the fluid at the outlet of the pump was higher than that at the inlet and also higher in the centre of the fluid. This gave rise to an accelerating force tending to increase progressively the velocity of the suspension in the centre of the pump tube. This preferential increase in velocity, together with the extra kinetic energy added to the suspension in the pump tube created conditions of shear and turbulence in the fluid which increased the extent of low velocity areas, thus creating the conditions necessary for a deposit of the observed formation.

2.4.6 Bottom Limb

Uranium particles were deposited on the bottom of the tube in a similar manner to that observed when the sodium flow was stopped in order to determine the time required for resuspension. The deposit was evenly placed on either side of the bottom valve and had built up over the valve poppet and at each end where particles collected after falling from the vertical limbs.

This aspect of the examination shows the need for further detailed investigation into component design to avoid deposition of uranium during operation, such as in the pump and flowmeter tubes. Such deposition would be velocity dependent and to some extent dependent on powder size distribution and could therefore fluctuate with changing operational conditions.

The pattern of uranium deposition on quick shutdown was as expected in the absence of substantial thermal convection currents, i.e. the uranium deposited effectively under gravity. As such it could be forecast with considerable accuracy. By suitable design, deposition of critical amounts of powder could be avoided.

The effect of a noticeable temperature gradient in larger structures in causing thermal convection flow would depend on the magnitude of the flow, but could be largely nullified if desired by introducing some quick-freezing passages into the pipework similar in effect to the flowmeter in the experimental loop.

3. METALLURGICAL EFFECTS

3.1 Calcium Gettering

The high initial purity of the sodium charge in the loop was maintained under operating conditions first by the extremely low leak rate into the apparatus and secondly by the addition of calcium to act as a soluble getter in case of any unexpected in-leakage of oxygen. Calcium was selected on thermodynamic grounds as calcium oxide is more stable than the oxides of sodium, uranium, and beryllium. Any calcium oxide formed would be suspended and would circulate in the main stream.

The calcium was added to the loop sodium in two stages as follows:

(1) By digesting the sodium in the dump tank with excess calcium before the sodium was transferred to the loop at 250° C. The sodium therefore contained 0.4 per cent. calcium before further additions were made to the loop. (See solubility curve, Figure 20).

(2) By adding 8 grams (or 1 weight per cent.) of calcium to the loop at a temperature of 300° C.

The solubility of calcium in sodium at 300°C is 0.73 per cent. (Figure 20). However, as it was found that a total addition of 1.4 weight per cent. calcium had been made to the loop at this temperature by suspending pea-sized pieces in a stainless steel mesh basket in the sodium, it is clear that 5.4 grams (or 0.67 weight per cent.) of undissolved calcium had thus passed into the loop by temperature dependent mass transfer as opposed to solution. Mass transfer was possible as a temperature gradient existed between the stainless steel basket and the vent tank walls as indicated by the variation of temperature at the following points on the vent tank with the controller set at 300° C:-

Top of vent tank (above sodium surface)	99°C
Middle of vent tank (above but near sodium surface)	273°C
Bottom of vent tank (below sodium surface and near basket)	291°C
Loop sodium	300°C

The free calcium settled on the shoulder angle of the vent tank and was observed through the cover plate viewing ports when the sodium level was reduced into the loop.

A sample of sodium was removed from the vent tank in a stainless steel bucket at 300°C. Subsequent chemical analysis of this sample showed a calcium content of 1.27 weight per cent. This result was greater than the expected value of 0.73 weight per cent. as free calcium was included in the sampling bucket when the sampler was drawn over the deposit in the vent tank during removal.

At temperatures below 365°C, the calcium deposit was not at all times stationary but became dislodged and circulated through the loop when the velocity pattern in the vent tank was disturbed by vibration or by the insertion of a probe or other device into the sodium. The passage of the calcium around the loop with the sodium stream was accompanied by a drop in flow velocity.

At temperatures above 365°C no undissolved calcium, as metal, was present in the loop as 1.4 weight per cent. calcium dissolves in sodium at 365°C. (See Figure 20). The rejection of calcium from solution was expected to occur at this temperature and in fact did occur at an average loop temperature of 366° C. This rejection of calcium was evidenced by an abrupt fall of 0.85 ft/sec in the flow velocity.

At a temperature of 300° C, calcium was deposited on the surface of a silver steel probe which was suspended in the sodium. Approximately one eighth of an inch of the probe was below the surface for 94 hours, while one half inch of the probe was below the surface for only 4 hours. The deposit was thicker at the tip and indicated that the deposition was dependent on the residence time in the sodium. The deposit was examined visually in the vacuum viewing chamber before contacting the atmosphere and then identified as calcium by X-ray diffraction and spectrographic analysis. The deposit was built up by the mechanism of temperature dependent mass transfer as the temperature

at the end of the probe was lower than the general sodium temperature. Heat was extracted from the rod by conduction due to a temperature gradient of at least 250°C which existed between the hot and cold ends of the probe.

A deposit of calcium was also found on the surface of the uranium sample suspended for 100 hours in the sodium at 300°C. The deposit was wiped from the uranium surface and identified by spectrographic analysis. The mechanism of this deposition is obscure as the uranium sample was suspended further below the surface in a stainless steel basket by three lengths of fine Nichrome ribbon and hence the conduction of heat from the sample would have been negligible. It is also interesting to note that no deposit of calcium was found on stainless steel components immersed in the sodium during the investigation. However, this is inconclusive as a detailed study was not made of this phase of the experiment.

The results of the experiment indicate that the calcium performed successfully as a getter but further investigation is necessary so that the deposition of calcium from solution may be predicted on the basis of temperature, velocity, and metallurgical effects.

3.2 Compatibility of Stainless Steel with the Suspension

It is possible that the concentration of calcium necessary to prevent oxidation of sodium may be greater than the minimum concentration of calcium that would cause solution of or intergranular attack on the stainless steel container material.

Chemical analysis of samples taken from the loop after 3,800 hours of operation showed that the sodium contained less than 5 p.p.m. each of iron, chromium, and nickel. Physical examination showed no evidence of temperature dependent mass transfer and concentration gradient mass transfer was neither expected nor found. Therefore little solution of the container material had occurred and no preferential solution of the nickel from the stainless steel had taken place. Metallographic examination of the loop tube revealed that some sigma phase had formed as a result of the time and temperature conditions of operation but there was no indication of intergranular penetration or other attack. No evidence was found of reaction between the uranium and the stainless steel, in spite of the period of operation at 625° C.

It was concluded from this evidence that the stainless steel was compatible with circulating sodium which contained 1.4 weight per cent. calcium in solution and 0.76 atomic per cent. uranium in suspension.

3.3 Compatibility of Uranium with the Suspension

As reported by Bett et al. (1961), a rod of uranium was suspended in the sodium for 100 hours at 300°C and then examined for corrosion products. No oxidation was found by X–ray diffraction and metallographic examination and it was decided on the basis of these results that the uranium powder would not be oxidized during the experiment providing that the Calcium was successful in removing any further oxygen introduced into the loop at a later stage.

The uranium particles were then circulated in the sodium for 2,600 hours before further examination of the powder was possible. On completion of the experiment the uranium was exposed to the atmosphere during the disposal of the sodium and was still pyrophoric, indicating that negligible oxidation of the uranium had taken place. It is not known whether the uranium was protected by the sacrificial oxidation of calcium to calcium oxide or whether the oxygen level in the sodium was low at all times. Considering the chemical reactivity of the fine uranium powder and its intimate contact with the sodium it is likely that the latter conditions prevailed. The rejection of calcium from solution occurred at the same temperature at the beginning and near the end of the experiment indicating that little oxidation of calcium had occurred but the reliability of the temperature measurements would not be sufficient to make a conclusive point of this fact. However, in the conditions of the experiment the uranium was compatible with the sodium–calcium solution.

3.4 Compatibility of Beryllium with the Suspension

A specimen of beryllium was suspended in the path of the main stream below the vent tank for 164 hours at 400° C and 506 hours at 375° C . The maximum velocity of the suspension during the residence time of the beryllium in the loop was 6.9 ft/sec and the average velocity was 5.0 ft/sec.

The deflection of the stream as it passed around the beryllium rod resulted in the formation of a low velocity region adjacent to the lower end of the sample in which particles of uranium were deposited. This deposit can be seen in Figure 21 and has a similar contour to the deposit in the pump tube described in Section 2.4.5. Figure 21 also indicates that the obstruction to flow caused by the beryllium specimen has disturbed the normal velocity distribution in the main stream and hence the deposit of uranium on the lower surface of the top tube has been displaced from its normal position and has concentrated downstream from the vent tank. This velocity effect is consistent with the previously observed behaviour of the suspension as discussed in Section 2.

When the beryllium was removed from the loop, it was washed several times in alcohol to remove the adhering sodium, dried, and weighed. The specimen had increased in weight by 77.1 mg which was equivalent to 9.45 mg/cm2/month. This increase in weight was higher than the true value as uranium was still present on the surface and subsequent metallographic examination indicated that the surface of the sample was such that it could have retained uranium in deep cracks. No mass transfer of beryllium to other parts of the loop was found and beryllium was not detected in the drillings of sodium taken from the loop after shutdown indicating that no solution had occurred. Consideration of these facts suggest that the above weight gain figure is without significance as an indication of corrosion.

The surface of the beryllium was dark in appearance and had a black powder adhering to it. This powder was removed by wiping and spectrographically identified as uranium. This uranium was deposited in the low velocity boundary layer present on the surface of the sample during the operation of the loop and remained in position when the sample was removed. Uranium was also identified in the alcohol washings collected during the cleaning operation. The retention of the uranium on the sample was a velocity effect and would not indicate any reaction between uranium and beryllium. No beryllium was detected in the powder removed from the surface or in the alcohol washings so that, if beryllium oxide was formed it was adherent and remained on the surface of the specimen.

The beryllium sample was machined on one end and spectrographic analysis was carried out on the clean and dark surfaces. The results of this analysis are listed below:-

Element	Clean Surface	Nominal Order	Dark Surface	Nominal Order
Be	High	> 50%	High	> 50%
Ca	Very faint trace	0.002%	Medium	10%
Cu	Very faint trace	0.002%	Trace	0.05%
Fe	Not detected	–	Not detected	–
Ni	Not detected	–	Not detected	–
U	Not detected	–	Not detected	–

The presence of calcium on the unmachined surface of the sample is significant. The amount of handling that the specimen received before the spectrographic analysis was carried out would have removed any loosely adhering deposit of calcium on the surface. The analysis shows, for example, that all of the uranium had been removed. At the temperature of the experiment the sodium contained 1.4 weight per cent. calcium in solution and no free calcium as metal, was present so that the build–up of the calcium on the surface of the beryllium was brought about by a different mechanism from that discussed in Section 3.1 which resulted in the formation of a loosely adhering deposit of calcium on the surface of the probe. The photomicrographs shown in Figures 22–24 indicate that an intermetallic compound of beryllium and calcium may have formed on the surface but further samples would need to be examined to obtain conclusive evidence on this point. The final chemical analysis of the sodium after shutdown indicated that the copper content was less than 5 p.p.m. The trace of copper found on the surface of the beryllium may be significant and indicate that the copper had also been associated with the formation of a compound on the beryllium surface.

Metallographic examination showed that the surface was pitted and contained fissures which could allow penetration of the sodium into the beryllium; also that sub–surface voids were present. However, this may have been the condition of the surface before the specimen was exposed to the suspension so that no conclusions can be drawn from these observations.

In summary it may be said that the actual measurements of beryllium compatibility are inconclusive but that, while no reaction with either sodium or uranium was obtained, some slight surface reaction with calcium appears to have occurred. This problem would require further study by itself.

4. MECHANICAL EFFECTS

4.1 Erosion

Kelly (unpublished work) has described the uranium particles as being "highly irregular in shape but tending to be platelike". It would therefore be expected that some erosion might occur on the inner surfaces of the loop tube even though the suspension velocity did not exceed 9 ft/sec. The ductility and very small size of the uranium particles together with the cushioning effect of the boundary layers would however tend to reduce erosion.

Measurements of the loop tube showed no measurable erosion to a limit of 0.001 inch. Thus the rate of erosion would have been a maximum of 0.002 inch/year. Visual inspection of the inner tube wall showed a slight degree of polishing on the outer radial surfaces but no other effects.

4.2 Pumping Power

As has been mentioned in Section 2.1.2, addition of uranium powder to the loop caused a decrease in flow which was partially recovered as part of the added uranium was removed from suspension. As this decrease in flow occurred at a fixed pump setting and could be recovered independently, it was evident that the power required to pump the suspension was higher than that required to pump sodium alone.

Measurements made at the time of the powder addition, while not being specifically for the purpose of power calculations, indicated that the increase in pumping power requirements was of the order of 10–15 per cent.

5. APPLICATION TO A REACTOR CIRCUIT

From evidence so far presented, the following facts relating to behaviour of the uranium/sodium suspension are relevant to possible use in a reactor circuit:

(1) Inhomogeneities in suspension will occur at changes in fluid flow direction, especially at low velocities when deposition of uranium may occur.

(2) Inhomogeneities in suspension should not occur in straight pipes, except at tube walls.

(3) Changes in internal pipe contour will produce suspension inhomogeneity.

(4) Concentration of uranium in boundary velocity layers will occur.

(5) Uranium will readily deposit from suspension if velocity is lowered sufficiently.

(6) Precipitated uranium can be very rapidly suspended if exposed to sufficiently rapid flow. "Slug" flow may occur for short periods in appropriate conditions.

(7) Adherence of uranium to loop component walls did not occur in the conditions of the experiment, except as deposits which could be removed by appropriate alterations to the velocity distribution.

(8) No evidence was obtained to indicate that uranium particles had sintered together during operation of the loop.

For use in a reactor circuit, suspension conditions must be under close control. An initial figure of 2 per cent. variation in suspension concentration(Dalton, 1956) was later modified extensively by Thompson (1958) to allow concentration variations of the order of 15 per cent. in any core conductor. Figure 11 shows that for fully suspended downflow in a tube with curvature, the departures from the ideal distribution are of the order of 15 per cent. Straightening of the tube and closer sizing of the uranium particles would considerably reduce these departures. The concentration of uranium in downflow boundary layers would be reduced by (a) the tendency of gravitational forces to oppose thickening of the layer by hindered settling effects, and (b) the convective flow induced by the heat liberation in the uranium. Fully suspended downflow of a closely sized uranium sodium suspension in a uniform straight conductor should therefore be acceptable in a reactor core region.

If the convective flow due to heat liberation from the uranium in the boundary layer more than compensated for the effect of hindered settling conditions in thickening the boundary layer, fully suspended upflow of a closely sized uranium powder suspended in sodium in a uniform straight conductor would also be acceptable in a reactor core region. On first appraisal, upflow would make for easier layout than downflow (see Figure 25 referred to later). It would be necessary to maintain the region of highly uniform flow past the zone of delayed neutron emission although, due to the lower neutron flux, some decrease in uniformity would be permissible.

Removing the uranium from suspension as soon as possible after the delayed neutron emission zone would reduce the problems of deposition during heat transfer, would provide a convenient take-off point for chemical processing, and would reduce the circulating load of uranium and thus the fuel investment. This removal could be assisted by locating the separation unit at the change of flow direction toward the heat exchanger. Then while the depleted sodium flowed to the main heat exchanger, the concentrated suspension would flow through a smaller "straight-through" type heat exchanger to a position on the inlet side of the core where it would be injected into the cooled depleted sodium from the main heat exchanger. Injection of the concentrated suspension should be performed at a position of maximum fluid energy, e.g. at the outlet from the circulating pump. Injection of a suspension under these conditions should avoid slug flow and the consequent fluctuations of uranium in suspension.

Close control of the separation unit would be necessary to guard against build-up of uranium. Build-up of uranium in the main heat exchanger would not be expected to be a problem because (a) uranium in suspension in the heat exchanger zone would be very fine and therefore unlikely to settle out, (b) careful design of the heat exchanger would minimize low velocity areas or "dead spaces", and (c) experience with the loop indicates that deposits in such areas quickly reach a state of dynamic equilibrium and do not release uranium into suspension in a haphazard fashion.

Space for thermal expansion of the sodium could be provided above the separation unit. This space might also be a convenient location for addition of processed or makeup uranium powder. Sealing of this space against oxygen inleakage should not be impossible especially as the system would run at at least the pressure of the separation unit; of the order of 100 p.s.i.

By dividing the circulating suspension circuit into a number of smaller circuits, problems of out of pile criticality in the concentrated suspension would be eased. This arrangement would also reduce the effect of fluctuations in the uranium concentration of the suspension and would reduce the significance of chance component failure.

Figure 25 illustrates the model described above, but should be taken as being drawn solely in the light of the results of this investigation. No attempt has been made to indicate a possible layout for a horizontal loop as no information is available from the experiment, even though on theoretical grounds, horizontal flow has attractive features, e.g. reduced deposition in secondary velocity areas of horizontal bends in conductors.

6. RECOMMENDATIONS FOR FURTHER WORK

The present investigation has given a general semi–quantitative picture of the behaviour of suspension flow in an almost isothermal vertically disposed loop.

Additional information would be required on the following points before detailed consideration could be given to reactor design:

(1) the effect of horizontal disposition,

(2) quantitative information on suspension behaviour in secondary velocity areas,

(3) the effect of particle size distribution,

(4) the effect of a large temperature gradient on operation, (a temperature gradient of between 10 and 20°C existed in the loop during operation but no evidence of mass transfer or other faults was found as a result of this gradient – see Section 3).

(5) the effect of higher velocities; up to 30 to 40 ft/sec,

(6) kinetics and dynamics of both separation of uranium from and mixing of uranium into suspension,

(7) the mechanism and dynamics of boundary layer concentration, especially under irradiation, and

(8) the effects of irradiation on suspension behaviour in general.

7. SUMMARY

The hydrodynamic behaviour of a uranium–sodium suspension containing 0.76 atomic per cent. uranium has been explored up to velocities of 8.3 ft/sec and temperatures of 625°C.

Suspension is affected by the particle size distribution and the velocity distribution in the conductor whi ch is influenced by the internal contours of the conductor, the direction of flow, the bulk flow velocity, and the flow path.

Deposition occurs readily in low velocity areas but resuspension of deposited uranium rapidly follows an appropriate increase in bulk flow velocity.

Temperature has no discernible effect on suspension behaviour with the exception of that associated with the deposition of excess soluble getter.

Successful oxygen gettering of the sodium has been achieved by the use of calcium dissolved in sodium. No adverse metallurgical effects due to calcium were observed.

The system uranium–sodium–calcium–beryllium–stainless steel was compatible under the conditions of loop operation.

Erosion was not measurable to a limit of 0.002 inch/year.

Approximately 15 per cent. extra power was required to pump the suspension.

A model has been suggested to illustrate how the uranium–sodium suspension could be used successfully, as judged from the results of this investigation, in a reactor circuit.

Lines of further work necessary to amplify the findings of this investigation have been indicated.

8. REFERENCES

Abraham, B.M.,Flotow, H.E., and Carlson, R.D., 1957. UO_2–NaK slurry studies in loops to 600°C. Nuclear Science and Engineering, July, 1957.

Bett, F.L., Hilditch, R.J., Kluss, T.N., and Mepham, R.J., 1961. Studies with a uranium–sodium suspension. Part 1. Construction of an experimental loop AAEC/E69.

Cairns, R.C., and others, 1957/58. Studies of small particle suspensions for L.M.F.R. Parts I to VI, AAEC/E5, 16, 17, 34, 37, 38.

Dalton, G.C.J., 1956. Review of uranium–sodium–beryllium reactor proposals Internal report AAEC/K77.

Goldstein, J., 1938. Modern developments in fluid dynamics. Part I. p.85. Clarendon Press.

Thompson, J.J., 1958. Statistical aspects of the kinetics of a circulating liquid metal fuel suspension reactor. 2nd U.N. International Conf. on the Peaceful Uses of Atomic Energy, September 1958.

9. ACKNOWLEDGMENTS

To Dr. J. J. Thompson for deriving the mathematical expressions in Appendix 4.

TABLE 1

RADIOMETRIC SURVEY OF URANIUM/SODIUM SUSPENSION LOOP

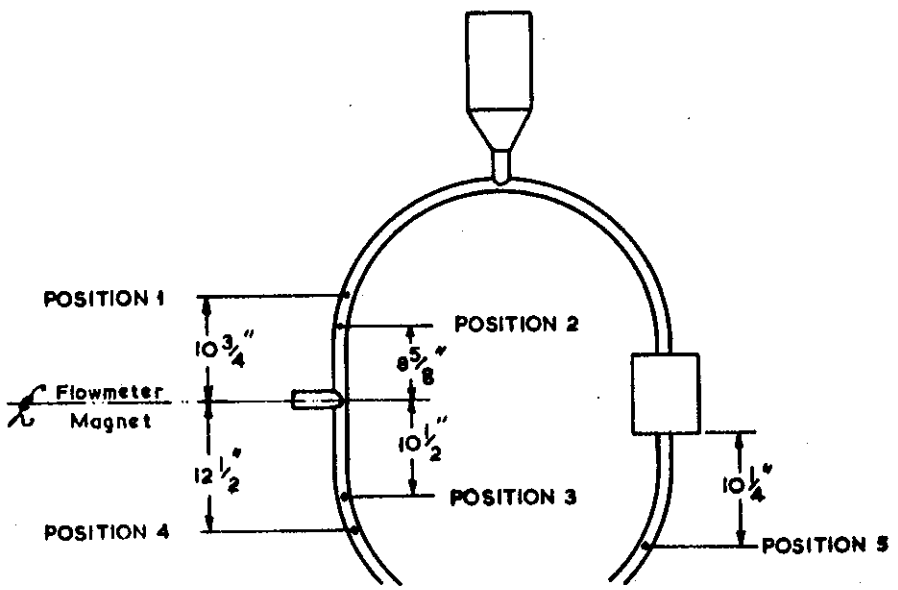


FIG. 6

		L.	M.L.	C.	M.R.	R.	
POSITION 1							
350°C	25V	53	68	78	75	83	
"	45V	71	85	89	92	100	
"	65V	93	99	114	118	119	
"	65V	90	110	121	117	132	(check count 60 hours after)
"	85V	95	118	127	126	130	
"	105V	100	95	131	135	127	
POSITION 2							
350°C	65V	94	92	98	86	59	
"	85V	106	107	99	75	75	
"	105V	105	111	96	105	92	
POSITION 3							
350°C	65V	40	45	45	49	46	
"	85V	43	50	63	51	56	
"	105V	52	56	60	58	63	
POSITION 4							
350°C	65V	38	45	49	41	47	
"	85V	46	56	60	61	63	
"	105V	38	46	51	49	42	
POSITION 5							
350°C	65V	3	17	18	11	4	
"	85V	39	42	40	34	46	
"	105V	22	41	43	31	32	

TABLE 1 (continued)

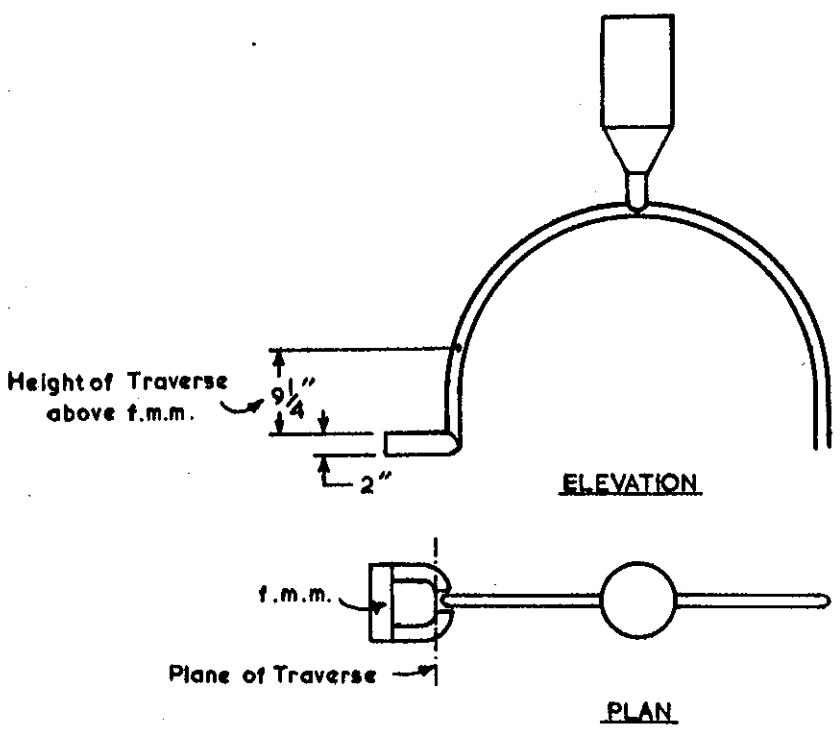
Date: 4.2.60

Loop Conditions: 300 °C 80V.

Experiment: Traverse of loop tube with counting head. AT RIGHT ANGLES TO PLANE OF LOOP.

Collimator: Lead with 3/64" diameter hole, as before.

Position of Traverse on Loop:



Counts on Loop:

Extreme Right:	173, 183, 164, 166, 152, 158, 153, 173, 143, 169, 163, 167, 161, 177, 144
	½ min. counts, average 325 c/min.
Mid Right:	171, 142, 177, 145, 152, 154, 185, 171, 172, 156, 162, 156, 173, 173, 168
	½ min. counts, average 328 c/min.
Centre:	175, 168, 155, 168, 191, 163, 163, 168, 168, 152, 176, 144, 153, 185, 176
	½ min. counts, average 334 c/min.
Mid Left:	160, 180, 167, 170, 167, 167, 198, 169, 174, 128, 165, 154, 159, 180, 170
	½ min. counts, average 335 c/min.
Extreme Left:	186, 168, 159, 167, 155, 159, 158, 170, 167, 186, 172, 187, 160, 154, 173
	½ min. counts, average 336 c/min.

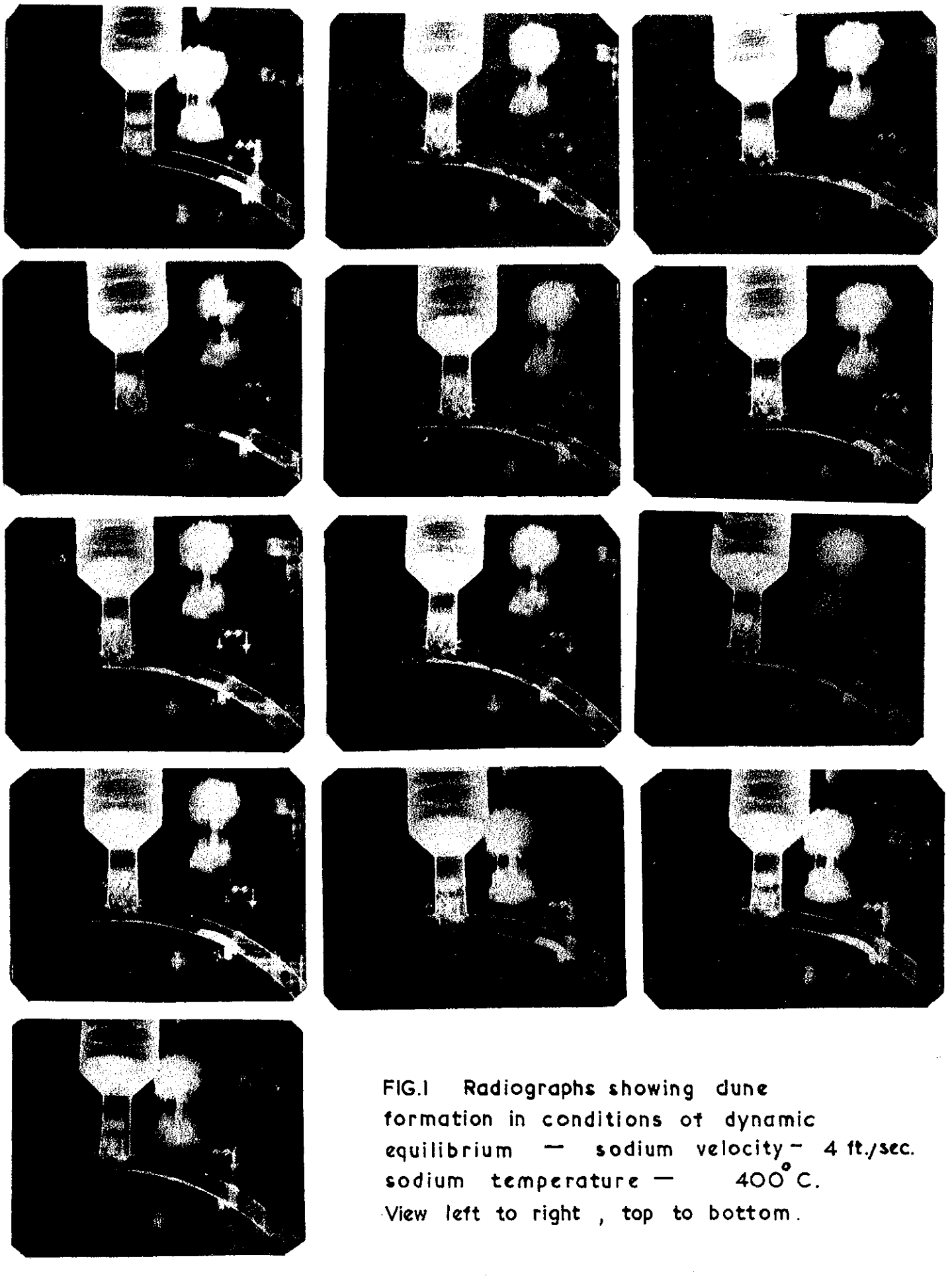


FIG.1 Radiographs showing dune formation in conditions of dynamic equilibrium — sodium velocity - 4 ft./sec. sodium temperature — 400° C. View left to right , top to bottom.

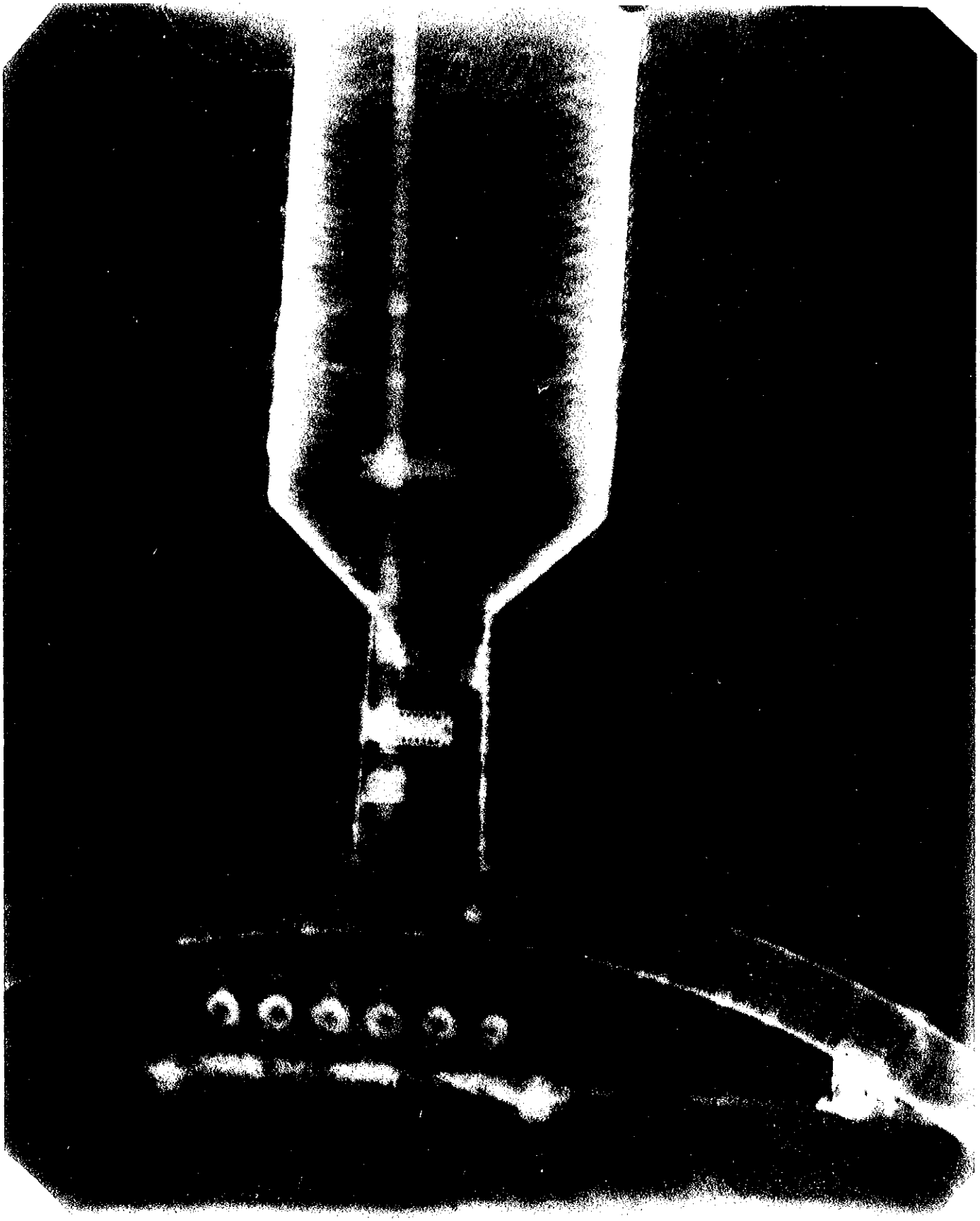
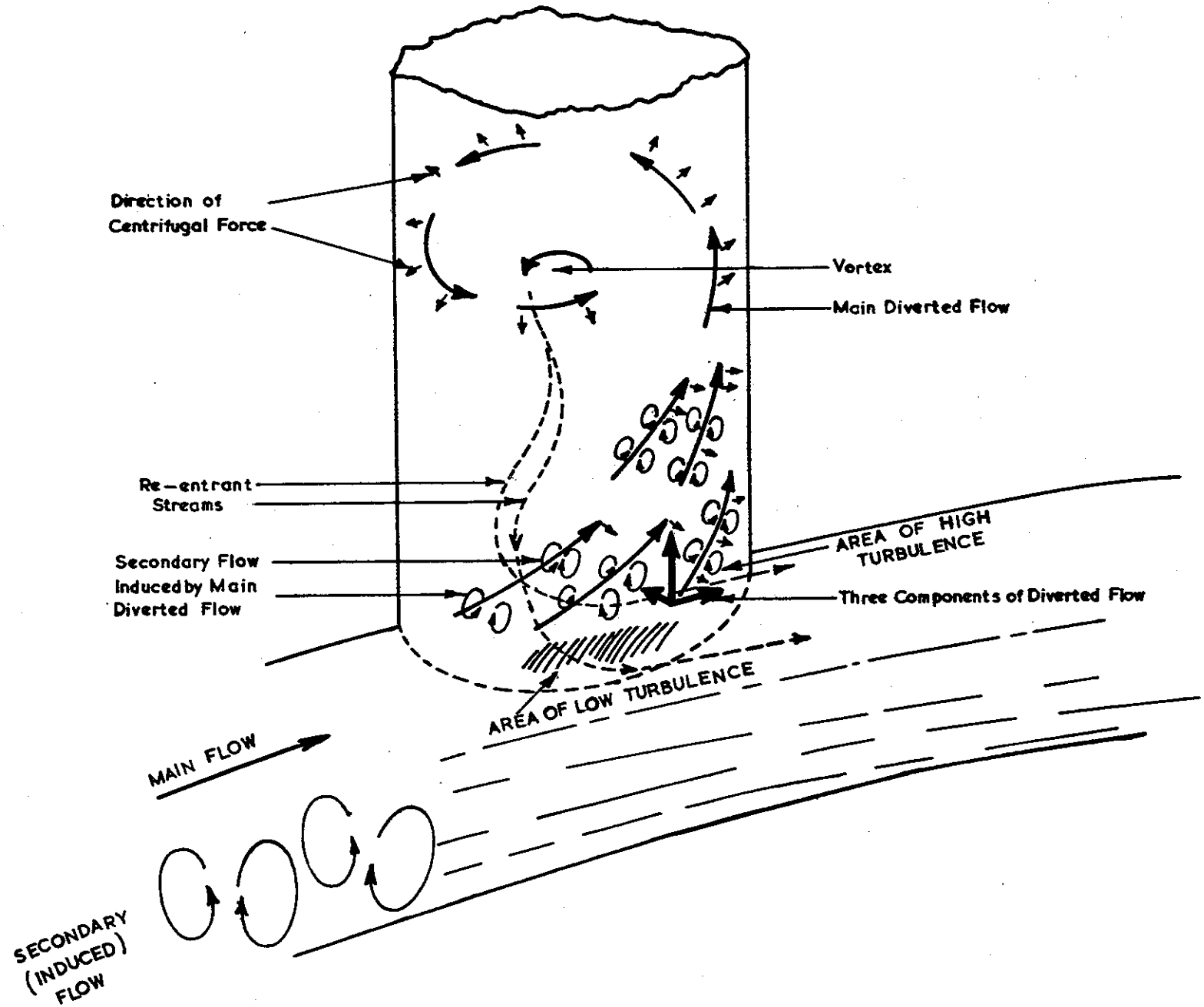


Fig. 2 Radiograph of vent tank tube showing spiral deposit


Direction of
Centrifugal Force
Vortex
Main Diverted Flow
Re-entrant
Streams
Secondary Flow
Induced by Main
Diverted Flow
AREA OF HIGH
TURBULENCE
Three Components of Diverted Flow
AREA OF LOW TURBULENCE
MAIN FLOW
SECONDARY
(INDUCED)
FLOW

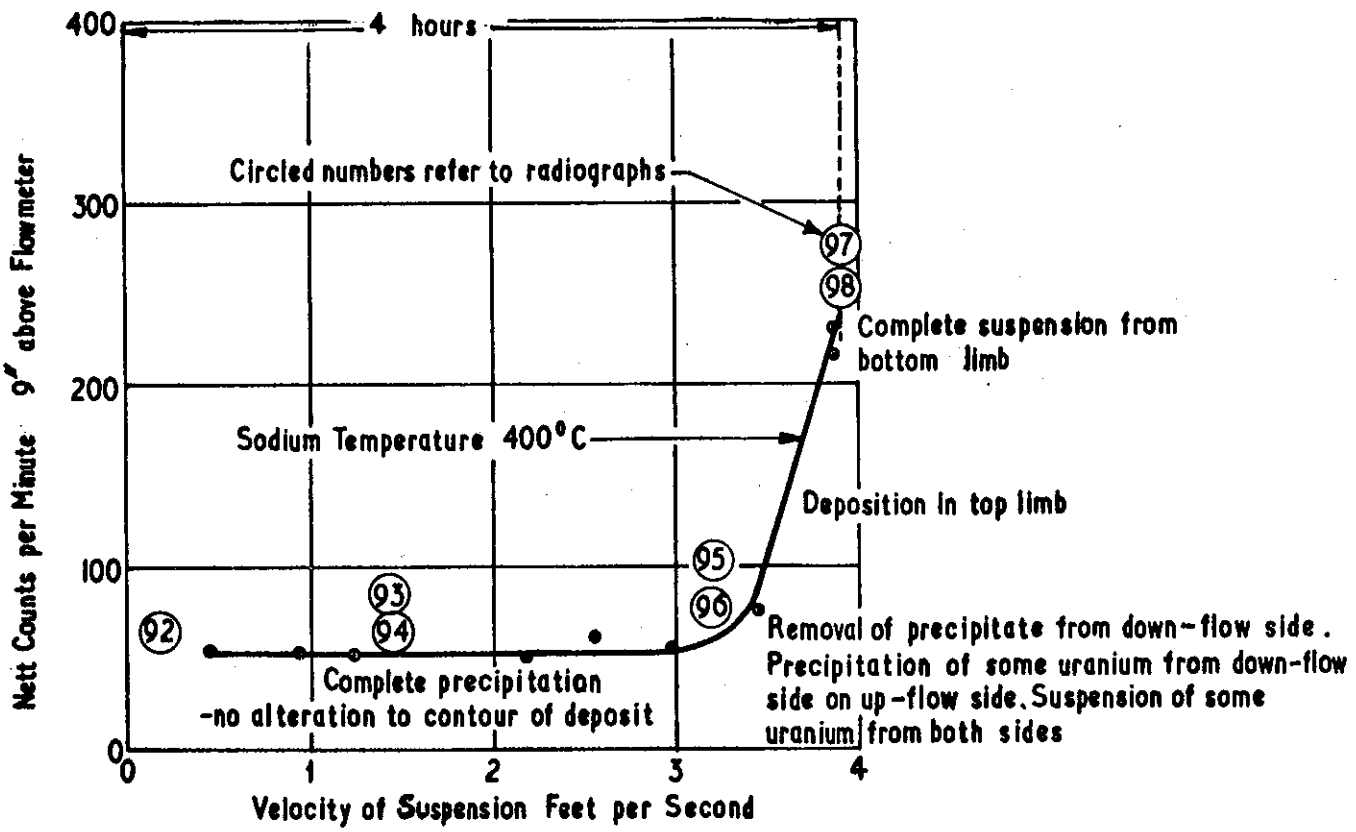
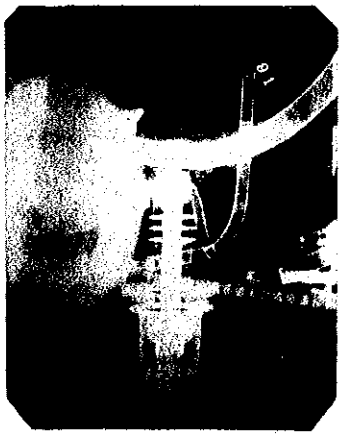
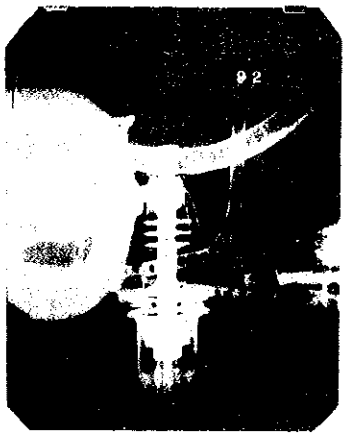


FIG. 4 COUNTS PER MINUTE vs VELOCITY OF SUSPENSION at 400°C to find Suspension Velocity from bottom limb of loop.



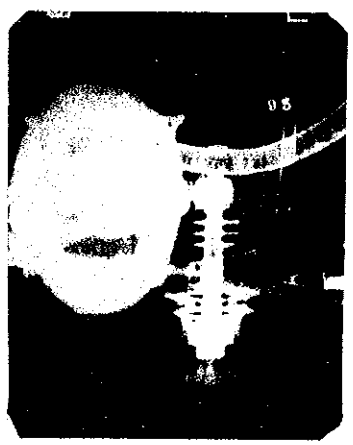
No. 91 - bottom, before precipitation



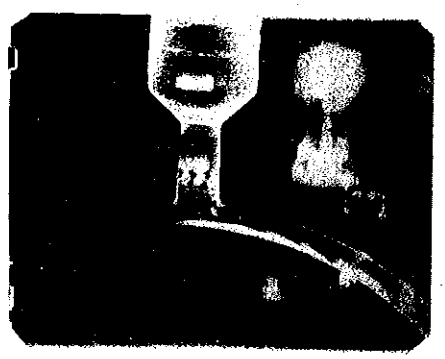
No. 92 - bottom

No. 93 - bottom

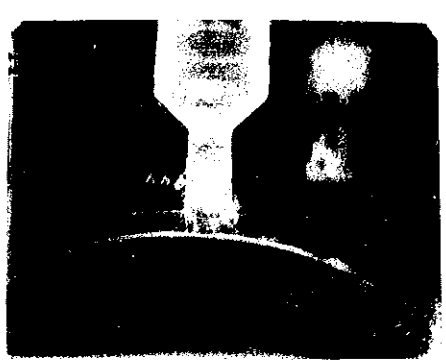
No. 94 - top



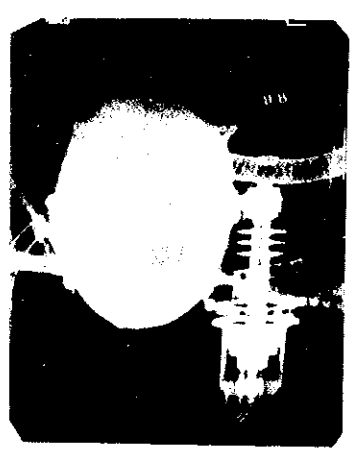
No. 95 - bottom



No. 96 - top



No. 97 - top



No. 98 - bottom

FIG. 5 Radiographs taken during suspension of powder from bottom limb — *see* FIG. 4.

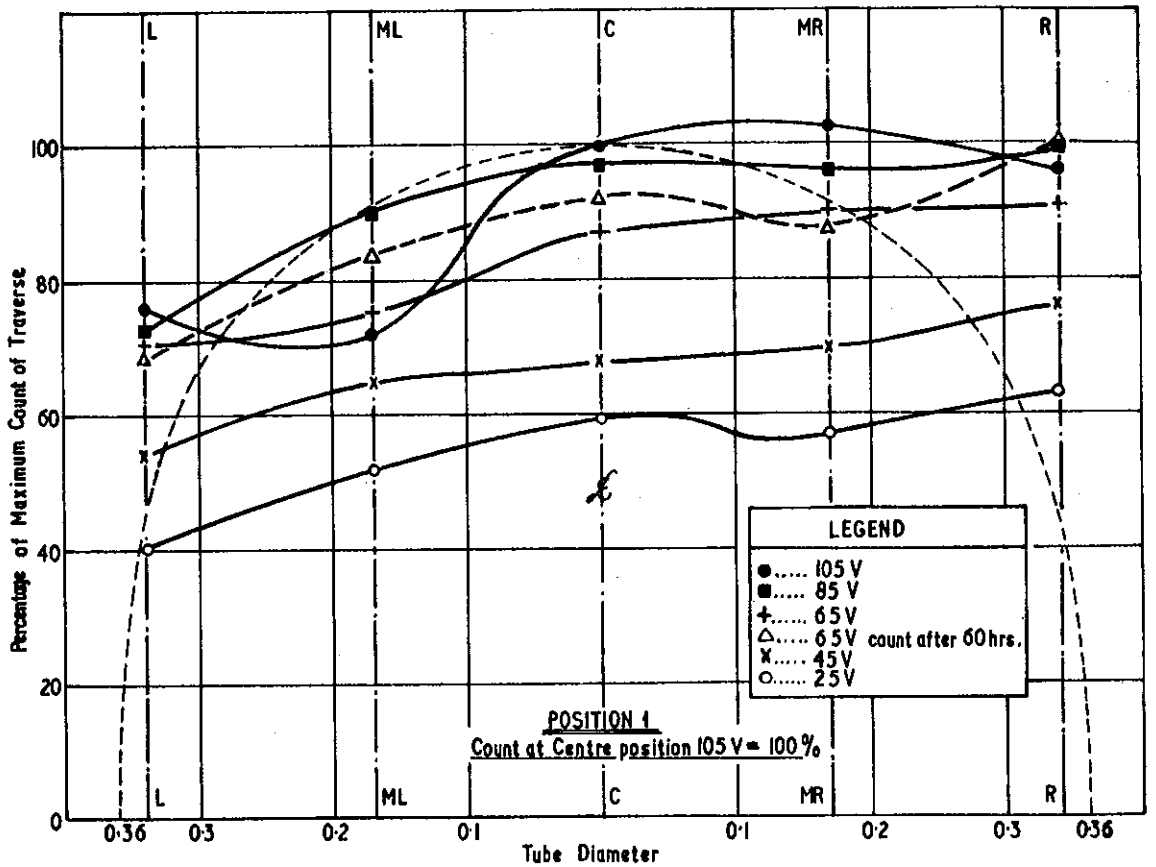


FIG. 7 RADIOMETRIC TRAVERSE OF POSITION 1

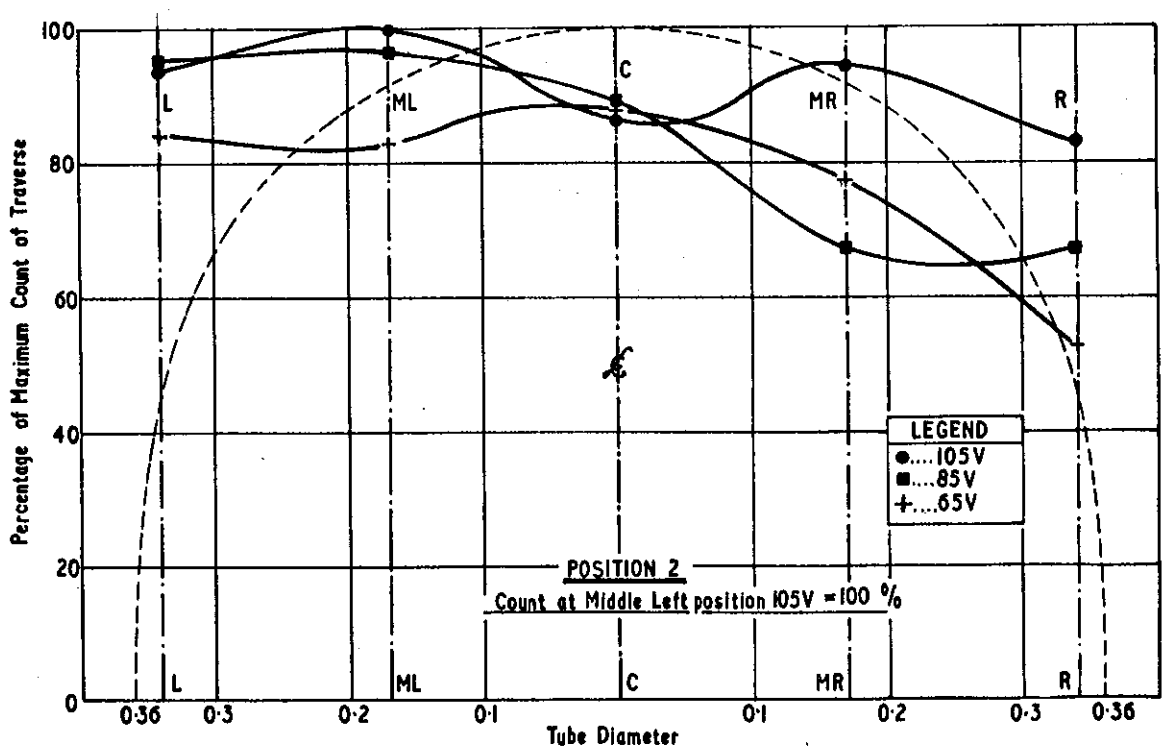


FIG. 8 RADIOMETRIC TRAVERSE OF POSITION 2

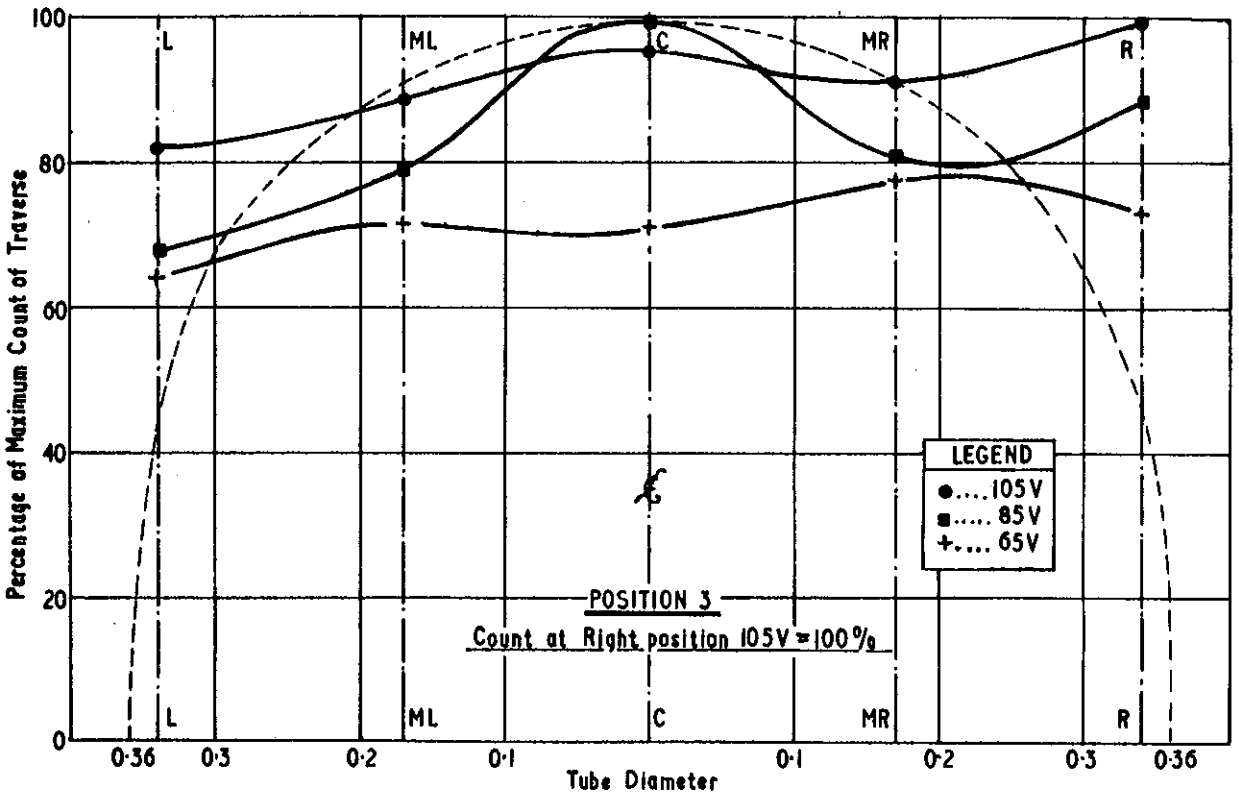


FIG. 9 RADIOMETRIC TRAVERSE OF POSITION 3

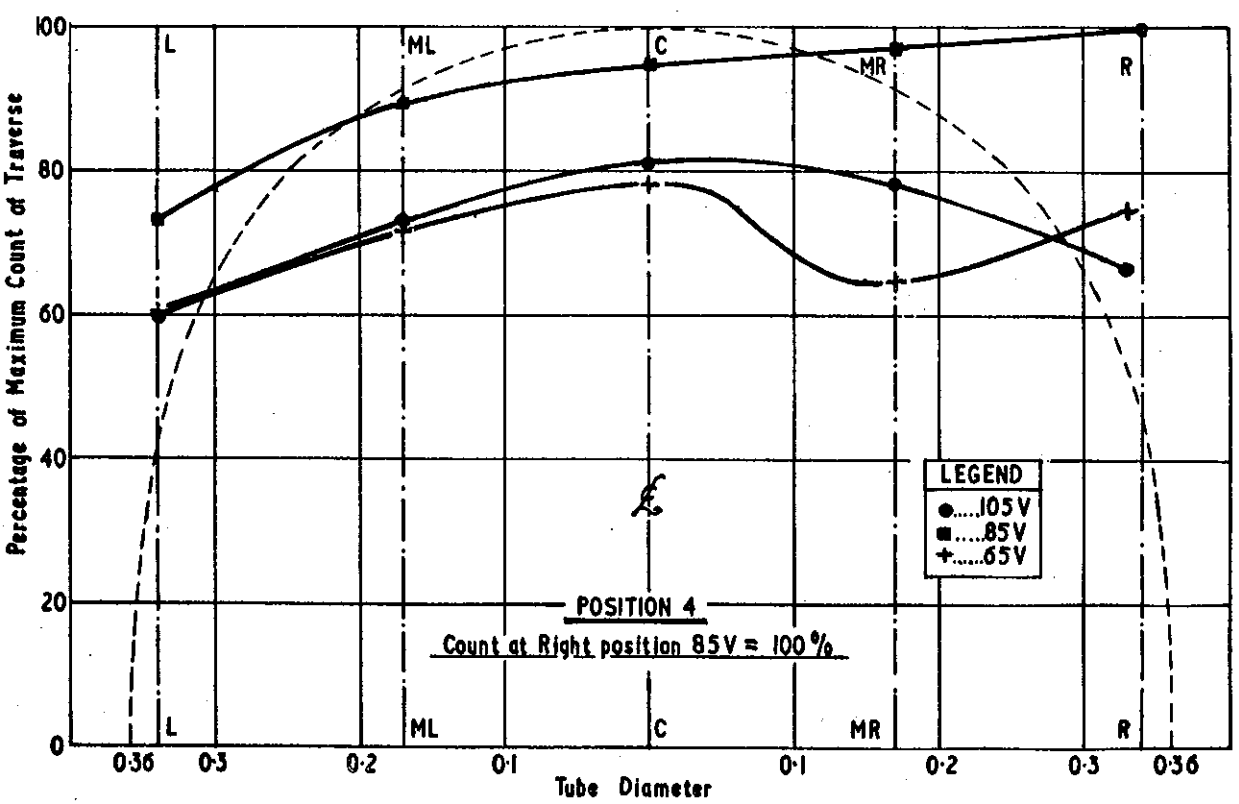


FIG. 10 RADIOMETRIC TRAVERSE OF POSITION 4

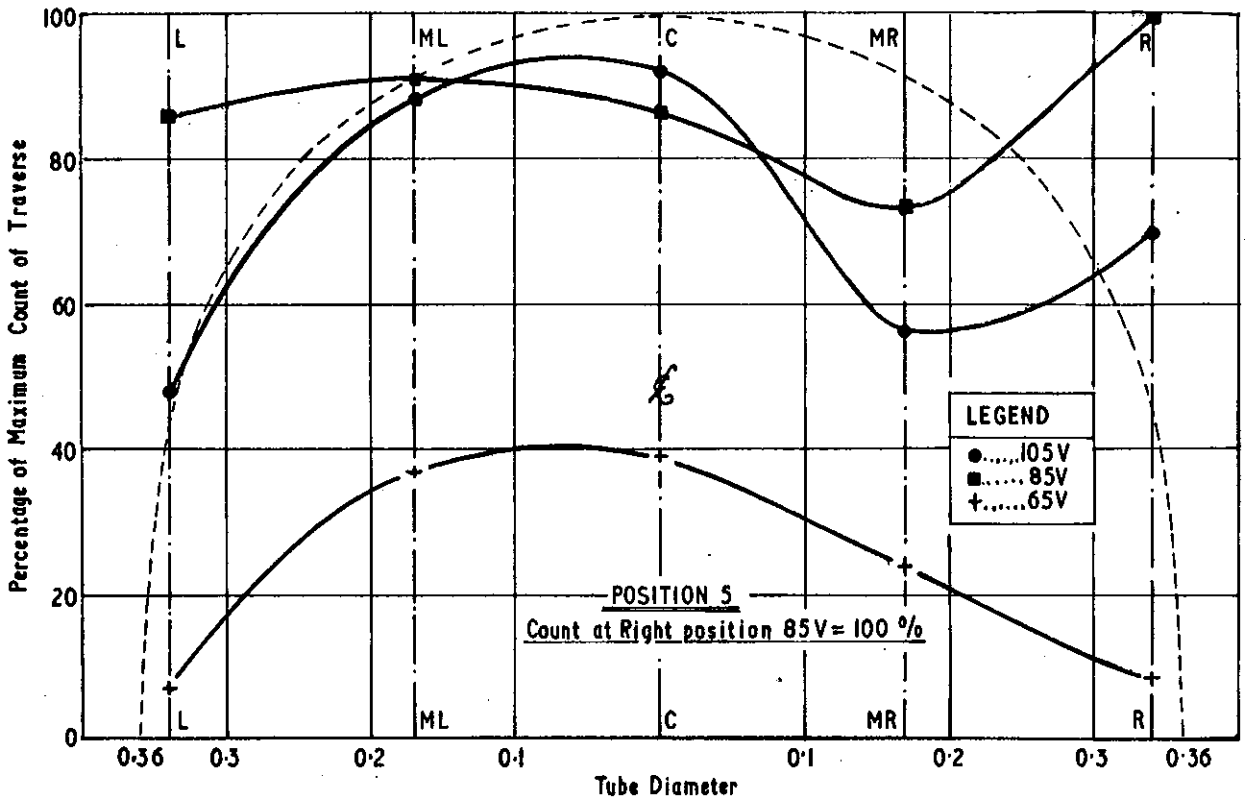


FIG. 11 RADIOMETRIC TRAVERSE OF POSITION 5

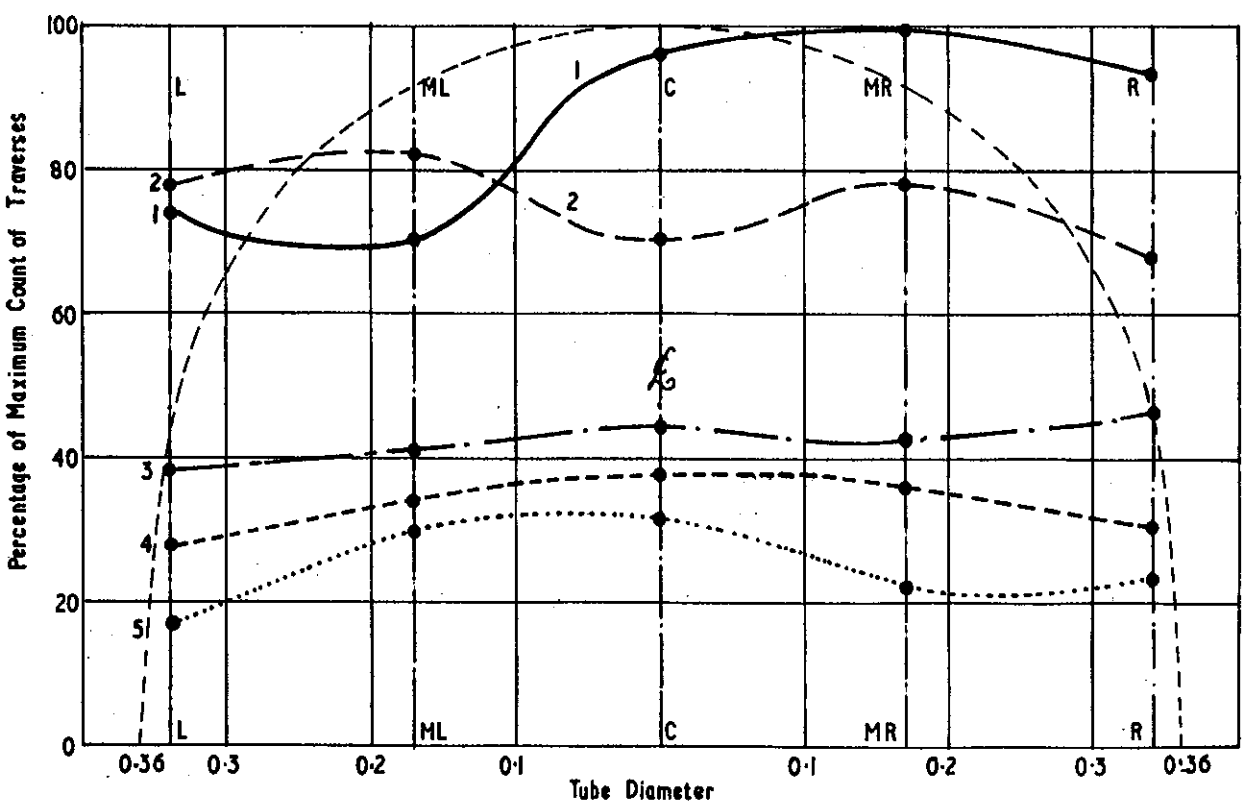


FIG. 12 RADIOMETRIC TRAVERSES AT 105 VOLTS PUMP SETTING

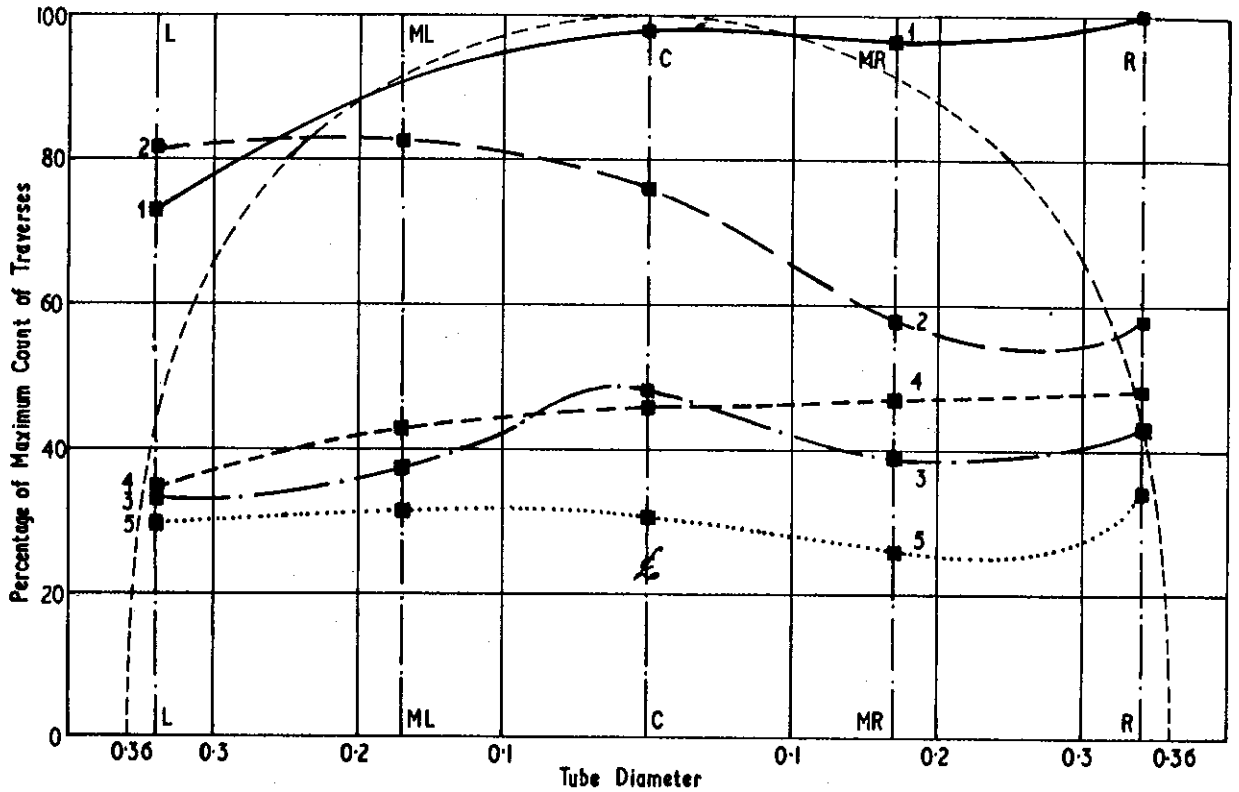


FIG. 13 RADIOMETRIC TRAVERSES AT 85 VOLTS PUMP SETTING

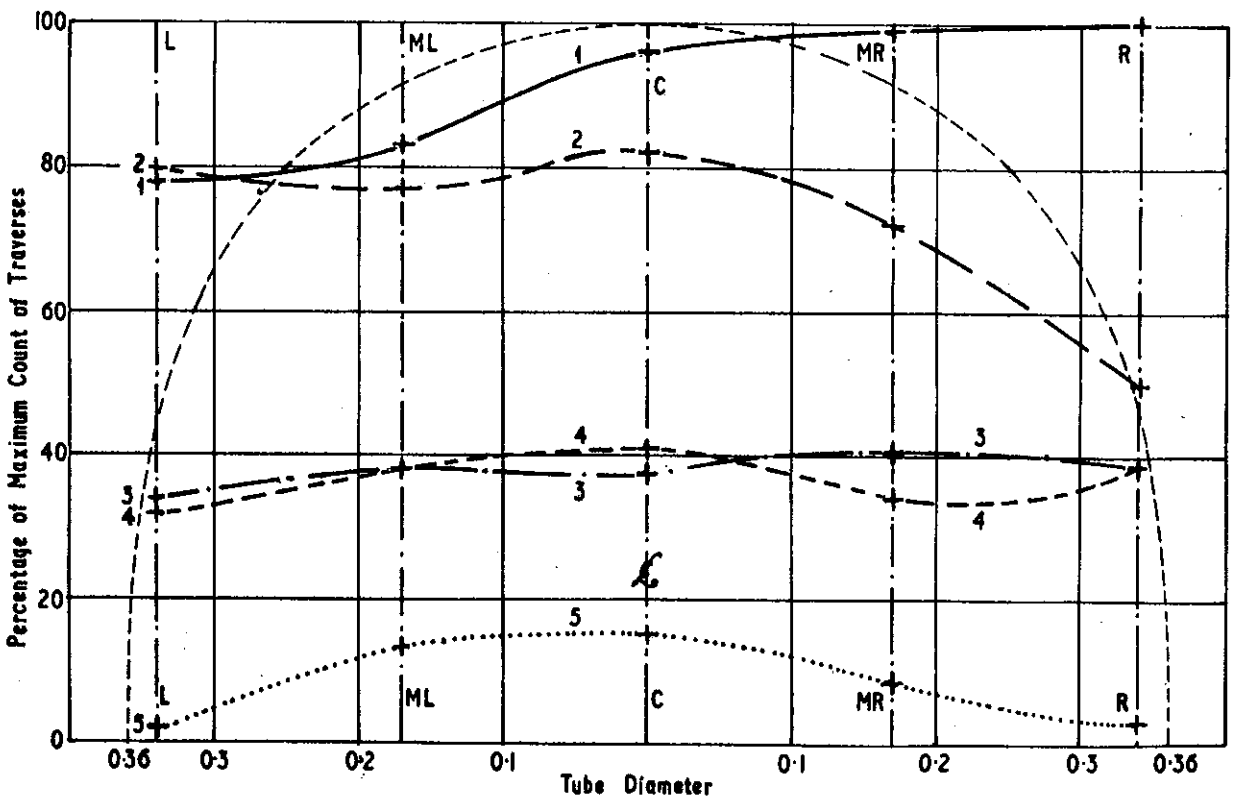


FIG. 14 RADIOMETRIC TRAVERSES AT 65 VOLTS PUMP SETTING

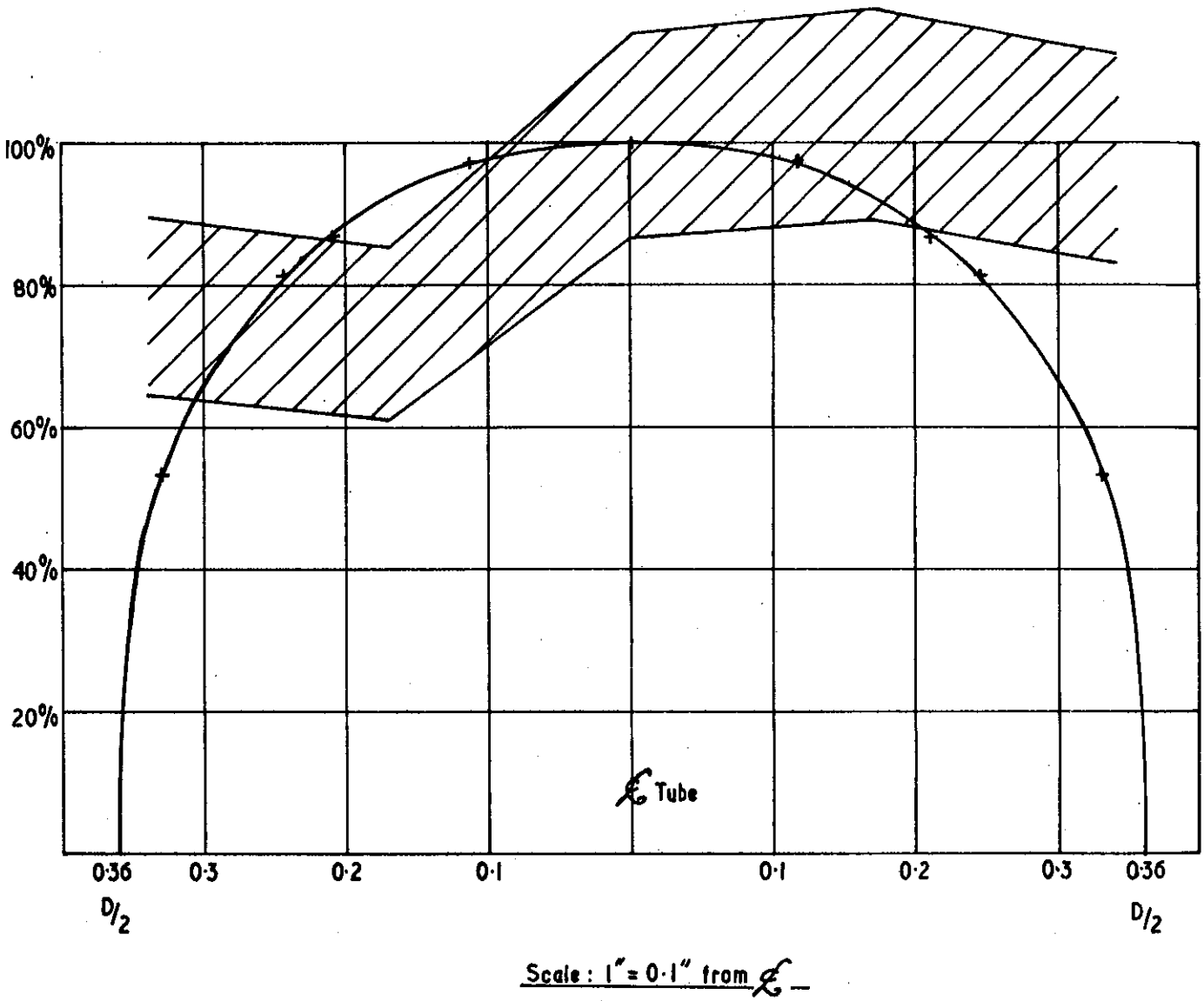


FIG.15 COUNTS EXPRESSED AS PERCENTAGE OF CENTRE COUNT SUPERIMPOSED ON IDEAL COUNT CURVE

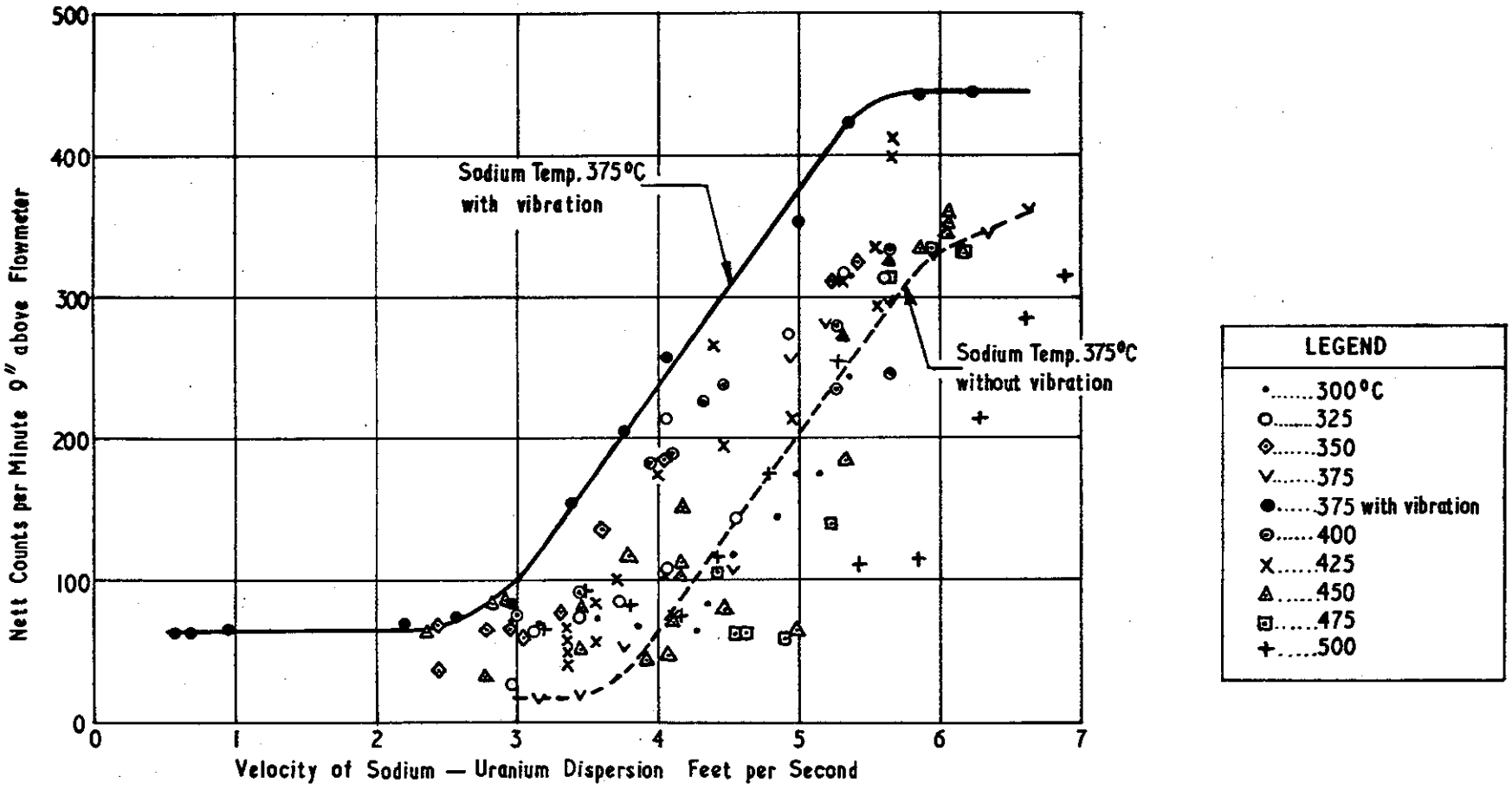
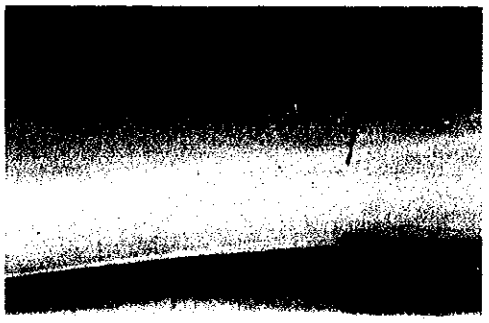
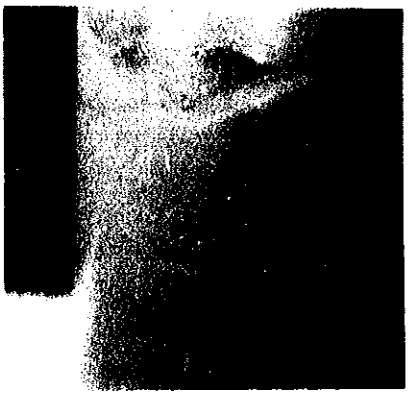


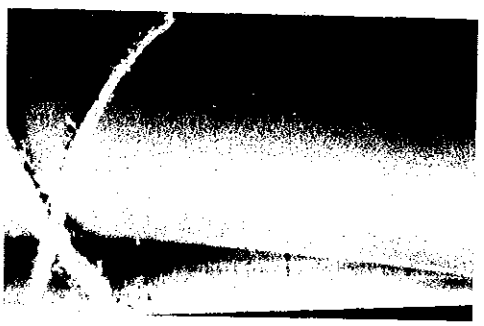
FIG. 16 COUNTS PER MINUTE vs VELOCITY OF DISPERSION AT SODIUM TEMPERATURES SPECIFIED



No.1



No.2



No.3

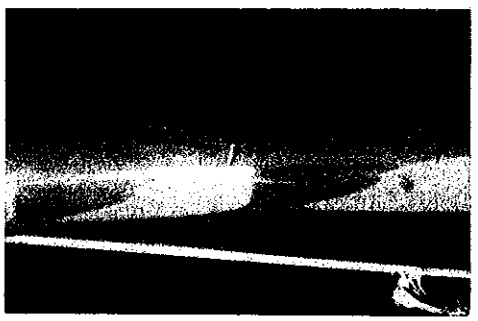
No.4

No.5

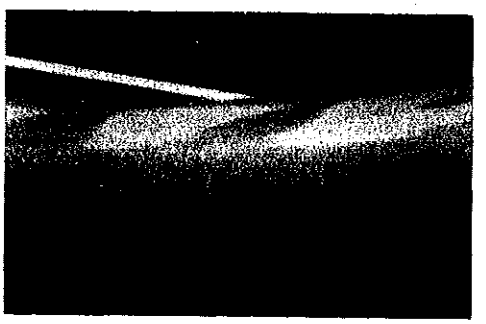
No.6

No.7

FIG.17 Photographs taken of tungsten - water analogue loop.

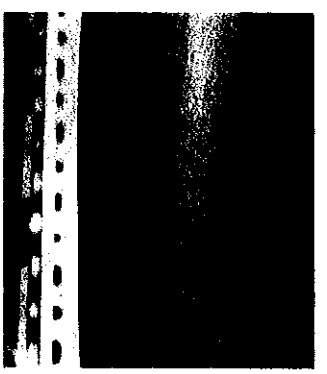


No. 8



No. 9

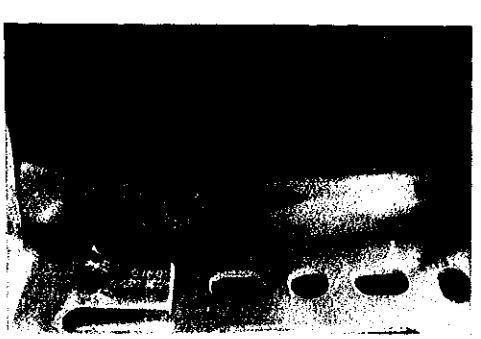
No. 10



No. 11

No. 12

No. 13



No. 14

FIG. 18 Photographs taken of tungsten - water analogue loop.

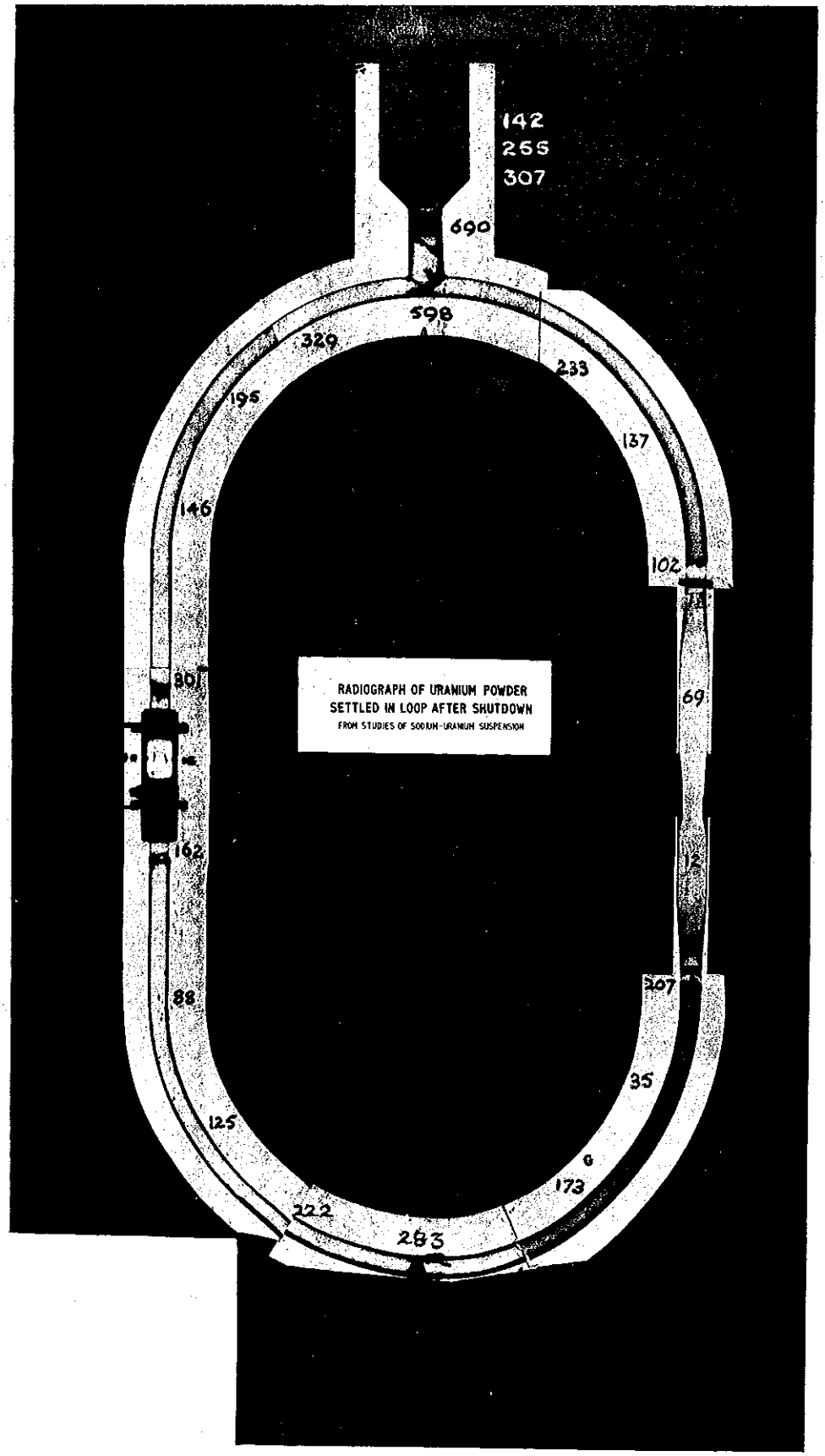


FIG. 19 Radiograph of stripped loop after shutdown.
Radiometric counts for positions immediately above tube centre are shown.
Flow direction is UP in left hand limb.

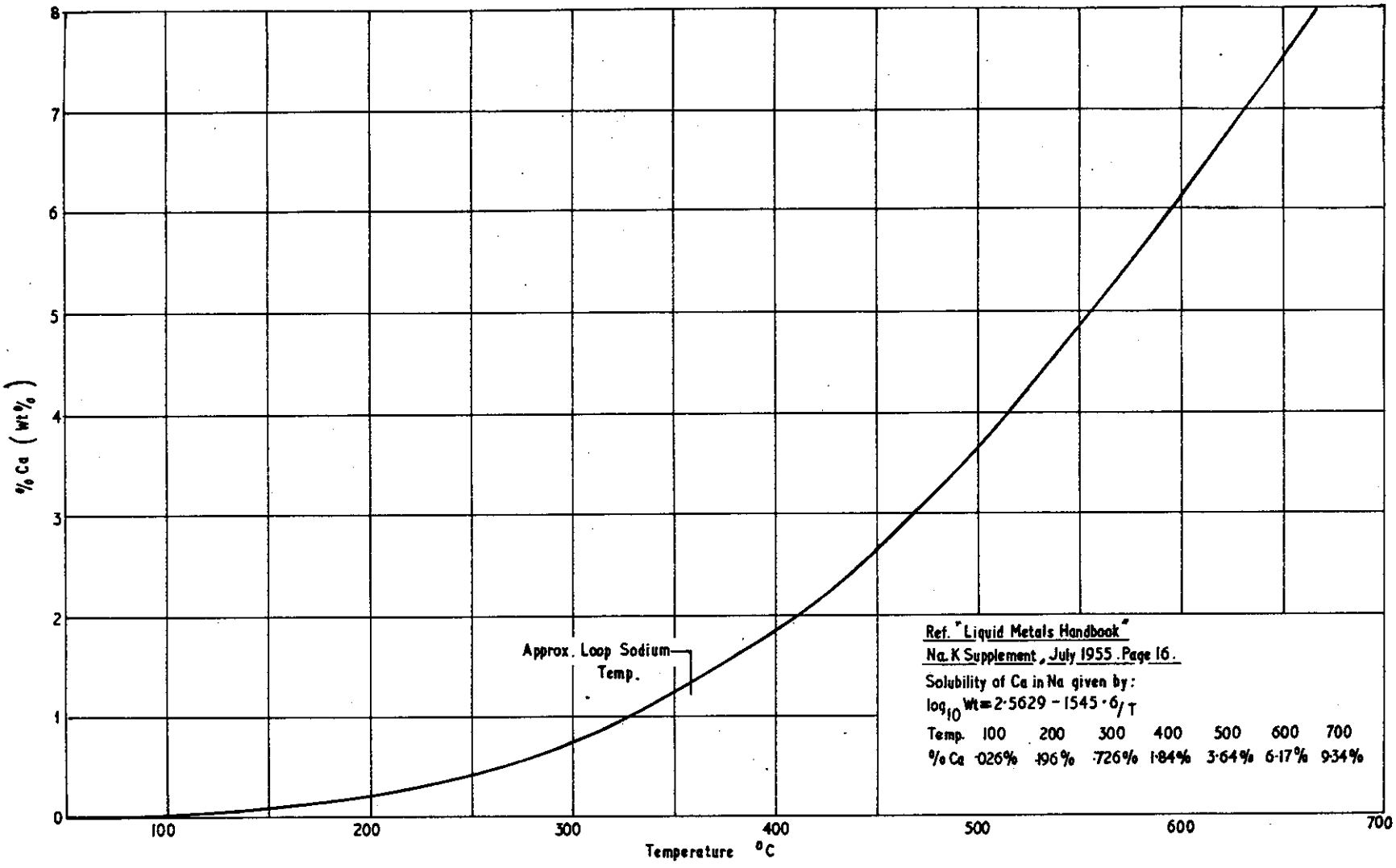


FIG. 20 SOLUBILITY OF CALCIUM IN SODIUM

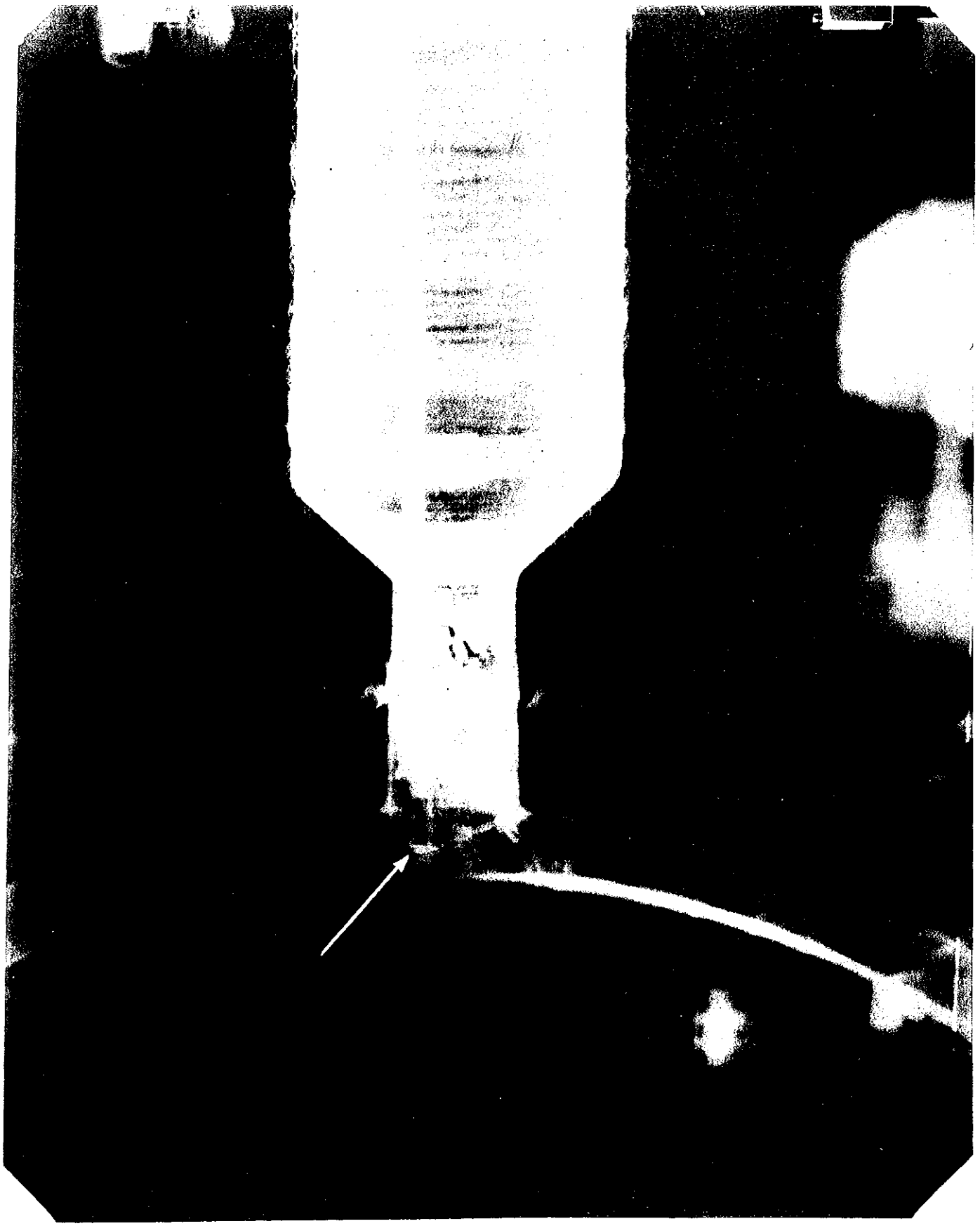
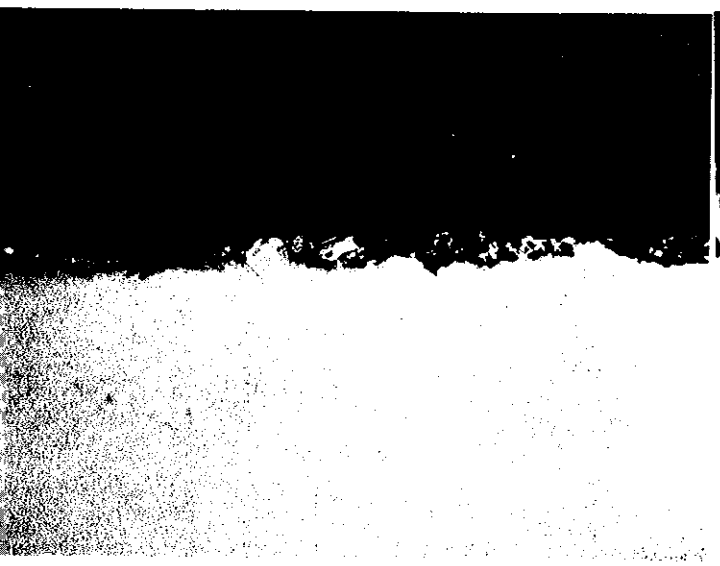


Fig. 21 Radiograph showing deposition of uranium powder in low velocity areas below the beryllium specimen .



g. 22 Surface of beryllium specimen
owing some evidence of a surface phase.
x 250).

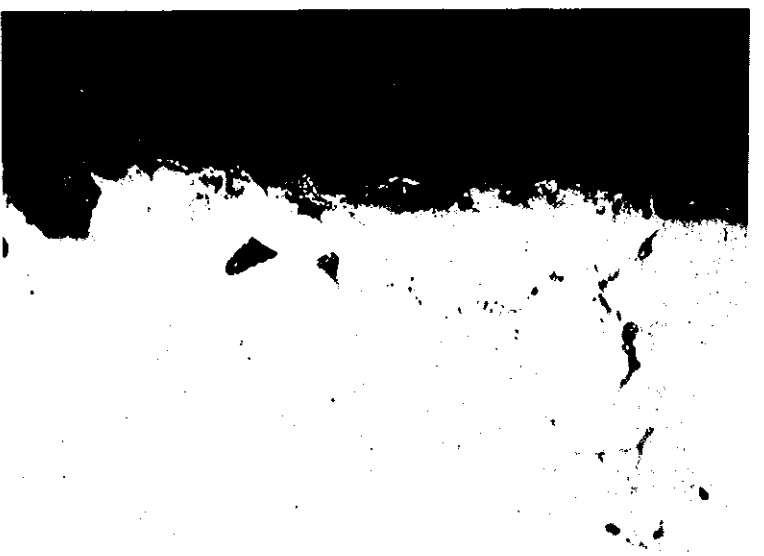


Fig. 23 Surface of beryllium specimen showing some evidence of a surface phase and of possible penetration into surface cracks. (x 250).

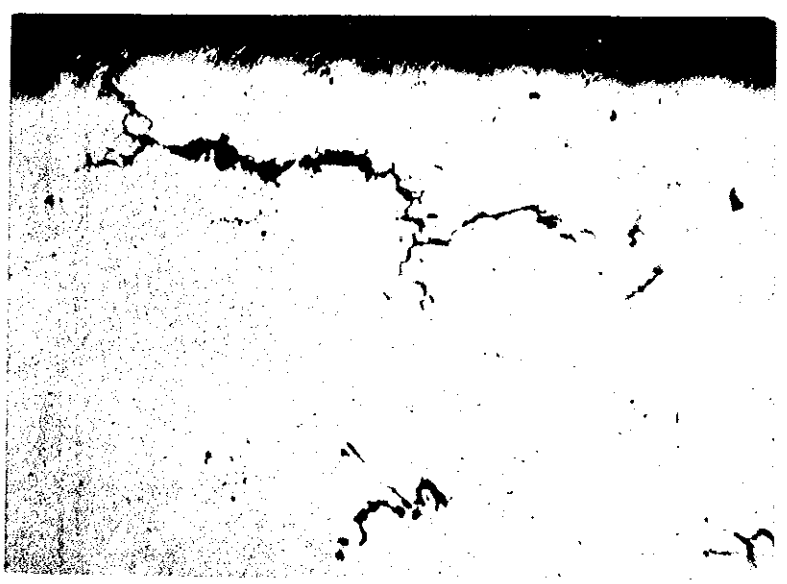


Fig. 24 Surface of beryllium specimen showing some evidence of possible penetration into surface cracks. (x 250).

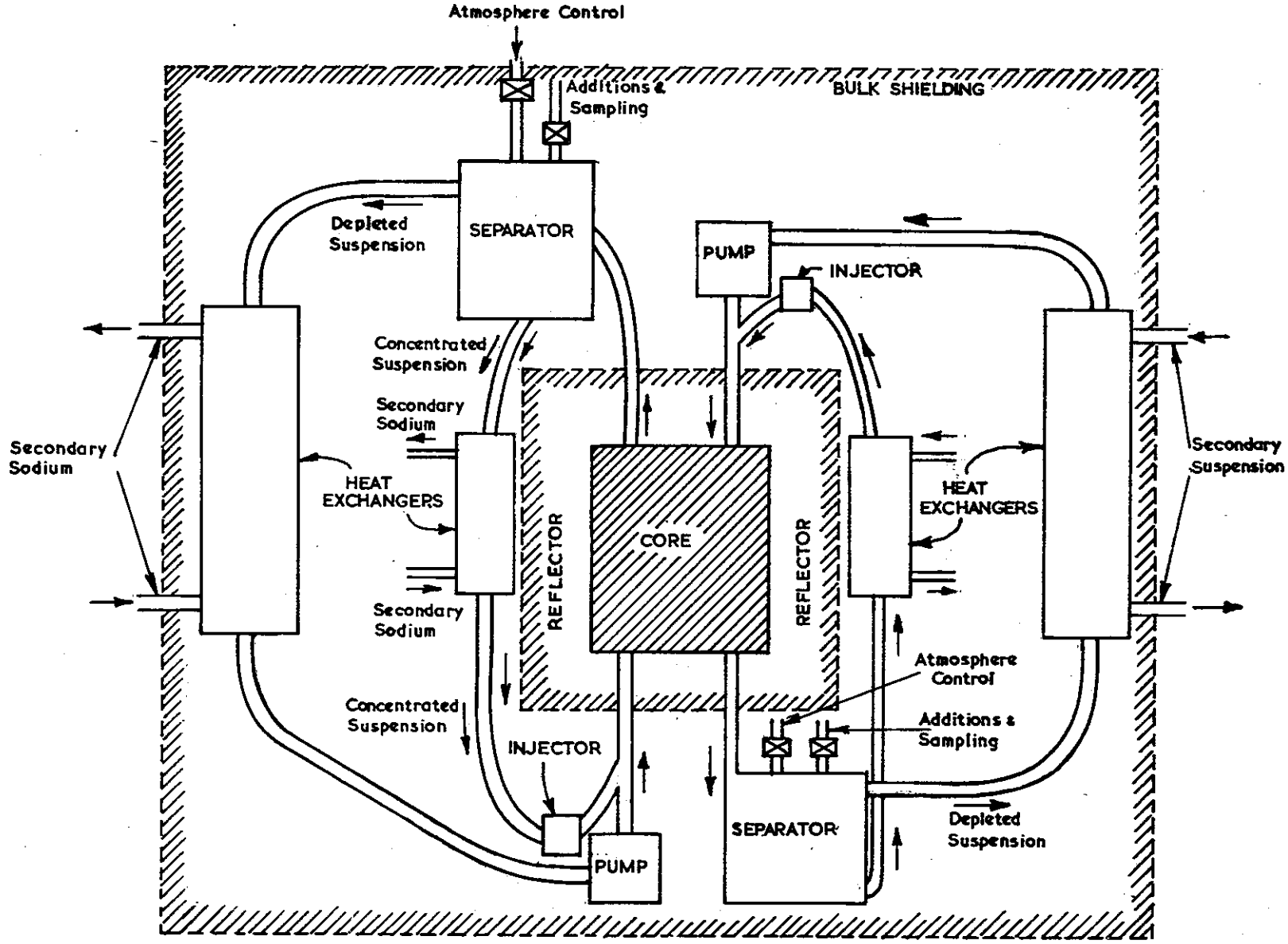


FIG.25 SCHEMATIC ARRANGEMENT OF VERTICAL UP—AND—DOWN FLOW LOOPS IN SUGGESTED MULTI—CHANNEL SUSPENSION—FUELLED REACTOR

APPENDIX 1

DETERMINATION OF BULK FLOW VELOCITY FROM FLOWMETER E.M.F.

LIST OF FIGURES

The bulk flow velocity of the suspension was determined by use of the formula and correction factors given in the section on flow measurement in the Liquid Metals Handbook, Sodium–NaK Supplement. On page 343 the formula for the output e.m.f. of the flowmeter is given as:–

$$E = 7.74\ B\ v\ d K_1 K_2 K_3\ 10^{-4}\ mV$$

where B is in gauss measured at 77°F.
v is the average velocity in feet per second
and d is the inside diameter of the pipe in inches.

The data required to evaluate this formula are listed below:–

(1) E.m.f. output of the flowmeter at various electromagnetic pump voltage settings as a function of sodium temperature. The required values were found by experiment and are shown in Figure 1.

(2) Zero error of the flowmeter. This error was indicated by Figure 1 and the zero errors are shown in Figure 2 as a function of sodium temperature.

NOTE: Radiographic examination indicated that the zero error of the flowmeter was due to excessive braze metal in the voltage tapping connections, generating an independent e.m.f.

(3) Zero corrected e.m.f. output of flowmeter at various electromagnetic pump voltage settings as a function of sodium temperature. (See Figure 3).

(4) Variation of e.m.f. output of flowmeter with sodium temperature at constant pump voltages. (See Figure 4).

(5) Data required to evaluate correction factors K_1, K_2, K_3, as follows:–

APPENDIX 1 (continued)

(i) Physical dimensions of loop tube, flowmeter venturi, flowmeter magnet base, and poles.

(ii) Electrical resistance of sodium and stainless steel as a function of temperature.

(iii) Flowmeter magnet gap flux as a function of pole temperature. The variation of the gap flux with temperature was measured with a Thomson Houston type G1 gaussmeter. The conditions under which the magnet was operated in the loop were reproduced while taking the experimental readings, i.e. the magnet base was air cooled to room temperature while the magnet poles were indirectly heated by radiant heat from a gas flame. The probe of the gaussmeter was kept at room temperature. The results are shown in Figure 5.

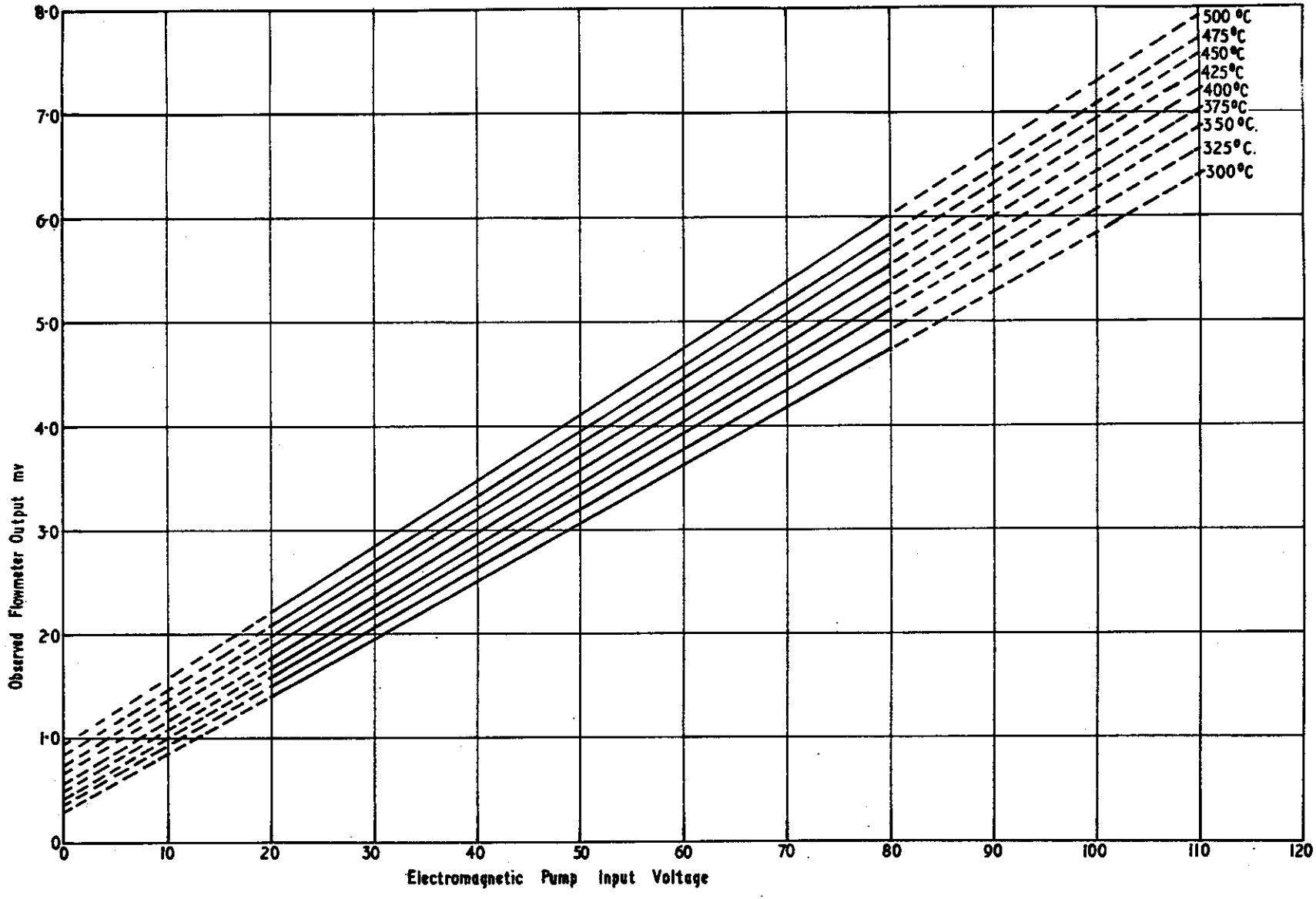
(6) The value of the flowmeter correction factor equals $K_1 \cdot K_2 \cdot K_3$. This value is shown in Figure 6 as a function of sodium temperature.

(7) Flowmeter magnet flux decay as a function of time and temperature.

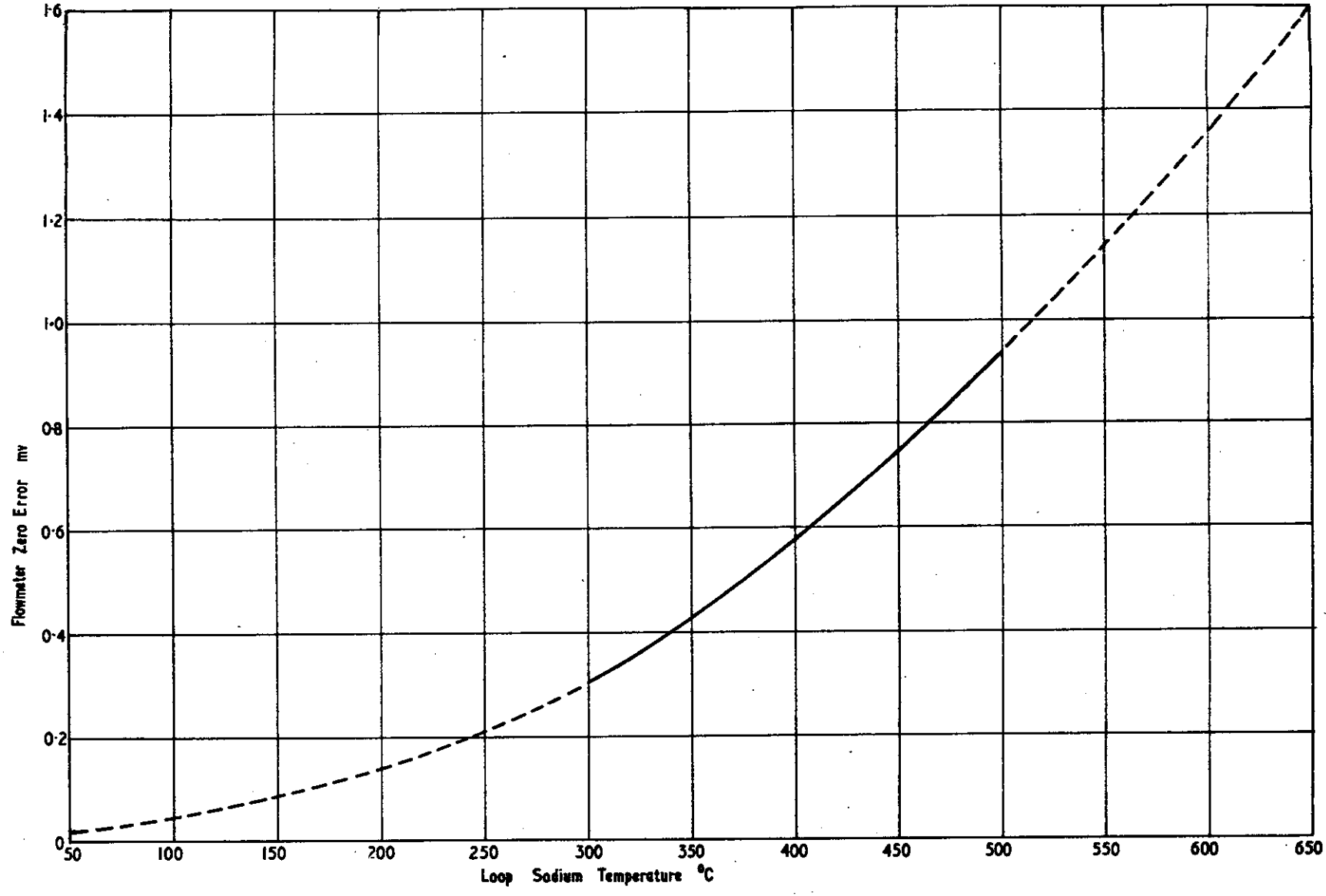
During the course of the experiment it was found that the flowmeter output e.m.f. slowly decreased at any given electromagnetic pump voltage due to the instability of the magnet flux. In Figure 7 the decay in the value of the flowmeter magnet flux is plotted as a function of time and temperature at constant pump voltage. The electromagnetic pump voltage of 30 volts was selected as little uranium would be suspended at the corresponding sodium velocity (2.7 feet per second) and the e.m.f. measured would be comparable without a correction factor for the increased power known to be required to pump the Na/U dispersion.

Use of graphs for velocity determinations

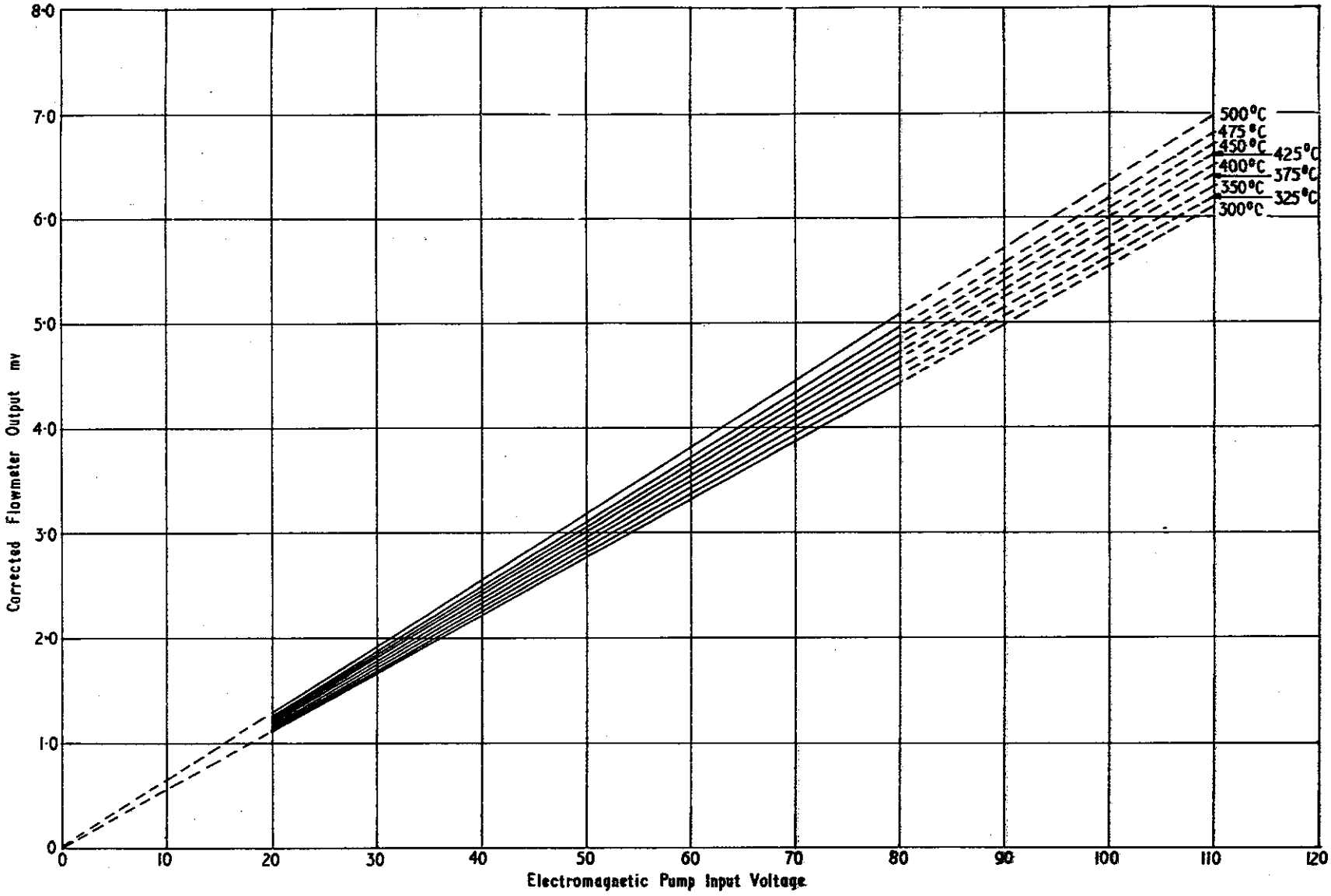
Figure 8 shows the sodium velocity at sodium temperatures between 300°C and 625°C based on the corrected output of the flowmeter. An experimental flowmeter reading is corrected by the use of Figure 2 and the velocity determined from Figure 8. Any pump voltage setting is converted to equivalent velocity by the use of Figure 3 and Figure 8.



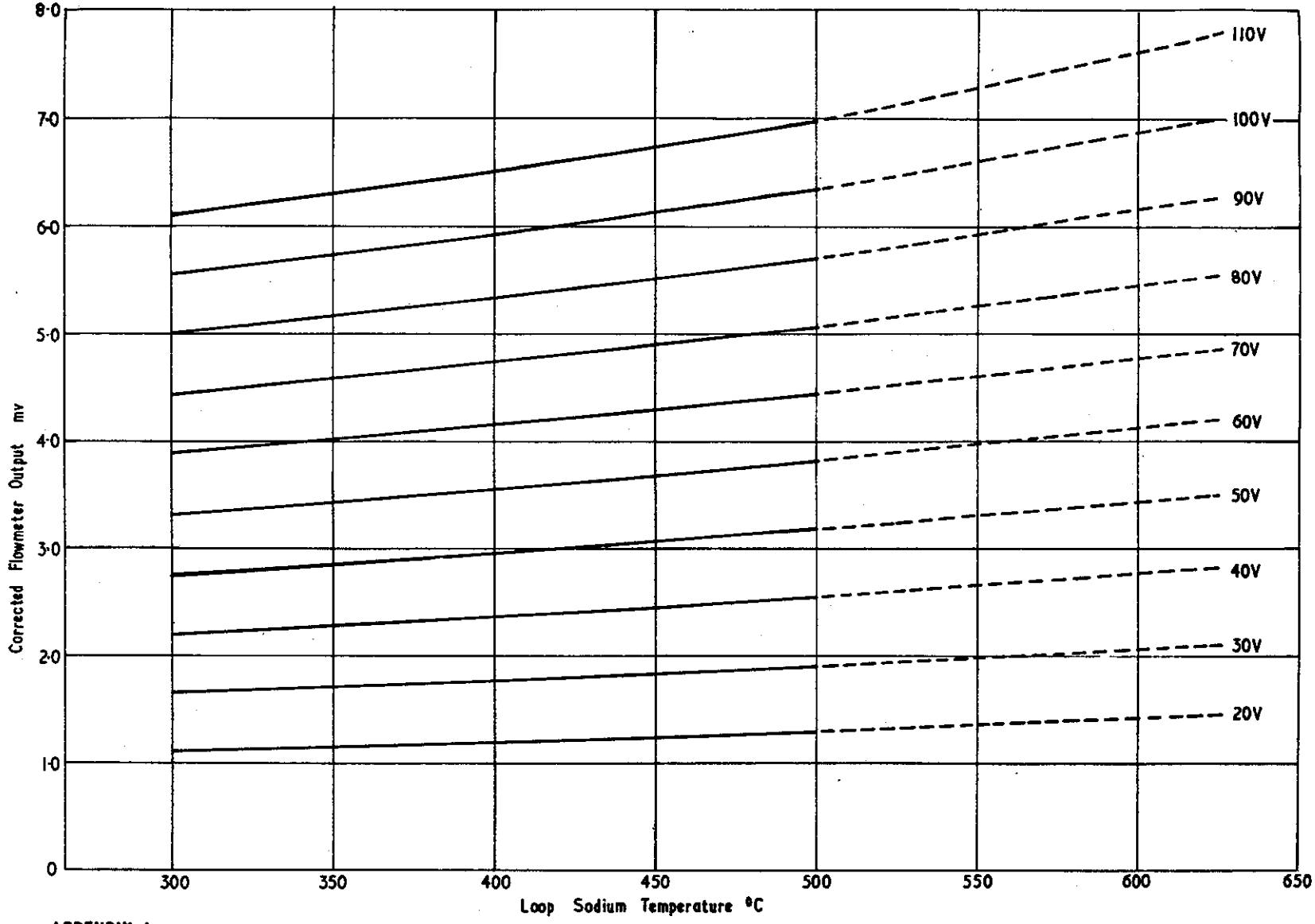
APPENDIX I. FIG. 1 OBSERVED FLOWMETER OUTPUT MV v EM. PUMP INPUT VOLTAGE



APPENDIX 1. FIG. 2 ZERO ERROR OF FLOWMETER MV v LOOP SODIUM TEMPERATURE °C

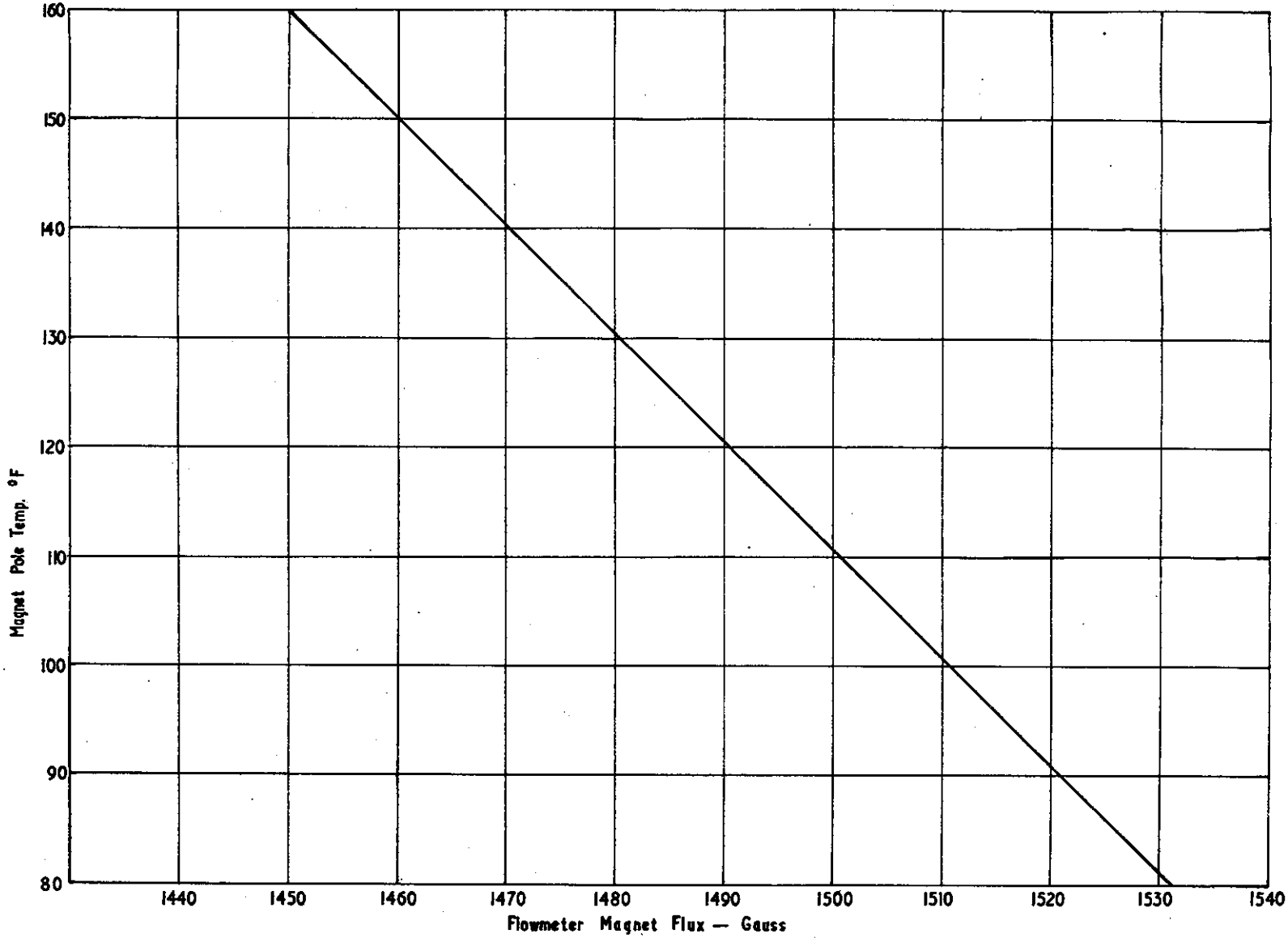


APPENDIX 1. FIG.3 CORRECTED FLOWMETER OUTPUT MV v EM. PUMP INPUT VOLTAGE

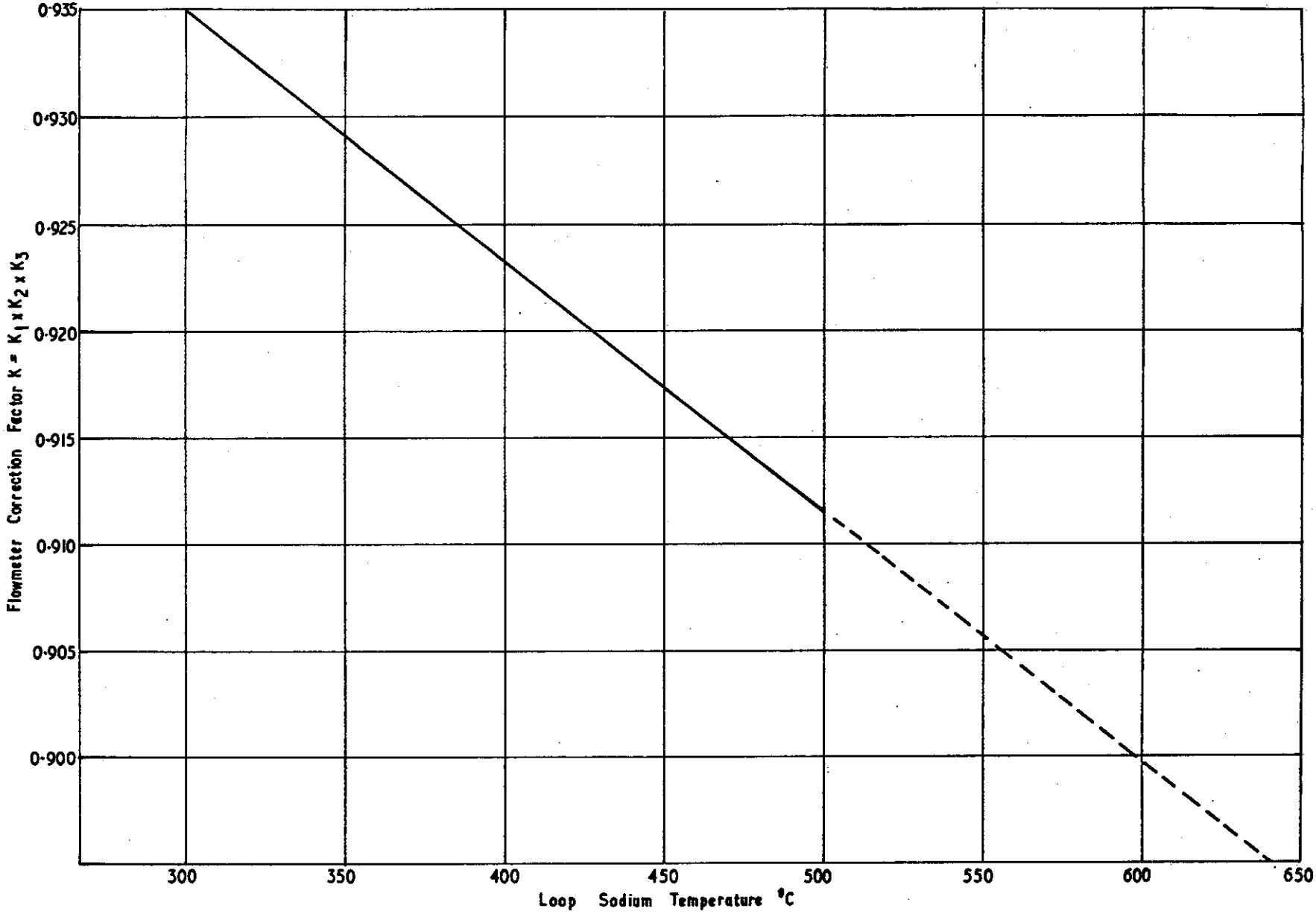


APPENDIX 1.

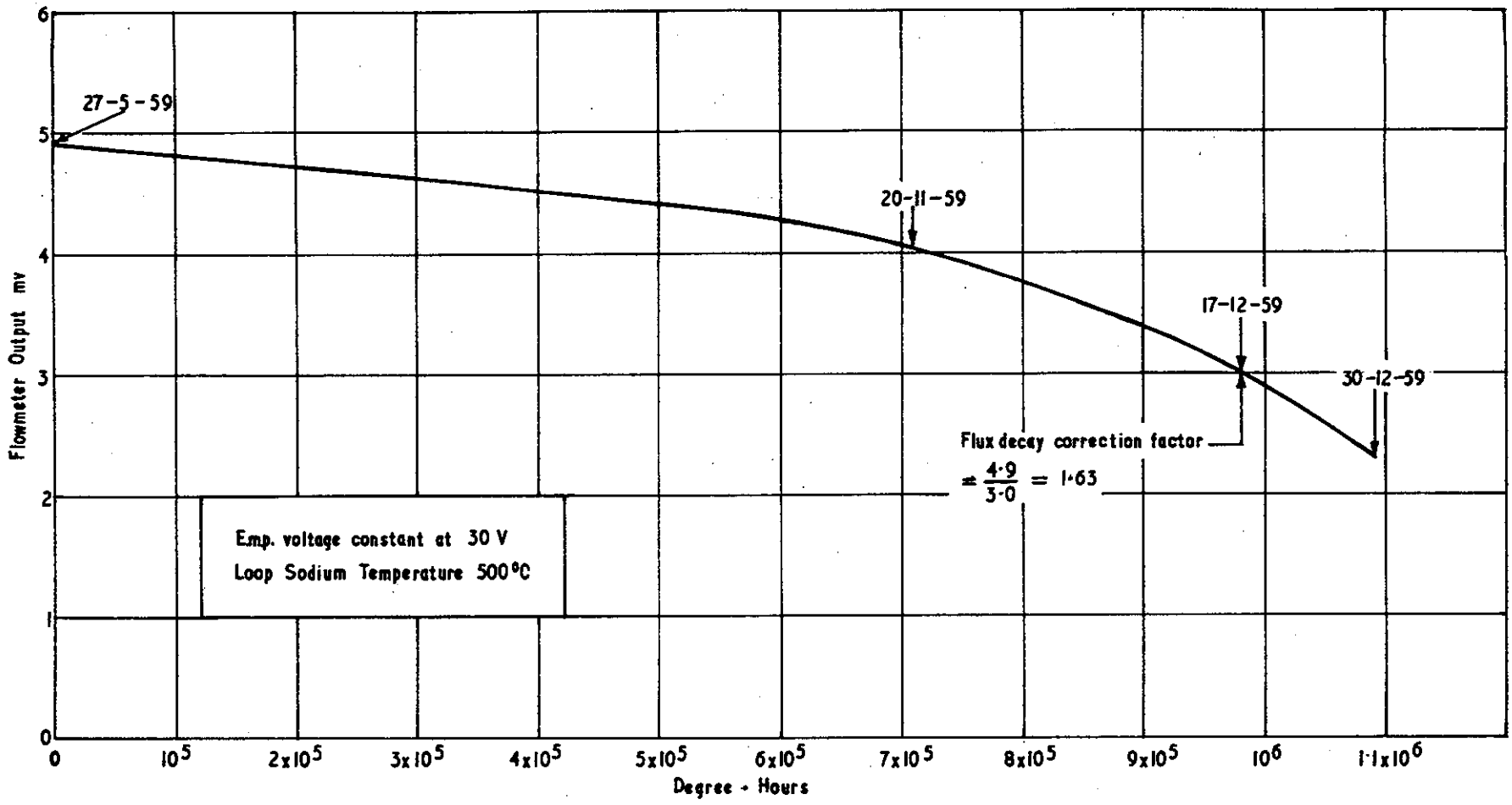
FIG.4 CORRECTED FLOWMETER OUTPUT MV v LOOP SODIUM TEMPERATURE AT 20,30,40,50,60,70,80,90,100,110 VOLTS E.M.P. INPUT



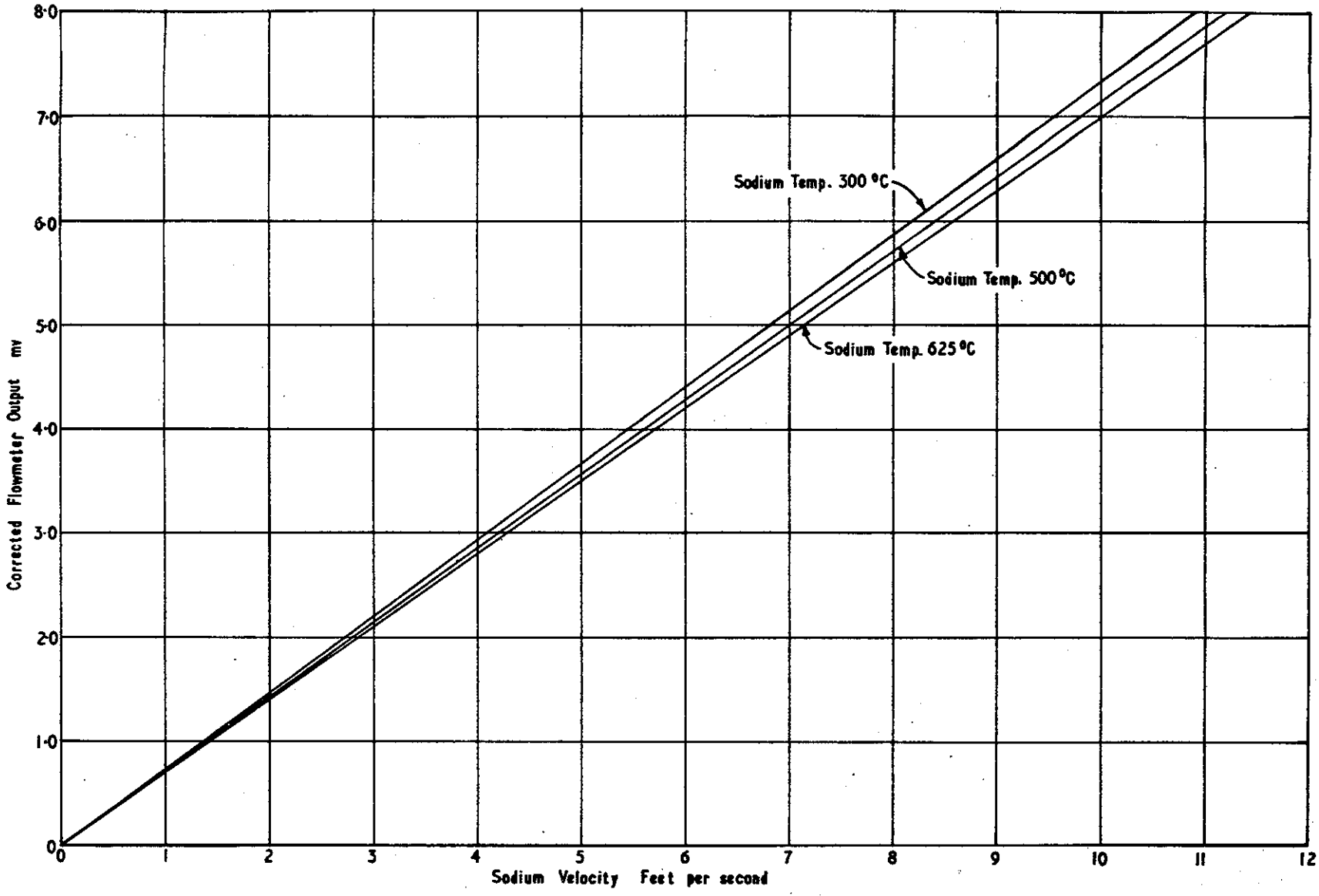
APPENDIX I. FIG. 5 MAGNET POLE TEMPERATURE °F v FLOWMETER MAGNET FLUX



APPENDIX 1. FIG. 6 FLOWMETER CORRECTION FACTOR K v LOOP SODIUM TEMPERATURE



APPENDIX I. FIG. 7 FLOWMETER OUTPUT MV v DEGREE-HOURS OF LOOP OPERATION



APPENDIX I. FIG. 8 CORRECTED FLOWMETER OUTPUT v SODIUM VELOCITY FEET PER SECOND

APPENDIX 2

RADIOGRAPHIC TECHNIQUES

The choice of a technique for the radiographic survey of the experimental uranium/sodium suspension loop was influenced by the materials used in the loop, the general construction of the loop, and the features which were required to be demonstrated by radiography.

The penetration of the comparatively high density walls (stainless steel) of the loop and the recording of a lighter component (sodium) necessitated a low contrast technique. This was achieved by the use of high kilo voltages and short exposure times in conjunction with a medium contrast film making use of a fine grain while retaining some degree of film speed. With the use of higher kilo-voltages than is necessary for adequate penetration of the object, there is less selective absorption as the penetration power increases. Thus the difference in intensity between sections of the emergent beam corresponding to thin and thick parts of the object is also lessened – the developed radiograph consequently has soft gradations or low contrast.

Exposure times were reduced to the lowest practical limits (by increasing x-ray output) to reduce the effects of film movement caused by the considerable vibration of the loop and also the effect of the rapid movement of the suspension within the loop. The use of metal filters at the tube head was thus precluded because of increased exposure times and definition was reduced. However, the use of an unfiltered beam produced radiographs with higher sensitivity.

The existing conditions provided a favourable opportunity for the use of flash radiography. Difficulties in positioning the unit and the premature failure of the high voltage pulse transformer caused the abandonment of tests in this aspect of radiography. Flash radiography would undoubtedly have produced useful records of flow patterns of uranium in the liquid sodium as the 1 microsecond exposure time of the unit would have been sufficient to "stop" the motion of the suspension.

Gamma-radiography using iridium 192 was used but radiation hazards in the laboratory and lengthy exposure times prohibited general use. Radiographs obtained were of low contrast and poor sensitivity.

Radiographs shown in the report were produced under the following general conditions:-

X-ray

200 – 250 Kv. 25–50 milliampere–seconds
Target film distance 3 – 4 feet

Gamma-ray

Iridium 192 to 5 curies, 30 minutes
Source film distance, 3 feet

Films

Ilford B
Ilford G
Kodak Industrial
Kodak Crystallex

Variations in technique failed to produce a record of the actual sodium level except when flow conditions within the loop outlined the sodium level with deposits of uranium. The poor sensitivity obtained could be attributable to the secondary scattering from the asbestos lagging, beaded heater wires, and thermocouple leads obscuring the outline of the sodium level. No difficulty was experienced in determining the sodium level, or gas bubbles in the sodium, in the radiographs taken of the stripped loop tube after shut-down. The geometry of the exposure set-up would have contributed to this lack of sensitivity for, due to insufficient reach in the tube trolley, the tube head was positioned 1 foot below the sodium level in the vent tank for all frontal radiographs taken at right angles to the plane of flow.

Over one hundred radiographs of the loop were prepared during the survey. Details of uranium powder dispersion and deposition were recorded radiographically under varying conditions of flow and temperature.

APPENDIX 3

RADIOMETRIC TECHNIQUE

Figure 1 Lead shield

Figure 2 Collimator

Figure 3 Stage for probe

1. Counting equipment

The apparatus used for counting the gamma emissions from the daughter product of uranium, thorium 234, consisted of a scintillometer crystal, photomultiplier, preamplifier, and scaler. These are listed below:–

(a) Scintillometer crystal. Sodium iodide, thallium activated, type M533A.

(b) Photomultiplier, type 6097B.

(c) Preamplifier, type 1186A.

(d) Scaler, type N529.

2. Crystal shielding

Lead shield – The crystal was shielded with lead when the probe was mounted above the flowmeter for the determination of the suspension and deposition velocities – for dimensions of shield, see Figure 1 (this appendix).

Collimator – The dimensions of the lead collimator, used while traversing the loop tube with the scintillation probe, are shown in Figure 2 (this appendix).

3. Stage for probe

The scintillometer crystal and photomultiplier tube were mounted on a stage constructed from perspex sheet and Lab–Lox rod and fittings. The stage was mounted at an angle to the horizontal to increase the travel required to traverse the loop tube. The probe unit was locked in position opposite the appropriate alignment markers scribed in the front guide rail. The stage is shown in Figure 3 (this appendix).

4. Position of probe unit

The probe was mounted 9 inches above the centre line of the flowmeter magnet when counting to determine the suspension and deposition velocities. This position was selected for the following reasons:–

(a) The flow would not be affected by the disturbance caused by the flowmeter.

(b) This position was immediately before the top limb curve following a reasonably straight length of pipe.

APPENDIX 3 (continued)

5. Effect of ionisation smoke alarm unit in counts

The radium in the ionisation smoke alarm detection head caused high counts to be recorded on the loop as shown by the following figures:-

	Lab. Background	Loop Count
Detection head above loop	136	332
Detection head removed from Lab.	118	308

The detection head was therefore removed from its position above the loop when counts were being recorded.

6. Spread of results due to standard deviation from mean count

The effect of the standard deviation on the results obtained in traversing the loop tube at position 1 is discussed below:- (See Figure 15 and Section 2.1.3).

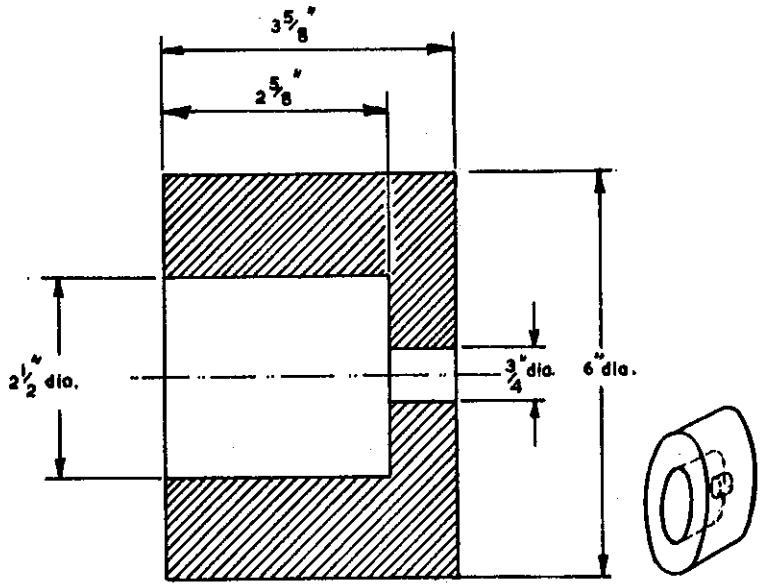
Loop conditions 350°C. Electromagnetic pump voltage 105.
Position across tube.

	Left	Mid left	Centre	Mid right	Right
20 min. count	6900 ±83	6800 ±82.5	7529 ±86.7	7595 ±87	7449±86.2
Count/min.	345 ±4.1	340 ±4.1	376 ±4.3	330 ±4.3	372 ±4.3
Background	2454 ±49.5 / 10 min., i.e. 245 ±5 counts/min.				
Observed count less background	100 ±9	95 ±9	131 ±9.5	135 ±9.5	127 ±9.5

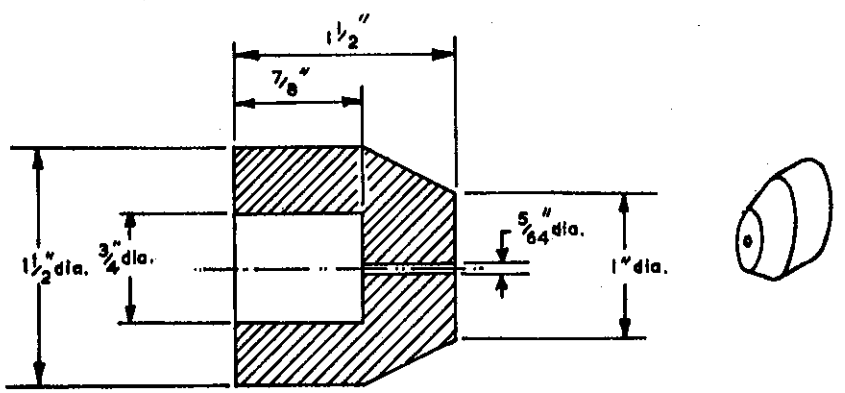
Considering the maximum and minimum counts at each position and taking the central count as 100 per cent., the counts recorded at each position expressed as a percentage of the central count become:-

Left	Mid left	Centre	Mid right	Right
64.7% to 89.8%	61.2% to 85.7%	86.6% to 115.5%	89.4% to 118.8%	83.7% to 112.3%

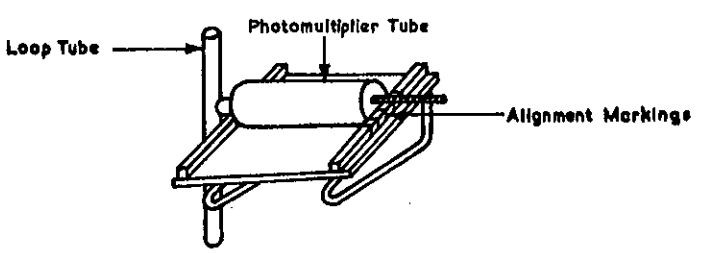
Plotting these figures on the ideal curve gives Fig. No. 15. The spread of results due to the standard deviation from the mean counts does not affect the interpretation of the counts as an indication of the trends to be expected. The counts towards the wall of the tube are higher than expected and the counts to the right tend to be higher than those on the left of the tube indicating the buffer layer of uranium in the walls and the deposition of uranium particles in the secondary velocity region on the inside of the curve of the loop tube.



LEAD SHIELD FIG. No. 1



COLLIMATOR FIG. No. 2



STAGE FOR PROBE. FIG.No 3

FIGURES ATTACHED TO APPENDIX 3

APPENDIX 4

MATHEMATICAL DERIVATION OF THE DISTRIBUTION OF COUNTS FROM A UNIFORM DISTRIBUTION OF FINE URANIUM PARTICLES IN SODIUM IN A CYLINDRICAL CONTAINER

Figure 1 Calculation of intensity at detector 'O'

An approximate solution, neglecting the effect of scattering and approximating to volume integrals is as follows:–

Consider only the primary (uncollided) flux

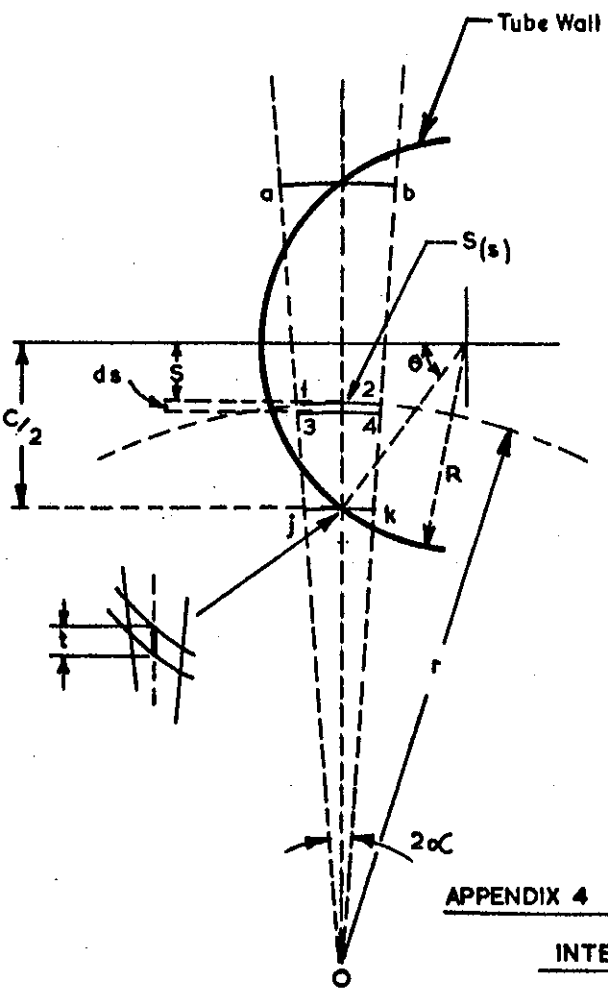
Let μ_f = absorption coefficient for fluid (cm^{-1})

μ_s = absorption coefficient for steel (cm^{-1})

(absorption coefficient = total attenuation cross section)

S = source density (photons/cc/sec.)

I_o = intensity at detector due to primary flux (photons/cc/sec.)



APPENDIX 4 FIG 1 CALCULATION OF INTENSITY AT DETECTOR 'O'

APPENDIX 4 (continued)

Referring to Figure 1, with α small and the beam not near the edge of the pipe, the effective volume under consideration is abjk, a portion of a sphere.

Assume $S_{(s)}$ constant over the element 1234 whose volume is approximately

$$\pi \cdot r^2 \cdot \alpha^2 \cdot ds.$$

then assuming no scattering between jk and 0

$$I_o \approx \int_{-c/2}^{+c/2} S(s) \cdot \frac{\pi r^2 \cdot \alpha^2}{4\pi r^2} \cdot e^{-\mu_s \cdot t} \cdot e^{-\mu_f \cdot (c/2 - s)} \cdot ds$$

$$\approx \frac{\alpha^2}{4} \cdot e^{-\mu_s \cdot t} \int_{-c/2}^{+c/2} S(s) \cdot e^{-\mu_f \cdot (c/2 - s)} \cdot ds \qquad (1)$$

Assume $S_{(s)} = S$ (constant), i.e. an effective mean value

$$I_o = \frac{\alpha^2}{4} \cdot e^{-\mu_s \cdot t} \cdot \frac{S}{\mu_f} (1 - e^{-\mu_f \cdot c}) \qquad (2)$$

Thorium 234 was the isotope most likely to be detected and μ_f and μ_s were calculated for the gamma radiation from this isotope using data from APEX 176 by Moteff.

The value of μ_f was calculated by averaging on an atomic per cent. basis. These calculations gave values as follows:-

$$\mu_s = 0.033 \text{ cm}^{-1}$$

$$\mu_f = 0.35 \text{ cm}^{-1}$$

Hence the formula becomes

$$I_o = \frac{\alpha^2}{4} \cdot e^{-0.033\,t} \cdot \frac{S}{0.35} (1 - e^{-0.35\,c})$$

Calculations from measurements of the loop tube at the location of traversing, and expressing I_o as a percentage of I_o max, gave the following values:-

Distance across tube (traverse distance) (inch)	0.03	0.115	0.15	0.245	0.36 *
t (inch)	0.118	0.082	0.064	0.065	0.05
c (inch)	0.33	0.567	0.625	0.72	0.75
I_o ($S. 10^{-4}$	0.661	1.032	1.047	1.237	1.271
I_o as per cent. of I_o max.	53.2	81.2	86.3	97.3	100

* N.B. 0.36 inch = half tube diameter