ASPECTS OF THE STUDY OF HEAT DISSIPATION USING MODELS

being

A Thesis submitted for the degree of Doctor of Philosophy

in Engineering of the University of Glasgow

by

D.I.H. Barr, B.Sc., D.R.T.C., A.M.I.C.E., M.ASCE.

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The Thesis is bound in two Volumes

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SUMMARY

(The reference numbers correspond with the Sections of the Thesis)

The Author had been engaged on a model study of the dissipation and the possible recirculation of heated water which was to be discharged from the circulating water system of a steam power station sited on a tidal river. He has described this investigation in a paper "A hydraulic model study of heat dissipation at Kincardine power station" (a copy is attached to the Thesis). It seemed that further work on the basis of design of such models would be worth while and that the various modes of flow involved might be examined for scale effects in isolation(1).

Various aspects of small density difference phenomena which affect free surface hydraulics are reviewed (2), together with the present status of model simulation of these phenomena (3).

In describing the circuit of flume and tank which was built for the studies, the general requirements for apparatus for small density difference studies are discussed (4). A thermopile recording system was chosen from the various possible means of indicating the mixing and dilution of introduced water, and the construction (5), use (8) (9) and possible development (13) of the indicating probes is described. This system is thought to be very suitable for any future ad hoc or basic studies.

The first mode of flow to be studied was the pure density current exchange flow as found in idealised lock experiments. Some additional information on the overall characteristics of the overflow was obtained, and a scale effect, caused by small variations in surface tension, was noted. This easily obviated phenomena might seriously impair similarity in heat dissipation models. It was found that the requirements for

similarity in lock experiments are applicable to internal gravitational advance in open water, and some success was achieved in the simulation of small scale prototype phenomena in very small scale models (7) (9).

Vertical mixing was studied using the recording apparatus and the applicability of the general Froude model law was confirmed (8). Modified forms of lock flow are suggested as being pertinent to the spread of less dense water over more dense water, when both are combined as an external gravitational current (10).

The effect of heat losses on model simulation is considered (11) and the economics of heat dissipation are reviewed in some detail (12)

After summarising, the possible form of future ad hoc studies is discussed and recommendations made for future basic studies (13).

A comprehensive list of references (14), the tables and figures collected at the start of the second volume (15), the test recordings (16) and the notation (17) follow.

A subsidiary outfall scour model had been run in conjunction with the main Kincardine model and this also left some uncertainties which were partially elucidated in a series of tests described in an appendix (18). In a further appendix, some minor aspects of the Kincardine investigation are discussed (19).

1. - PREFACE

1.1 - The topic and the background to the research project.

1.1.1. The dissipation and the possible recirculation of steam power station circulating water discharged into tidal waters has been studied in a hydraulic model on several occasions,[1.1-7] including an investigation for Kincardine Power Station, on the Forth, which has been described in a paper by the Author.[1.4] (Attachment 1 at back of Volume 2 of thesis). Generally, the intention has been that the travel of isolated currents of the heated water, the spread of the heated water over the colder river, estuary or sea water, the intake of non-homogeneous water (where applicable) and turbulent mixing should all be simulated as closely as possible. In some cases, these movements have been studied at slack water as well as when superimposed on the general tidal flows. Thermal density variations have commonly been adopted to simulate the thermal variations of the prototypes, with the same initial temperatures in the models as would obtain in the prototypes. Linear scales and approximate sizes of the models reported are listed in Table 1.1, velocity scales having been taken as the square root of the vertical scales, and the temperature differences having been as for the prototypes. The aim of such studies may be summarised as the restriction of recirculation of the discharged circulating water, which would normally be expected to reduce station efficiency, and the minimisation of damage to marine life, both at the least cost possible. Conditions simulated may well include unlikely, but possible, combinations of adverse circumstances.[1.4] Although practical decisions have been based on the results obtained,[1.2,4,8] some dubiety remains as to the degree of correspondence that can be achieved in this type of non-homogeneous model study, particularly as little has been reported on model prototype comparisons.

1.1.2 It was thought worth while to attempt to provide some further information on the circumstances where a heat dissipation and recirculation model study concerned with tidal waters is likely to be found profitable, on the design of such models and on the reliability of the results therefrom obtained.[1,4] Knowledge of the relative importance of the various aspects of the prototype water movements seems as necessary as knowledge of the extent to which it is possible to simulate these aspects in a model. It was recognised that reports of other types of non-homogeneous models and small scale basic studies might provide valuable guidance and information. In the assumption that the various aspects of the water movements involved might be considered in isolation to a certain extent, some experiments were carried out to supplement the aforementioned small scale studies. These later studies were not, of course, designed to cover all aspects of similarity in heat dissipation, and recirculation models, and it was intended from the start, that if any overall survey of the possibilities of utilisation and of the design of such models were to be prepared subsequent to the submission of this thesis, use would have to be made of other experimental and theoretical work. For example, methods of obtaining similarity of velocity distribution for a homogeneous body would be fundamental to the initial phases of a model study concerned with heat dissipation, but these were not specifically investigated as part of the project, although some recordings were made of velocity distribution in a flume. Parallel to the study and corelation of previous work, practical and theoretical, and the practical research, a study of the economic aspects of heat dissipation has been made (Section 12). To complete this latter work it would be necessary to obtain further information from turbine manufacturers and from the Electricity Boards, and it is hoped that eventually a paper can be prepared.

For the present, a fair general estimate can be made of the economic value of the alternatives in circulating water systems which might be investigated using a model.

1.1.3 To be able to cover the range of travel lengths and of depths likely in models of the size listed in Table 1.1 (apart from the Severn model which is a special case) and perhaps somewhat larger, seemed a reasonable starting point in the determination of the size of the apparatus for the practical experiments. That this was achieved was due to Professor Frazer's generous allocation of space in the main Civil Engineering laboratory of the Royal College of Science and Technology. Nevertheless, it was inevitable that the extension of some, at least, of the series of laboratory tests into conditions even approaching the border of prototype scale would be impossible. However, the project was of necessity largely exploratory, and information as to where larger scale tests were likely to be worth while seemed desirable. The basic apparatus and the temperature recording apparatus were designed and built for the project. This had obvious advantages; but also the disadvantage that a considerable preliminary effort had to be made on design, making working drawings, pricing materials and constructing parts of the hydraulic and recording apparatus; all valuable experience, but time-consuming.

1.1.4 This was, as far as is known to the Author, the first series of basic studies aimed specifically at the understanding of the design and use of heat dissipation and recirculation models, apart from some tests carried out by Allen and Allen[1.4a] in 1946, which were apparently not continued as far as had been intended and which were only briefly reported in 1959. Since such models are obviously fairly complex, the inability to fully explore certain aspects of simulation, through regrettable, was not serious as regards leaving sufficient ground to be covered during the period of research.

1.1.5 The thesis is therefore concerned primarily with some basic studies designed to be of assistance in the elucidation of similarity in heat dissipation and recirculation models; and with the implications of these studies, ranging from information which it is thought would be of value in an ad hoc investigation to recommendations for further basic studies. It has been intended that most of the aspects of flow suggested by the Kincardine model investigation should be considered, although a more detailed examination of one aspect might have lead to a more typical thesis. The discussion contains an attempt to summarise briefly how an ad hoc investigation might be approached in the light of the studies reported here and drawing on other recent work on density current simulation and on studies of velocity distribution, heat losses and other related subjects.

1.2 - Sources of information and precautions against repetition of previous work

1.2.1 For nearly a year prior to the Author's registration as a research student and throughout his period of research, the literature has been searched for relevant matter. Where references to unpublished reports were noted, an attempt was made to obtain these. For instance, such material includes reports on a prolonged series of studies of "Model Laws for density currents" carried out by Dr. G. H. Keulegan in the Hydraulics Laboratory of the National Bureau of Standards, Washington, D.C., U.S.A., on one of which[1.9] much of the initial stages of experimental work for this project was based. Reports of particular model investigations are often impossible to obtain. For example, the Bradwell and Berkely investigations[1.5] referred to in Table 1.1 are thought to have been, in aim and scope, very similar to the Kincardine investigation,[1.4] but apart from the brief note published in

"Research and Application - No. 2",[1.5] the Central Electricity Generating Board was not willing to give any details.

1.2.2 It was recognised that the analytical approach, as opposed to the use of a physical model, should always be under consideration as an alternative to a model study of a particular problem, or as complimentary to such a study. So far the proportion of model studies to new stations using tidal waters for heat dissipation is extremely small. In any particular case where money is spent on the amplification of a circulating water system from the simplest arrangement possible without consideration of recirculation, it may reasonably be assumed that some attempt at analysis of the water movements is first made. There is remarkably little reference in published literature to this type of work, either as regards the United Kingdom or overseas. The only detailed example of such an analysis available to the Author was provided from an oceanographic research station in Canada on the understanding that no reference would be made to it in open literature. In a United States Geological Survey report[1.10] a different aspect of this problem is considered, though not in detail. The sources of these reports typify the diversity of the bodies who may, for logical reasons, study heat dissipation and recirculation. The first were concerned with the marine life environment, the second with water losses caused by increased evaporation from an inland reservoir used as a cooling pond.

1.2.3 It was known from before the start of the project that "Density Currents" had been chosen for one of the topics at the Eighth Congress of the International Association for Hydraulic Research which was held in Montreal in August, 1959. Thus modification of the last part of the programme in the light of the papers presented there was always envisaged as a possibility. In the event there were fourteen papers on density currents, including one by the Author on the initial stages of the project. None of the other thirteen papers suggested a need for revisal of the programme, and they are referred to in the normal way where relevant.

1.2.3. The foregoing is intended to show that every endeavour was made to carry out original work. A full list of references is given which includes both the sources of the work of others utilised in this thesis and a comprehensive background bibliography.

1.3 Layout of Thesis

1.3.1. Following this preface is an introduction in which occurrences of non-homogeneity in water, of interest to the civil engineer, are listed and the status of non-homogeneous hydraulic modelling is outlined. By status is meant the degree to which it is known that the model technique can provide information on prototype behaviour and the extent to which this knowledge is used. Then the hydraulic apparatus and the recording apparatus for the project as a whole are described and the basic theory applicable to non-homogeneity model studies is restated. The various experimental studies are then described. Where the modification and development of previous theoretical work has been attempted, this is placed after the details of the observations which it is sought to explain, and the various studies are discussed in isolation in the sections where they are described, while their meaning in relation to the project is considered in the final discussion. Since the studies were somewhat heterogeneous, it is hoped that the intended clarity results from this arrangement.

1.3.2. Consideration was given to the placing of the survey of non-homogeneity recording methods and the review of heat loss analysis as Appendices instead of in the body of the thesis. However, because of the relevance of recording methods and of heat losses to the possible substitution of other density difference agents for temperature in a model study, the present arrangement was chosen. The original recordings, and other material not necessary to the sequence of the thesis, are given as Appendices.

1.3.3. The thesis is divided into sections, sub-sections and paragraphs, with decimal identification; under "Contents" the page numbers down to sub-section level are listed. Figures and Tables have a common numbering based on the section in which reference is first made to them. For ease of reference, the Figures and Tables are bound in the second volume.

1.4 Postcript references

1.4.1. References to the postcript are marked in red. The postcript is attachment 5 at the back of Volume II, and in it is included brief details of material published, or obtained, after the appropriate parts of the thesis had 'gone to press'.

2. - INTRODUCTION - I NON-HOMOGENEITY AND THE EFFECT OF SMALL DENSITY DIFFERENCES GENERALLY.

2.1. General

2.1.1 Non-homogeneity, or in effect variations in critically identifiable characteristics, may be present in water with or without density difference. Density difference can be the result of varying temperature, varying salinity or varying turbidity caused by silt, finely divided sewage and the like. Non-homogeneity without density difference, or with negligible density difference, may arise from chemical characteristics, either naturally occurring or associated with waste disposal, or bacterial pollution or radio-active waste pollution. Each of these factors, except radio-active pollution, are present, for example, in most large rivers and estuaries in the United Kingdom and all are present in the Thames. (Radio-active waste disposal in the Thames[2.1]) In particular studies it can often be assumed that for practical purposes one factor predominates. Normally, though not invariable, this factor is one causing a density difference.

2.1.2 Figure 2.1 shows the temperature-density relation for fresh water.[2.2] The density differences within the range of temperature found in practical hydraulic studies are small compared with that between normal sea water and fresh water. For example, in fresh water the density difference corresponding to a temperature variation of 45°F to 80°F is 0.00325 gm/m.l. compared with 0.0277 gm/m.l. difference between fresh and sea water. Figure 2.2[2.2] shows the relation of density difference to dissolved sodium chloride. Turbidity, of course, knows no standard density difference, the density simply varying with the amount and specific gravity of the particles producing the turbid conditions.

2.1.3 In nearly all cases where density differences are present, there is superimposition of motions resulting from the density difference on the state of motion, or of lack of motion, which would exist in the case of no density difference being present. Keulegan states,[2.3] "The existence of a small density differential between two fluid strata reproduces to merely a lesser degree the same gravitational situation as normally exists at the free surface of a body of water in contact with the air above". He goes on to say that "essentially all free-surface" channel and wave phenomena "can occur at the interface between two such strata". As "the density variation is usually sufficiently small for the density to be regarded as unchanged so far as inertial conditions are concerned, and hence the sole effect of the variation is to reduce the apparent magnitude of the gravitational coefficient". That is $g^1 = g \frac{\Delta\rho}{\rho}$

where g^1 is the effective gravitational coefficient and ρ and $\Delta\rho$ are the average and differential density respectively.

Of course, in sub-surface gravitational phenomenon the inertial effects of both strata are nearly the same and this, together with the much greater interfacial resistance and the probability of mixing as compared with a water to air boundary, must be considered in a practical analysis.

2.1.4. Keulegan on one occasion deprecated the use of the name "density current"[2.3] but the term is now generally accepted. Certain definitions, though valid and helpful, have perhaps been slightly lacking in generality. For example: "A density current is the movement without loss of identity by turbulent mixing at the bounding surfaces, of a stream of fluid, under, through, or over a body of fluid, with which it is miscible, and the density of which varies from that of the current, the density difference being a function of the differences in temperature, salt content and/or salt content of the two fluids".[2.4a] Or more especially: "The term density current .... refers to a flow of water maintained by gravity forces through a main body of water such as Lake Mead and remaining separated therefrom because of the difference in density between the current and the lake."[2.4b] Knapp[2.5] has listed "General characteristics of density currents" which, though too long to be termed a definition, explain the term usefully, though again with a tendency to neglect the overflowing case. This list is given as an Appendix to this section (2.4)

2.1.5 Where turbulent flow obtains, as in practically all prototype scale water movements, whether the flow is general gravitational, internal gravitational, or a combination of these, mixing and dissipation of non-homogeneous water across any internal variation in concentration is practically identical with mass transfer by turbulent eddies.[2.6,7] Coefficients of eddy conductivity and eddy diffusion have been evaluated for particular conditions.[2.6-9] These coefficients are analogous to, but far exceed, the coefficients of conductivity and diffusion (and are defined in Section 6 - Basic Theory and Definitions). Density differences tend to cause stratification and thus the return of a displaced eddy from one density zone back to its parent zone. This may result in widely varying changes in the vertical and lateral coefficients of eddy conductivity and eddy diffusion.[2.6]

2.1.6 Observable full scale examples of density currents of material interest which are not in any way associated with normal gravitational currents are difficult to find. The case of the opening of a gate or lock separating bodies of still water of the same level but varying in density would approximate. But it is relatively simple to produce an almost pure density current in a laboratory flume by lifting upwards a thin vertical barrier/separating bodies of water of differing density at the same level;[2.10,11;1.8] this type of experiment is particularly valuable as illustrative of the inertial effects of both strata and of the interfacial friction between them. In one such experiment, included in the investigation to be described here, a density difference of 1.8 parts per million resulted in a well defined density flow. Even on a small scale the setting up of such an experiment required care but it illustrates how such commonplace occurrences as sunshine differentially heating the surface of a river or lake shaded by trees can give rise to slow mass transferring density currents, in the absence of more forceful suppressing motions. Negligible density difference must be thought of as a relative term in the light of such demonstration.

2.1.7 Although some studies of non-homogeneous water movements in natural and artificial bodies of water were carried out within the field of civil engineering before the last war, it is only recently that interest has become widespread. Of course, accurate measurements of temperature and salinity have been made by oceanographers for many years and have been related to very large scale movements.[2.6] The penetration of inland waterways by saline sea water has obviously been observed, if only by tasting, from pre-historic times, and limited attempts to prevent this may have been made about three thousand years ago.[2.12] Small density difference phenomena have also been met with by the civil engineers with regard to sewage treatment over a considerable period.[2.13,14] Every day occurrences ranging from the freezing of the surface layer of ponds, rivers, lakes and, in northern and southern regions, the seas and oceans, to the operation of domestic hot water systems and the like, all owe their nature to thermal density movements.

2.1.8. It has often been the undesirable effects of small density difference phenomena, other than thermal, which have drawn attention to them, although in some cases benefits can be obtained. Typical illustrations of density currents occurring in large scale bodies of water are as follows, the examples cited being in no way exhaustive.

2.2. Typical small density difference phenomena where the agent of density difference is itself the critically identifying feature

(i) Thermal density variation

2.2.1. The economic loss due to recirculation of power station circulating water, together with the possibly harmful effects of heated water, and more particularly, the sudden temperature changes therewith associated, on marine life,[2.15-19] is the reason for the type of investigation with which this thesis is concerned.

(ii) Saline density variation

2.2.2. That saline water penetrates inland waterways, though sometimes regretted, must normally be accepted. Man may increase the extent of the penetration by either deepening a waterway,[2.20] or by obstructing the fresh water flow.[2.21-23] In the first example cited, a water supply intake for Gothenburg was affected and had to be moved upstream.[2.20] The second and third examples resulted from the development of landward irrigation projects. In the Sacramento-San Joaquin Delta, California,[2.21,22] this has caused a deterioration in the quality of the water available for local irrigation. Various barrier schemes have been suggested by which the need for a minimum balancing fresh water flow during the whole year would be much reduced. At present, the port and city of Calcutta[2.23] are affected by increasing salinity intrusion in the River Ganges. The water supply intake is threatened and siltation of the navigation channel is increasing. Since the minimum balancing flow for any salinity intrusion length would be reduced with decreasing depth, remedial dredging probably adversely affects the water supply situation.

2.2.3 The mechanics of saline penetration in general have been widely studied.[2a.1-4] At the risk of over repetition, it should again be stated that the references to prototype observations are intended as representative only. That the study is of continuing importance is illustrated by a recent policy statement of the American Society of Civil Engineers.[2.2.4]

(iii) Turbid density variations

2.2.4 The passage of turbid water through Lake Mead[2.4,25] (the Boulder or Hoover Dam Reservoir) is the classic example, though such occurrences are commonplace where a silt laden river enters a relatively still lake or reservoir.[2.5,26-30] In the case of Lake Mead, it was noted that during construction when the reservoir was partially formed, the overflow was essentially clear, as had been expected. But in 1935, at some critical discharge, turbid water containing particles of silt from the Colorado River was discharged through the temporary openings three times in eleven months. It was estimated that some 6,000,000 tons or about 2.5% of the average annual load of silt brought to the lake, passed through the partially filled reservoir on these occasions. Such by-passing of the silt is clearly beneficial as loss of storage capacity, due to the deposition of silt on the reservoir bed affects the efficient life-span of the reservoir. There was no claim, however, that the Boulder Dam was constructed to allow the passage of large flows of turbid water or that the positions of, and approaches to, the construction discharge outlets were so arranged as to intercept this dense turbid water which appeared to be moving downstream on the bed of the reservoir as a density underflow. By accident, at some critical capacity, lake conditions were suitable for the passage of the turbid water. However, this illustration was largely responsible for the now prevalent belief that in such cases, normal overflows should be arranged so that if water has to be spilled, as much silt as possible should be discharged. Smreek[2.31] had suggested such a course some years prior to this.

2.2.5 Other important cases of turbid density currents occur in sewage treatment plants. A recent paper[2.14] describes how radio-active tracers were used to confirm the existence of a density underflow in a settling tank. The particle laden inflow traversed the tank as an underflow then lifted towards the outlet weir, while clearer water recirculated above. This is far from the design requirement of a slow flow, practically uniform throughout the depth, so as to allow a considerable retention time during which settling can occur.

2.3 Typical small density difference phenomena where associated non-homogeneities have objectionable effects.

(i) Thermal density variations

2.3.1 The Tennessee Valley Authority controls a system of 30 reservoirs, water being released from one to the other through hydro-electric stations, apart from times of flood. Since the temperature of the water may vary from reservoir to reservoir, thermal density currents are commonplace. In one instance it was found that the town water intake for Harriman,[2.32] situated near the backwater limit of the embayment of a tributary of the River Tennessee and upstream of the sewer outfall, was affected by pollution. Due to the temperature difference between the natural tributary river flow and the released reservoir water in the main river, upstream underflow penetration occurred in summer and overflow penetration occurred in winter. Both carried some sewage from the sewer outfall to the water supply intake, which had to be moved upstream. This example has been chosen because the experience of the T.V.A. with inconvenient density currents has led to a most interesting scheme whereby the intake temperature of the circulating water for Kingston Steam Plant, sited on the same reservoir as Harriman and the largest in the world, is beneficially reduced by the artificial control of a density underflow.[2.33]

2.3.2 The need to prevent thermal stratification in service reservoirs has been noted both in this country[2.34,35] and in the U.S.A.[2.36] If an amount of water is unduly retained at the bottom of such a reservoir, it may be objectionable when eventually released.

(ii) Saline density variations

2.3.3 A recent investigation of the regimen of the Thames, carried out on the river and by models, has shown that the nett landward movement of the bottom water in the river can carry silt upriver from what had been used as a disposal area to the most constantly dredged part of the navigation channel.[2.37] In the Thames the salt wedge is very decayed, the average density difference from top to bottom being only about 2 gm./litre. Nevertheless the maximum nett landward flow at the bottom is of the order of 12,000 ft., per tide.

2.3.4 The penetration of a saline underflow into a newly formed backwater on the Fraser River, Canada,[2.38] was found to result in the transport of and the maintenance of the environment for, ship worms, which attacked the wooden piles of the Stevenson Cannery Basin wharfs.

2.4 In conclusion

2.4.1 These examples show the diversity of the small density difference problems encountered by the civil engineer and others. Studies of non-homogeneity without density difference in large bodies of water are more or less restricted to radio-active waste disposal[2.39] and sewage disposal.[2.8] In the latter case the point of dilution where density differences can be ignored may not, at times, be fully understood[2.8a,b] and this will be referred to later in this thesis.

2.6 Appendix to Section 2. "Knapp on density currents: flow characteristics"

"Density currents have all the properties of normal fluid flows. However, the relative magnitudes of different factors governing the flows have been altered and these alterations cause corresponding changes in the flow pattern. The following items describe some of the principal alterations and also outline some of the general flow characteristics of density currents:

1. The most striking difference between a density flow and a normal flow of the same fluid is the great decrease in the magnitude of the gravity force, due to the buoyancy of the surrounding fluid. Consider a muddy stream which flows into a reservoir of clear water and becomes a density current. Suppose that the muddy flow weighs 64 pounds per cubic foot and the clear water in the reservoir $62\frac{1}{2}$ pounds. Just before the flow enters the reservoir, the effective driving force acting on each cubic foot of muddy water to cause it to flow down the channel is 64 pounds times the slope of the bed. Just after this same cubic foot of water enters the reservoir and becomes a density current, the driving force reduces to $1\frac{1}{2}$ pounds (64-62.5) times the slope, which is less than $^1/_{40}$ of what it was in the open channel. However, the momentum of the muddy water is unaffected by the buoyancy of the surrounding clear water.

2. Due to the large decrease in the magnitude of the gravity force as compared to that of the inertia force, inertia effects become much more important. Thus, for a density flow, vertical movements which would be inconceivable for the normal open-channel flow become a common place method for getting around an obstacle.

3. A density current is bounded on all sides by friction surfaces at which energy can be liberated to maintain or increase the turbulence level. This is in contrast to the flow of water in an open channel, for example, in which the friction of the air-water interface is generally so small as to be negligible." (This neglects the surface flow case, a tendency already noted) [illegible])

"4. Density currents maintain their movements by decreasing their total of energy just as do normal flows. Thus, if a stream flows into a larger body of fluid of different density, the flow will continue if the slope or pressure gradient and the density difference are maintained. Conversely, to stop the flow either the gradient or the density, difference must be eliminated. When this happens, the flow will persist as a distinct element only until its kinetic energy has been expended in friction.

5. Density currents may be lighter or heavier than the main body through which they flow. If lighter, the energy gradient causing the flow may come either from a pressure difference produced by an open outlet spillway, etc., or from a negative hydraulic slope which results from the decreasing thickness of the floating layer. It should be noted in this connection, that a light density current flows "uphill" in the surrounding fluid. If the density current is heavy, the necessary energy gradient may also be caused by a pressure difference produced by an open outlet. If it is caused by a slope, however, this slope must be in the direction of the flow.

6. These same forces act to produce flow in the more complicated case in which several density currents or density layers are present and the stream in question must flow between a lighter and a heavier fluid. In such case the gradient often comes from a change in the thickness of the flow."

3. INTRODUCTION II - STATUS OF MODEL SIMULATION OF DENSITY CURRENTS WITH PARTICULAR REFERENCE TO HEAT DISSIPATION AND RECIRCULATION MODELS

3.1 General

3.1.1. In the more usual types of hydraulic model, the dispositions and effects of the boundary of a body of homogeneous water are under examination. Interest in velocity distribution is the common ground with non-homogeneity models where portions of the water are, for some reason, identifiable and their disposition is of interest. Because of the considerable difficulty of observing small density difference phenomena in the field, very simple small scale illustrations of such occurrences have been of rather more importance in recent years than in comparable cases of homogeneous hydraulic phenomena.[2.5,9,31;3.1,2 2] Small scale hydraulic illustrations have been made of the mixing of methane and air in mines.[3.4]

3.1.2 The small scale illustrations naturally led to both small scale basic studies, where quantitative rather than qualitative observations can be made and by which theoretical deductions can be checked, and to model studies. In the latter of these more complicated circumstances may be elucidated, sometimes quantitatively, though often merely qualitatively. However, even where particular results are regarded as qualitative, it may be hoped that the ratio of results from tests of differing circumstances may be reasonably quantitative.[1.4] Small scale basic studies may be intended to lead to the analysis of full scale problems, or to the design of models: the first example known to the Author[2.10] did, in fact, combine these objects. No clear pattern of the development of understanding of small density difference models can be given. Much of the work has been conducted in isolation in various countries. For example, Inglis and Allen make no reference, in their account of the Thames model investigation,[2.37] to previous successful model simulations of decayed salt wedges.[3.5-8] So it is best to pass on to a survey of the status of such models as it is at present drawing illustrations without regard to sequence.

3.2 <u>State demarcation of non-homogeneity problems.</u>

3.2.1 Non-homogeneity problems are readily separable into steady state, cyclic steady state or non-steady state. This is, perhaps, rather obvious, but becomes especially relevant when model simulation is considered. The particular study which aroused the Author's interest was very much concerned with non-steady conditions.[1.4] Other tidal heat dissipation model studies have been proposed,[3.9] or are being carried out,[1.7] which are more concerned with the general pattern of dissipation throughout the course of a series of tides than with close simulation of the conditions during one semi-diurnal cycle, or part of a cycle. Such studies are really cyclic steady state, albeit tending towards the non-steady. There have been several non-tidal river,[3.10-13] or canal models[3.11] (Leading details are listed in Table 3.1) in which the possibility of upstream surface flow has been studied. In some of these, the steady state balanced flow conditions have been the principal interest, and the time to reach that state in the model has been more or less irrelevant. In fact, although such models have, of course, a velocity scale, they do not have a meaningful time scale. But the complication of heat losses, or of a relatively short prototype duration of critical conditions, may bring in the time element, or indeed bring the model into the non-steady class.[3.13]

3.2.2 An analytical approach to the river or canal problem, with corelation to small scale basic studies was given a year or two ago by Bata.[3.14] His study was rather academic, perhaps too academic, and the increasing use of models in the United States[3.13] suggests that the analytical approach may be difficult in practice and where rivers are concerned, however interesting in theory, and considering a canal.

3.2.4 Thus, although there might be expected to be a connection between the various types of models concerned with power station circulating water, the line of resemblance actually follows the state demarcation of small density difference models generally, rather than the application demarcation.

3.3 Non-steady state models

3.3.1 Unfortunately after the early small scale illustrations, little in the way of model simulation has been attempted for non-steady state problems apart from heat dissipation models, although a great deal of basic work has been done by Keulegan.[1.9;3.15] He, however, has dealt mainly with the case where normal currents need not be considered, and his method of model simulation (Section 7) is obviously not directly applicable to models concerned with heat dissipation in tidal waters. One saline example only can be cited, a successful attempt to simulate the penetration of a salt wedge up the Mississippi after flood clearing.[3.16] This will be referred to in more detail later; for the present it is sufficient to say that the status of non-steady state density current model simulation depends otherwise on heat dissipation models, for which, as stated earlier, little model-prototype comparison details are available.

3.4 Cyclic steady state models

3.4.1 Considerable success has been achieved in the model simulation of saline cyclic steady state phenomena.[2.37;3.5-3,17] (Listed in Table 3.2) The degree of correspondence achieved in the case of the Thames investigation was remarkable.[2.37] However, the authors, in reply to a question by the Author, stated; "the condition in the Thames model had been arrived at by trial and the Authors considered that any similar model of moderately large scale and relatively small vertical exaggeration might be expected to give good reproduction of salinity distributions if the rise and fall of the tides were reproduced accurately at all points in the model and if the rate of progress of the tidal wave was correct. Although some work had been done on the subject in the United States by G. H. Keulegan, much remained to be done in the study of mixing in scale models and it was too early to offer any numerical rules for guidance"[2.37a] This statement is, in general, borne out by the reports of the other salinity investigations in tidal models cited. The position is that these results are available as evidence for examination, rather than that firm theory has been given which might be adapted to cover the design of heat dissipation models. In fact, the Severn model,[1.7] for the study of heat dissipation from the grouping of nuclear power stations on that estuary, has probably been designed merely to be of the same order of scale and of distortion as the Thames[2.37] and Mersey[3.17] tidal models where the salinity distribution has been successfully simulated.

3.5 <u>Steady state models</u>

3.5.1 Steady state recirculation models have been referred to in sub-section 3.2. Again little or nothing has been reported as regards model prototype comparisons.

3.5.2 The steady state has attracted a great deal of attention in the field of basic studies,[3.14,18-23] both as regards the analysis of the forces holding stationary wedges and the interfacial mixing that takes place between statified layers, with one layer moving, and between the stationary and moving fluid in the case of a stationary wedge.

3.6 <u>In conclusion</u>

3.6.1 For anyone approaching an <u>ad hoc</u> investigation of the Kincardine type, there is plenty of evidence to be sifted, but little in the way of direct and generally accepted rules for the design of a model.

4. HYDRAULIC APPARATUS

4.1 General approach to design of apparatus for non-homogeneous hydraulic studies

4.1.1 In the design of apparatus for non-homogeneity studies, problems arise over and above those met with in more usual hydraulic topics. It is thought worth while to briefly consider these problems: although the apparatus for the presently described studies was designed and built for these studies, the possibility of the adaption of existing appartus, particularly large scale apparatus, cannot but be an ever present thought to those interested in non-homogeneity models. If phenomena could be observed on a scale sufficiently large to be of prototype order, but under strict control, the subsequent success or failure of simulation attempts at a small scale would, as doubtless applies to other aspects of hydraulics, go far to establish the usefulness, or otherwise, of non-homogeneity models. This does not, of course, apply to tidal river salinity intrusion models, for which, as shown in Section 4, no further justification is reasonably needed. It is interesting to note that in the very early work of O'Brien and Cherno,[2.10] an attempt was made to correlate laboratory experiments with field studies carried out in an irrigation canal. Lack of sufficient control and understanding of the problem undoubtedly led to the unsatisfactory results obtained. But the idea was a good one, and had greater interest been felt in density currents at that time, valuable information would have been obtained; information which shall be shown in this thesis to be still unavailable.

4.1.2 Continuous flows of homogeneous water are likely to be required in a non-homogeneity study, either as a steady state flow in the study or to fill some part of the apparatus. The nature of the experiments suffices to fix two such flows as the probable requirement and often, but with a most important exception, one flow will be much larger than the other. Differential control of the characteristics of these flows is essential, some absolute control is desirable but often unobtainable. If the flows are required for steady state studies, control of the quantities would be necessary, but if required merely to fill some part of the apparatus, speed of flow is the main necessity. Despite the illustration in Section 2 of the infinitesimal density difference needed to set up a density current, it is extremely difficult to speedily completely mix even a small volume of water contained in some shape with length to breadth ratio greater than 4 to 1 or so, and shallow in comparison to the breadth. At a ratio of 15 to 1 or so, the task is practically impossible, without some device such as a jet giving a complete turning over motion, and mixing must be done before filling.

4.1.3 In the case of a steady state problem, the combined outflow is contaminated. Immediate recirculation is thus not desirable. Two basic approaches are possible. Either the main flow can be drawn from a limitless reservoir, such as the sea or a lake, or a limited reservoir must be provided such that recirculation is negligible, but which can be readily mixed by the pump capacity available.

4.1.4 The foregoing is far from comprehensive. Many varieties of circuits have been described in the literature. But it is stressed that in non-homogeneity studies, it is insufficient, for example, to have a huge flume for 'Lock' experiments (Section 7). It must also be possible to fill it reasonably quickly with bodies of uniform but differing water, and to dump the mixed water after the experiment.

4.2 <u>The main hydraulic apparatus.</u>

4.2.1 The main hydraulic apparatus described here is undoubtably far from original. It does, however, follow from the Author's previous experience of apparatus for small density difference studies, and is, in effect, a combination of the Kincardine model circuit[1.4] with a very small scale apparatus built by the Author at home,[1.4] its size falling between these previous examples. The following list shows the interacting and conflicting general requirements which had to be met.

(a) A flume and a tank were required, in which, as stated in Section 1, the range of travel lengths and depths met with in the models listed in Table 1.1 could be covered.

(b) The least possible space should be used: in fact the floor space actually used, 9 ft. 3 in. by 26 ft. 3 in. was the limit set by reason of access requirements and the needs of other projected apparatus.

(c) As much as possible of the equipment available in the College should be used and the cost should be kept as low as possible.

(d) The apparatus should be reasonably easy to operate and the setting up of tests should not require excessive time.

4.2.2 An 18 ft. by 7.25 ft. by 1.75 ft., deep tank and an 18 ft. by 1.5 ft. by 0.9 ft., deep flume formed the main part of a closed hydraulic circuit. Fig. 4.1 (Attachment No. 3 at end of Vol. II) shows how the space available was utilised: the tank and pertaining guiding walls were built in 9 in. brickwork and the flume was supported on one side wall. At one end of the tank a 2 ft., wide opening led to a sump 1.7 ft. below floor level. This was formed from a cut-off part of the under floor channelling for the main hydraulic circuit of the laboratory. From the sump water was lifted by an 0.75 cusec capacity Siegmund pump and passed through a 6 in. dia. delivery pipe to a V-notch tank. A branched connection led to a constant head tank, to ensure a constant flow to the V-notch tank, and valves were fitted above the pump and beyond the branch. Excess water passed over a 4.5 ft. long weir in the constant head tank and was led back to the sump. Figs. 4.1 and 2 show the pumping arrangements. Most of the piping and the pump were from stock. The constant head tank was constructed by a contractor, being designed to sit above the sump and to support the pipework and pump by suspension during erection. This, in practice, proved most satisfactory.

4.2.3 From the V-notch the water fell into a stilling tank and was led along the flume as is shown in Fig. 4.1. The flume was mainly constructed of resin bonded plywood with one fixed side in perspex, and the other movable to 12 in. and 6 in. widths. The construction is illustrated by a cross-section (Fig. 4.1). Sealing was entirely satisfactory, being accomplished with 'Sylglass', a proprietory sealing strip. As far as is known, the design of the flume, so as to allow variation of width, was original. A weir gate at the downstream end of the flume controlled the level of water and the discharged water was led into the tank through a 2 ft. opening opposite the aforementioned exit opening. Various views of the circuit are shown in Figs. 4.3-6.

4.2.4 A switching point was placed on the floor near the V-notch tank. This consisted of a five way branch, each branch being controlled by a ½ in. valve. The branches were connected to:-

(i) a flexible lead to an outside drainage point in the far corner of the laboratory. Hot and cold water was also available at the drainage point.

(ii) a flexible lead covering the flume and tank

(iii) a pipe to the bottom of the main tank

(iv) pipes to the bottom of the V-notch tank and flume entry tank. (These could be separated using a clip)

(v) a pipe to the riser to the constant head tank.

This arrangement proved most useful. The uses included

(i) - (iii) Drainage of tank, or filling tank.

(i) - (v) Pumping out sump, and priming the pump.

(iii) - (iv) Bringing level in tank to some desired point after mixing by pumping round the circuit. In certain experiments in the tank, the flume was thus used as a reservoir.

(iv) - (ii) Providing a small flow of water of the same characteristics as the main body of water in the tank. An additional lead from the constant head branch pipe could be used to supplement this flow, which proved most useful in certain experiments. (Section 7)

4.2.5 Mixing tanks of 25 and 12 cubic feet capacity (8.94 and 4.835 sq. ft. surface area respectively) with hot and cold water feeds from the main college supply, were sited on the internal half floor above the main laboratory floor. The bottoms of the mixing tanks were 18 feet above the main floor level. Hand operated mixing paddles were fitted, the whole being shown in Fig. 4.7. Flexible down-pipes, ($1\frac{1}{2}$ in. and 1 in.) which could be moved to any part of the flume or tank were fitted with a regulating valve, an on-off control valve and a drain valve (Fig. 4.8) The high level tanks were equipped with thermometers and level indicating tube. (Fög. 4.7)

4.2.5 A practically constant flow could be obtained over a range of a foot or so of depth in these upper tanks. Setting of the control valve was somewhat tedious, especially so when the flow required was near capacity, since considerable delays were inevitable while refilling of the tanks took place (25 minutes in the case of the 25 cu. ft. tank, or a mains flow of about 1/60 cusecs.) A V-notch box was therefore used for certain experiments, as shown in Fig. 4.9. Calibrations for the V-notches are shown in Figs. 4.10 and 11.

4.2.6 A considerable number of devices, such as introduction boxes, were used at one time or another and will best be described with the experiments to which they pertained. Also, a subsidiary flume was built and placed above the tank for certain purposes which will again be dealt with later. (Figs. 4.11)

4.2.7 Perspex was found to be a most useful material. The end gate of the flume was formed from a sheet with reinforcing flanges cemented on. The V-notches were cut from perspex. These notches can be extremely costly when bought from specialist makers. At the Kincardine model experiment it was found reasonably simple to form a largish V-notch from two fairly narrow pieces of brass brazed to form an L shape, instead of cutting from a sheet. The edges could be more or less prepared on the straight before brazing, a much simpler operation. This procedure was again adopted for the main V-notch, but using perspex. For the intermittant running to which it was subject, the perspex notch proved quite durable. The smaller notch was cut from a solid sheet of perspex. The calibration of both (Figs. 4.9 and 10) seemed satisfactory, the systematic divergence in the case of the smaller doubtless being caused by the position of the gauge, or by an incorrect zero setting.

5. RECORDING APPARATUS

5.1. Survey of non-homogeneity recording methods

5.1.1. The alternatives available in the recording of the concentration of some non-homogeneity present at various points in a hydraulic model (or in a basic study) give rise to a considerable range of possible approaches to any particular case. There is a tendency, a natural tendency, to use the same motivating density difference agency in a model as in its prototype, or in a basic study as in the phenomenon which has suggested the study. This has been true of practically all of the many and diverse studies relating to salinity intrusion, though, to be sure, sodium chloride solution rather than sea water is most often used. However, in certain cases it has been convenient to use the sea as a limitless reservoir of homogeneous water[3.21] (see 4.1). But in a recent paper it is suggested that it may sometimes be convenient to use stable clay suspension to simulate salinity.[5.1]

5.1.2. Again, practically all heat dissipation model studies have been carried out with thermal density variations[1.1-5,7] as have steady state river model studies dealing with recirculation,[3.10,13] although in both cases, a case for the substitution of a saline density variation might be made, with certain reservations.[1.4] This will be discussed in more detail later. Small scale studies of turbid density currents, model or basic, have been less common. Blanchet and Villiat[5.2] have described the use of a silt suspension in a basic study of the flow of turbid water through reservoirs, though it is difficult to see that much was gained as compared with the simplifying substitution of salinity and the apparatus for the supply of the suspension was most complicated. More recently a kaolin suspension has been used in similar studies.[5.3] In small scale studies of sewage treatment plants it would be expected that some suspension other than that of the prototype would be

preferred.

5.1.3. Completing the illustrations of similarity of non-homogeneity as between model and prototype, radioactive tracers were used in the Savanah model to simulate the dissipation of radioactive waste.[2.39]

5.1.4. In the great majority of the afore cited examples measurements of concentration have been direct, but there is a less obvious possibility, the superimposition of a zero or negligible density difference tracer on a normal density difference agency. For instance, in the heat dissipation experiments carried out in the Thames Model[1.3] a chemical tracer, examined by titration after sampling, was mixed into the heated outfall water. This method is thought to have been adopted for other Hydraulics Research Station studies. Though really a full scale study, the recent use of radio-active tracers in studying flow in a sewage works settling tank[2.14] typifies the possibilities for small scale or pilot tests. Again for the early study of salinity intrusion in the Sacramento-San Joaquin delta,[3.5] referred to in Section 3, a method was devised whereby the amounts of water from up to four sources present in a sample could be distinguished by spectro-photometric analysis. Three of the sources were coloured by stable red, yellow and blue dyes. Although density difference was not normally simulated, the control tests to prove such simulation unnecessary afford a good example of the superimposed tracer method.

5.1.5. As an aside, it is remarkable that no published reference seems to have been made to this technique which is undoubtedly the most ingenious of the purely sampling methods of non-homogeneity identification yet used practically. Perhaps the unlikely circumstances which must have led to the Bureau of Reclamation undertaking the investigation provides the explanation. Certainly, the Waterways Experiment Station do not seem to have followed up this method in their later salinity intrusion model studies.

5.1.6. Summarising, there are a number of non-homogeneities found in prototype scale phenomena, some causing density difference, some virtually no density difference. In small scale studies similar non-homogeneities may be used, but substitution may be found convenient. The recording medium may coincide with, or be superimposed on, the non-homogeneity agency, transposed or otherwise. A further permutation comes from the possibility of in situ, sampling or continuous abstraction recording.

5.1.7. In situ recording of temperature may be accomplished by thermometer,[1.4] thermocouple[3.13,14] or thermister;[1.7] of salinity by conductivity[1.9]; of turbidity by photoelectric cell[5.4]; and of radio-activity by geiger counter.[2.14]

5.1.8. Sampling recording of salinity may be accomplished by titration[3.7.-9] or conductivity;[3.8] of turbidity by drying out and weighing;[5.2] of chemical tracer by titration;[1.7] of radio-active tracer by 'count';[2.39] and of colour tracer by photo-spectrometer.[3.5] Sampling is obviously inapplicable to temperature measurements.

5.1.9. Continuous abstraction recording has so far been restricted to salinity measurements.[5.5,6.] It has advantages in the localisation of the point of recording and in minimisation of flow disturbance, over the more normal in situ conductivity measurements. For similar reasons it might be adopted for radio-active tracers, but is unlikely to be suitable for temperature measurements because of heat losses.

5.2. <u>Non-homogeneity recording apparatus for the project</u>

5.2.1. Bearing in mind the foregoing, the following non-homogeneity recording apparatus characteristics were used to compare the possible alternative approaches.

(i) Accuracy over the desired range of density difference.

(ii) Speed of response to changes in concentration.

(iii) Ability to localise the point of measurement.

(iv) Disturbance caused to water movements.

(v) Whether recording would be automatic or be by observer; if automatic, whether continuous or intermittant; if intermittant, whether intervals would be suitable.

(vi) How many points could be observed during one test.

(vii) Whether measurements would be in situ or after abstraction, continuous or in samples.

(viii) Adaptability to differing aspects of non-homogeneity.

(ix) Ease of use, including ease of interpretation of recordings.

(x) Cost.

5.2.2. It appeared, other things being equal, that a method of in situ recording based on a superimposed recording medium would have the most general usefulness. Radio-activity being discounted because of cost and dangers in use, the superimposed medium method did not seem practical, at least for the present. As the present study was concerned with thermal density currents, the direct measurement of temperature seemed the obvious first approach.

5.2.3. The mercury bulb thermometer is accurate (after calibration), simple to read and cheap. Also it tends to average out varying temperatures, both in dimension and time because of the bulb size and its comparatively slow response.[1.4] Knowing that water is nearly pure, its density can be very quickly found using a thermometer; no comparable method is available for salinity or turbidity. Mercury bulb thermometers were widely used during the studies, being calibrated using the standard thermometer kept in the department.

5.2.3. Because of the limitations of the thermometer, a thermopile temperature recording system was developed and tested and, where necessary, constructed. This work was not carried out as a preliminary to the experimental work but was, for various reasons, interspaced with the initial stages of that work. It was fortunate that much could be done by simply using thermometers and making visual observations.(Section 7)

5.2.5. Pairs of thermopile probes were formed in the following manner. Twin laid and wrapped constantin and chromel wires (.0075" dia.) were cleared of insulation for a short distance at one end and the wires threaded through a fine twin bore silica tube. The thermoelectric pair constantin-chromel has a e.m.f. of about 33 micro-volts/°F at room temperatures as compared with 23.8 micro-volts for copper constantin, 22.2 micro-volts for alumel-chromel and 30 micro-volts for iron-constantin, these being more commonly adopted pairs. The ends of the wires protruding from the silica tube were twisted together and trimmed to about $\frac{1}{8}$ in. beyond the tube. A bead junction was formed by placing the wires in an electric circuit, with a controlled voltage, and closing the circuit by momentarily touching the twisted end against a carbon block in a reducing atmosphere. Groups of four of the paired wires were threaded through $\frac{1}{8}$ in. O.D. 24 in. long stainless steel tubes and then through 30 inch lengths of P.V.C. tubing which lapped the steel tubing. The other ends of the steel tubes were sealed and then formed the measuring point. Fig. 5.1(a) shows the appearance. The wires from two such probes were then connected so as to form a thermopile circuit, with four hot and four cold junctions. Sixteen pairs of probes were connected through a selection box and a rotary 'make before break' switch to a recording arrangement consisting of an oscilloscope with amplifier and camera. These are shown in Fig. 5.2 together with the rotary switch and selection box. A circuit diagram is shown in Fig. 5.4. The order of recording of the measuring probes could be arranged before testing, in any chosen way, by adjustment of the wiring in the selection box, the colour sequences of the wiring ensuring that the order of the probes and the order of the wiring in the selection box were the same. Fig. 5.3 shows the probes set up in position for testing in the flume.

5.2.6. The complete arrangement, therefore, has 16 thermopile channels and 24 switch positions on each of the two banks of the rotary switch. In the event it was found desirable to interspace each recording signal with a reference null signal obtained from a channel with hot and cold junctions at the same temperature and to use an additional reference signal as a marker. Eleven recording channels were thus selected for one bank of the switch and the other four, plus some duplication, could be obtained on the other.

5.2.7. Measurements could thus be made at the end of an $\frac{1}{8}$ in. diameter rod, the localisation from the tip in the direction of the axis of the rod also being about $\frac{1}{8}$ in. or rather less. Tests showed that the speed of response (to a 15°F change in temperature) was about $^1/_{30}$ sec. The test recordings are shown in Fig. 5.1(b). The accuracy of measurement, all measurements being referenced to the basic fluid in the flume, was to about 0.2°F over a 15°F range and about 1°F over a 45°F range. The maximum speed of reading was approximately 24 points (one revolution of the rotary switch) in $1\frac{1}{2}$ secs. or 8 effective recordings/sec. With this speed of turning, the return to the base between each effective recording practically eliminated the possibility of errors due to drift although sufficient time was spent at each position to allow two or three cycles of the 50 cycles/sec. alternating current. These cycles appeared as fluctuations which were impossible to completely eliminate but provided measurements were taken from top to top or bottom to bottom of the fluctuations, these did not affect the accuracy of measurement. Fig. 5.1(c) - (f) shows typical test recordings for the foregoing.

5.2.8. For certain tests it was found necessary to damp the speed of response of the thermopiles. This might have been achieved in the circuits, but would have required the device in each circuit. A simple solution was to form paraffin wax beads over the thermojunctions by successive submersions in molten wax, Fig. 5.1(g) shows the appearance of the end of the probe. Fig. 5.1(b) is a typical test for response. The probes, so treated, were similar to mercury bulb thermometers apart from the method of and the speed of reading.

5.2.9. So that the wiring for the probes could be more easily led to any part of the flume or tank, a 'Dexion' frame was hung above the apparatus.

5.2.10. Although the system was basically successful, it was found that after a few months with the probes in and out of water, an electrolytic current was set up in the circuits due to corrosion. This was very slight - up to the order of 50 micro-volts (or equivalent to one or two degrees farenheit) but it was not constant from day to day. The probes were reconstructed, on this occasion avoiding the twisting at the bead junction, and were dipped in lacquer immediately the bead was formed. The measuring probes were later scraped at the bead only. The extent to which the useful life of the probes has been extended is not yet known.

5.3. <u>Determination of flow velocities</u>

5.3.1. There are three 3 main methods of velocity measurement for models or small scale basic studies:

(a) Successive time and location of an identifiable point.

(b) Small current meters.

(c) Methods based on the inertia of the moving water, such as the use of pitot tubes.

5.3.2. For non-steady conditions it is often particularly suitable to use method (a) above. Two instances: first the proving of the Kincardine model by the comparison of float paths in model and prototype. This was far more convening and effective than measurements of velocity at particular points could have been. The pattern of the reversal of flow during the double low water would not have been observable with a current meter, certainly not in the model. Again, the advance of overlow or underflow fronts down a flume in 'lock' experiments as referred to in Section 2 and described in Section 7 is effectively studied by timing. In contrast to the first example no float is required, but by the colouring of the water on one side of the removable barrier, the advance of the fronts can be observed. During the present tests a stop clock was used with a circle of paper stuck to its face, of diameter just less than the markings. As the fronts passed foot, or half foot, marks, a tick was made at the position of the second hand and, if necessary, a recognition mark made. While this may appear rather crude, it is possible to gain a certain facility at the operation and no doubts regarding the results are felt on account of this method.

5.3.3. Two small current meters were available in the Department. The first was of the type developed at the Hydraulics Research Station, Wallingford,[5.7,8.] and manufactured by Messrs. Parkinson and Cowan, and was intended primarily for the measurement of low water velocities, of the order of 2 to 30 cm./sec. It is known as a miniature current meter.

5.3.4. The measuring head of the production meter consists of a polystrene rotor, of sweep diameter 1 mm., with 5 helical blades mounted on a stainless steel spindle. The spindle runs in adjustable jewel bearings and the setting of the rotor is protected by a circular framework fixed to a stainless steel tube, as shown in Fig. 5.5. A gold wire insulted from the tube passes down inside it and finishes about 1 mm., clear of the rotor blades. Connection to the electronic recording unit is made by coaxial cable.

5.3.5. The manner of detecting rotation of the propeller has been developed from a method previously employed by D.G.B. Pegram.[5.7] The cable, gold wire and the measuring head form one arm of a Wheatstone bridge network. This network is initially balanced, the recording unit being so set that the variation of resistance as each rotor blade passes the tip of the gold wire does not disturb this first balance. The variation of resistance is received by the recording unit as a pulse rate which thus varies with the velocity of rotation and can so be related to the water velocity. In the apparatus as originally developed by the Hydraulics Research Station, the pulses were counted using a Dekatron counter but in the apparatus as supplied by Messrs. Parkinson and Cowan, the pulse rate is converted to a deflection on a gauge on the recording unit.

5.3.6. A photograph of the small measuring head is shown in Fig. 5.5. and of the complete apparatus as set up for testing in Fig. 5.6.

5.3.7. It is recommended that the meter be calibrated by drawing the measuring head at known velocities through still water in a circular flume. Since such a flume was not available, it was decided to calibrate the meter against velocities in a straight flume as determined using a calibrated Ott meter, the second small meter available, and by timing visual objects over measured lengths in the flume. In fact, the density current flume was the first suitable flume for such work that had become available in the Department.

5.3.8. The small propeller meter supplied by Messrs. A. Ott, Kempten/Bayern, is capable of measuring velocities from about 2 in./sec. to 16.4 ft./sec. by the use of a range of propellers, supplied with the instrument. The particular instrument available had been calibrated with each propeller. The complete apparatus, as shown in Fig. 5.6, consists of the current meter and a stand, both of stainless steel, (Fig. 5.7), a rev. counter set, actuated by a "make and break" mechanism at each revolution of the propeller, the battery and mechanism of which are contained in a small light wooden box for convenience in handling, the requisite wiring and contacts, a stop watch and tools for fixing or dismantling the meter.

5.3.9. A suitable propeller (3 cm. diam.) was chosen for the Ott meter, bearing in mind the velocities to be expected and the relatively narrow range of depths at which a more or less constant velocity could be assumed. Having obtained the number of revs./sec. for a given flow, the velocity of the water was interpolated from calibration charts supplied by the manufacturers. For velocities lower than about 7 cm./sec., the starting velocity of the chosen propeller on the Ott meter, the velocity of the water was found by timing very small spheres (of density approximately equal to that of water) over a measured length in the flume. This procedure was also carried out with higher velocities when using the Ott meter and very good agreement was found to exist between results as obtained by the two methods. (Results in Section 16)

5.3.10. Several flows, each of different velocity, were measured by the Ott meter and by timing the small spheres. Gauge readings on the recording unit of the miniature current meter were also noted and, at sufficiently low velocities, the number of revs./sec. of the rotor in the measuring head were found directly. This was done by marking one of the rotor blades and timing a selected number of revolutions.

5.3.11. The deflections of the miniature current meter set and the counted revs./sec. of the miniature propeller against velocities are shown in Fig. 5.8. Gauge readings of the instrument appear to be too inaccurate to permit the use of the recording unit at low velocities and at higher velocities the superior accuracy and ease of operation of the Ott meter make it preferable for tasks where its size is not a disadvantage. At low velocities direct counting of the revolutions of the miniature current meter, using an accurate stop watch with a 10 seconds per sweep hand, appears quite convenient. The probe unit of the miniature current meter cost £45 and its fragility was admitted by the makers who advised the keeping of a spare. An enquiry was made regarding the cost of probes not equipped for automatic recording, both of the standard pitch and pitched so as to revolve about half standard speed. This would allow velocities of up to about 1 ft./sec. to be observed. Unfortunately the manufacturers' production of and, it would appear, interest in the miniature current meters had ceased.[4] Of course, local manufacture to the H.R.S. designs could be considered for future projects.

5.3.12. Various developments of the pitot tube have been described[1.1, 2.7, 5.9] as has an even more sensative instrument based on a similar principle.[5.10] But it was not thought practicable to develop one of these techniques for the present tests. With single handed operation, a balance had to be struck between the ideal and the feasible, and it was decided to concentrate on non-homogeneity recording and visual recording of fronts or markers, augmented by the small current meters. As regards small markers, or fronts, a motion camera can usefully be employed for timing,[3.22, 5] but here again, the development of such a technique was not attempted during the present tests.

6. RESTATEMENT OF DERIVATION OF BASIC DIMENSIONLESS NUMBERS LIKELY TO BE APPLICABLE TO NON-HOMOGENEOUS MODELS

6.1 Notation

Symbol	Quantity	M L T system dimensions
L	Length	L
A	Area	L^2
V	Velocity	L/T
F	Force	ML/T^2
T	Time	T
g	Gravitational accelln.	L/T^2
ρ	Density	M/L^3
μ	Coefficient of dynamic viscosity	M/LT
ν	Coefficient of kinematic viscosity $(\frac{\mu}{\rho})$	L^2/T

6.2 Derivations of Froude, general or internal Froude and Reynolds numbers

6.2.1. Complete similitude between a model and prototype requires that geometric, kinematic and dynamic similarity obtains.

Geometric similarity exists when all corresponding linear dimensions in model and prototype bear an equal relationship.

Kinematic similarity exists when the ratios of the components of velocity at all homologous points in two geometrically similar systems are equal.

Dynamic similarity between two geometrically and kinematically similar systems requires that the ratios of all homologous forces in the two systems be the same.

6.2.2. For dynamic similarity between a model and prototype the ratio of the inertial and of the active forces must be the same. Suppose corresponding fluid elements undergo changes in velocity under dynamically similar conditions and that gravity is the predominate active dorce, then the ratio of the inertial forces of corresponding elementary masses between model and prototype is

$$\frac{\rho_p L_p^3 \times \frac{L_p}{T_p^2}}{\rho_m L_m^3 \times \frac{L_m}{T_m^2}}$$

Since $V_p = \frac{L_p}{T_p}$ and $V_m = \frac{L_m}{T_m}$ the ratio becomes,

$$\frac{\rho_p V_p^2 L_p^2}{\rho_m V_m^2 L_m^2}$$

The ratio of the gravitational forces on the corresponding elementary masses is

$$\frac{\rho_p g_p L_p^3}{\rho_m g_m L_m^3}$$

Cancelling $\frac{\rho_p}{\rho_m}$ appearing on both sides, then

$$\frac{V_p^2 L_p^2}{V_m^2 L_m^2} = \frac{g_p L_p^3}{g_p L_m^3}$$

or $$\frac{V_p^2}{g_p L_p} = \frac{V_m^2}{g_m L_m}$$

giving the standard form of the Froude Number, $F = V/\sqrt{(gL)}$

For normal comparative purposes, where the media of the model and prototype are air and water, the 'g' in the above expression can be conveniently cancelled, but in densimetric phenomena the effective gravitational force becomes

$$g\left(\frac{\Delta\rho}{\frac{\rho_1+\rho_2}{2}}\right)$$

Where $\Delta\rho$ is the density difference between two media of densities ρ_1 and ρ_2.

If $\rho_1 \doteq \rho_2$ then

$$F = V / \sqrt{(\Delta\rho/\rho \cdot g L)}$$

6.2.3. Similarly, if viscous forces predominate

$$\frac{\rho_p V_p^2 L_p^2}{\rho_m V_m^2 L_m^2} = \frac{\mu_p \frac{\delta V_p}{\delta L_p} A_p}{\mu_m \frac{\delta V_m}{\delta L_m} A_m}$$

where μ is the viscous resistance per area A of an element for difference in velocity δV across δL at right angles to the direction of flow. For the purposes of calculation, assuming geometric and kinematic similarity,

$$\frac{\rho_p V_p^2 L_p^2}{\rho_m V_m^2 L_m^2} = \frac{\mu_p \frac{V_p}{L_p} L_p^2}{\mu_m \frac{V_m}{L_m} L_m^2}$$

or $$\frac{V_p L_p}{\nu_p} = \frac{V_m L_m}{\nu_m}$$

where ν = kinematic viscosity

The expression $\frac{VL}{\nu}$ is the Reynolds Number

7. NON-STEADY DENSITY CURRENTS IN STILL WATER (EXAMINED BY OBSERVATIONS OF VISIBLE SALIENT CHARACTERISTICS)

7.1. Introductory

7.1.1. In 2.1.6. it was stated that a relatively pure density current could be produced in a laboratory flume by suddenly lifting a thin barrier separating water of slightly varying density and at the same level. This type of experiment was selected as the first of the 'isolated' studies (see Section 1)

7.1.2. The analogous free surface phenomenon, an idealised 'dam burst' in a flume, was the subject of analysis by Saint-Venant over a hundred years ago. Keulegan[7.1] in 'Engineering Hydraulics', has summarised this analysis and made comparison with experiments by Schoklitsch. Stoker has recently summarised the more recent mathematical work on this problem.[7.2] Very recently Bata[7.3] has reported related experiments with gasoline and water, which fluids differ considerably in density (as compared with the thermal density differences under consideration) and are immiscible. He has attempted comparisons with both the extreme cases, but without really adding much to Keulegan's published dissertation. Again Rouse[7.4] has very recently predicted that continuity of variation of coefficients of proportionality for the velocity of the fronts on general Froude law basis, could be found experimentally between the extreme cases. Neither Bata nor Rouse appears to have made use of Keulegan's later unpublished but comparatively freely available work on the small density difference case,[1.9] and this has, in the opinion of the Author, limited the value of their conclusions.

7.1.3. Paragraph 7.1.2. was inserted mainly because the work on the free surface case started earlier than O'Brien and Cherno's experiments, the first study of the small density difference case, which were reported in 1932,[2.10] together with some analytical work. Since then, several authors have briefly considered the problem,[7.4-7] in each case providing a figure similar to Fig. 7.1, explicitly or implicitly showing the initial velocities of underflow and overflow as equal. Analyses have been made by Keulegan[7.5] and Schijf and Schonfeld[7.7] but together with O'Brien and Cherno's original analysis,[2.10] these have started from the symmetrical assumption referred to above and have resulted in the prediction of

$$V_o = .5\sqrt{(\Delta\rho \cdot g \cdot H/\rho)} \quad \text{(See Fig. 7.5)}$$

Where V_o is the initial velocity of the underflow and overflow fronts. It has in each case been implied that an indeterminate amount of the 'wedges' behind the fronts should also have velocity V_o.

7.1.4. A comprehensive series of experiments were carried out by Keulegan[1.9] some years after his analysis.[7.5] He concentrated attention on the underflow, and his results, as regards the movements of the interface, particularly the tip of the underflow, are best summarised by reference to three of his figures reproduced here as Figs. 7.2,3 and 4. Keulegan uses the terms:-

$$V_\Delta \text{ (Densimetric velocity)} = \sqrt{(\Delta\rho \cdot g \cdot H/\rho_{mean})}$$

$$R_\Delta \text{ (Densimetric Reynolds number)} = V_\Delta : H/\nu_{mean}$$

$$\frac{V_o}{V_\Delta} = K \text{ (Coefficient of Proportionality)}$$

Where V_o is the initial velocity of the wedge tip and ρ, $\Delta\rho$, ν and H are density, density difference, kinematic viscosity and depth respectively as shown in Fig. 7.5.

7.1.5. Fig. 7.2 shows Keulegan's measurements of coefficient of proportionality for the initial velocity of the saline underflow. He took $K = 0.465$ as the mean (full line) but tentatively suggested that there might be a variation over the range examined, as shown by the broken line.

7.1.6. Keulegan's studies were aimed principally at understanding and, if necessary, simulating the flow resulting from the release of water from a comparatively short lock. He deals in detail with the effect of the wave or front reflected from the end of the lock and of the channel width on the motion of the unchecked front, and has shown that congruency exists for this motion only as between cases where the parameter $V_o H / \nu_{mean}$ is equal and where geometric similarity between depth (H) lock length (Lo) and breadth (B) is preserved. This is illustrated by Fig. 7.3

7.1.7 The third of Keulegan's figures reproduced (Fig. 7.4) shows an attempt to find the shape of the 'lock' experiment interface early in its development.

7.2. <u>Lock Experiments</u>

7.2.1. Lock experiments similar to those described in 7.1. as reported by O'Brien and Cherno[2.10] and later Keulegan[1.9] were carried out in the level smooth bottomed flume, with the gate as one end and a temporary barrier as the other so forming a tank (1.5 ft. wide and 17 ft. long) The thin (1 mm) vertical barrier was fitted in slight grooves 4 ft. from one end and prior to its sudden removal upwards, the levels of the dissimilar bodies of water were normally made equal. It was often found possible to time the advance of both the overflow and underflow at 0.5 or 1 ft. intervals, one of the bodies of water being coloured with potassium permanganate.[6] Otherwise, the flow progressing the longer length was timed.

7.2.2. In order to co-relate with previous work the saline underflow was examined. Agreement was found with Keulegan's tentative evaluation of coefficient of proportionality, relating to the initial velocity of the front of the underflow, against the product of densimetric Reynolds number and the aforesaid coefficient. Results are shown in Fig. 7.6. O'Brien and Cherno's laboratory results are also shown and these mainly come close to Keulegan's line. The divergences were considered to probably result from the rapid increase in relative time needed to lift the barrier with increasing depth and not to be of moment when compared with the amount of evidence in Figs. 7.2 and 6.

7.2.3 The initial velocity of the saline overflow (the fresh water advance) was found to exceed that of the underflow by about 12% throughout the range examined, as shown in Fig. 7.6. This lack of symmetry had been noted, though not evaluated by Keulegan (Fig. 7.4) There is considerable scatter in the results but where the underflow and overflow are paired the variation from the mean is often similar, somewhat strengthening the evidence for a constant ratio in the range examined. At small initial velocities there was difficulty in starting the test evenly, particularly as regards the overflow, and there was, perhaps, some surface tension effect on the overflow as will be described later.

7.2.4. General similarity with the saline underflow coefficient of proportionality was found for the thermal underflow as is shown in Fig. 7.7. Although the percentage difference in surface tension between cold and tepid water is small,[7.8] this was found to affect considerably the thermal overflow within the range studied, preventing the evaluation of the coefficient. Fig. 7.8 shows surface tension variations for comparable saline and thermal density differences. Fig. 7.7 shows values obtained with the surface tension difference balanced (7.2.5) by the addition of wetting agent to the colder water, and these correspond reasonably with the saline overflow results.

7.2.5. The surface tension comparisons were made by sprinkling aluminium powder on the water while still in the mixing tanks, and touching the one surface with drops of water abstracted from the other tank using a dropper. This shows up reduced surface tension in the abstracted water only and reciprocal checking is necessary near balance.

7.2.6. Slight differences in level, with either the surface of the less dense water above the other so as to give equal forces on the barrier or slightly below level, did not appear to cause observable changes in the flow.

7.2.7. The original recordings for the foregoing tests, i.e., depths, temperatures, salinity density differences and the timing observations as transcribed from the circular clock 'stickers' are given under "Recordings of tests A and B in Appendix 1." (Section 16 - Vol. II). On the relevant figures tests A are indicated by their number only, tests B by the addition of a zero before the number, and A before a number indicates O'Brien and Cherno's results. To obtain the given points required the plotting of the recordings, the selection of a best observed velocity and the working out of the value of K. Figs. 7.9 and 10 show typical plots of the recordings and calculations illustrating the process. Fig. 7.11 shows the variation of the kinematic viscosity of water with temperature. Mean values were used where appropriate. It can easily be shown that this cannot have a significant effect on the value of $K.R_{\Delta}$.

7.2.8. As opposed to Keulegan's work (7.1.6.) the present study was concerned primarily with flows unaffected by channel width or the reflected wave. Keulegan's results suggested that a breadth of depth ratio of six or greater approximates to the first requirement, at least for shallow depths. It seemed that for the design of heat dissipation models a Keulegan type congruency diagram for the infinite width and no reflected wave case would be desirable, with separation between overflow and underflow, and between saline and thermal cases as found necessary. Little could be achieved in this respect because of the very considerable travel lengths involved. Fig. 7.12 shows recordings which give some idea of the variation of the ratio L/H at $V = 0.9\ V_0$ for the small range of $K.R_\Delta$ possible in the apparatus within the aforesaid requirements. Though far from complete, valuable guidance was obtained from this figure in later experiments. These values were obtained from plots similar to those shown on Fig. 7.11.

7.2.9. The range of $K.R_\Delta$ covered included the change from laminar to turbulent interfacial conditions. In runs at approximately 0.3 ft. depth and with $K.R_\Delta$ about 5,000, interfacial waves just on the point of breaking were observed along the interface away from the wedge tips. With lower values of $K.R_\Delta$ at shallow depths a sharp interface was formed with laminar swirls causing mixing at the underflow tip. At the higher values of $K.R_\Delta$ obtained with increasing depth and maintaining a fair density difference, the oily appearance characteristic of intense turbulent mixing was noted.

7.3 Effect of surface tension variations in lock experiments

7.3.1. At depths about 0.8 ft. visible evidence of the effect of surface tension - a drawing forward of a surface layer in front of the overflow proper (Fig. 7.5) - was confined to two feet or so of advance, where it tended to be masked by the minor irregularities resulting from the sudden withdrawal of the barrier. Thereafter, the front tip appeared similar (perhaps slightly sharper) to the saline overflow although its apparent initial velocity was increased. Fig. 7.13 shows typical results for a range of temperature differences. Velocities as a proportion of the saline case initial velocity are plotted against distance travelled to depth ratio. Fig. 7.14 shows typical comparisons illustrating the effect of surface tension in a more graphic manner.

7.3.2. At depths about 0.2 ft. the effect of surface tension on the shape of the overflow was observed for 3 to 4 ft. of advance or about 8 to 10 times as far in terms of distance to depth ratio as at 0.8 ft. About this distance the true overflow shape overtook the surface draw forward. The typical results shown on Figs. 7.13 and 7.14 refer to the foremost point of the heated water. Between 0.2 and 0.8 ft. the effect, as would be expected, decreased and it seems reasonable to assume that it would have negligible effect in prototype conditions.

7.3.3. Lack of visible surface tension draw-forward after a certain travel length appeared to be due to the considerable surface advance (probably caused by the slightest trace of oily dust) which developed in front of the overflow even with virtually no surface tension difference. This was, for example, observed up to 4 ft. ahead of the saline overflow at velocities of the order of 0.1 ft./sec. after 7 ft. of advance. When such a surface movement was stopped by the end of the flume (or otherwise) the overflow tip velocity was checked and its form changed from that of the laminar overflow to something close to that of the laminar underflow. The characteristic 'over-riding' shape of the underflow with a roller, as noted by Harleman and Ippen[3.22] was observed (inverted) and sometimes, at the change from one condition to the other, a perfect roller with up to three complete turns was formed. This was similar to that illustrated by Prandtl[2.7] as the idealised case for the checking of an advancing front of cold air, and illustrated perfectly laminar mixing at the tip of the characteristic underflow shape.

7.3.4. Because of the much smaller surface tension difference for a given density difference in the saline case surface tension effect could not be isolated though it may have contributed to the erratic saline overflow results (Fig. 7.6)

7.4 Forced surface density currents

7.4.1. It was found possible to produce surface density flows along the flume into still water from an introduction box suspended with its bottom below water level and fed by a down pipe as illustrated in Fig. 7.15. The box was constructed from perspex with a 1. mm. thick bottom. This could be considered as approximating to zero thickness and so the vertical scale of the experiment could be reduced while using the same box, which is shown in Fig. 7.16. The water level was maintained constant by having a weir behind the box and introducing a homogeneous flow, equal to the heated density flow, into the flume near the weir up till the start of the density flow. For a given density difference a flow could be found at which the projected layer maintained a uniform depth approximately equal to the box depth, apart from a roller at the tip, for some distance along the flume. With increasing distance the rate of advance decreased and, consequently, the layer thickened. During the advance the roller deepened as the tip was diluted. If the flow was materially increased, the initial rate of advance from the box also increased but not sufficiently to accommodate the increased flow and the layer deepened below box depth from early in the advance. If the flow was decreased the front lifted from the box floor soon after passing through the screens and the initial speed of advance decreased, though not in proportion to the change of flow. No roller was formed and the typical overflow tip shape was observed. These cases are illustrated diagramatically in Fig. 7.15. When the scale of the experiment was halved, apart from the 1.5 ft. width of box and flume, (total depth decreased from 0.675 ft. to 0.3375 ft.) and the flow was decreased to give a projection velocity in proportion to the square root of the depth, the velocity of advance decreased relatively sooner. This is shown in Fig. 7.17 where the half scale results have been adjusted to the full scale times and distances for ease of comparison. Keeping the horizontal distances halved the depths were exaggerated so as to give a travel length ratio at 0.9 of the initial velocity (using straight part of the line on Fig. 7.12) which, when divided by the original travel length ratio and multiplied by the exaggeration would give 1. Only relative values of $K.R_{\Delta}$ were necessary because of the linear assumption, and an exaggeration of 1.4 was obtained. The density difference was increased slightly to give correspondence in initial velocities on the basis of Fig. 7.7. As shown in Fig. 7.17, similarity was attained regarding the velocity of advance of the front on the basis of the velocity scale being equal to the square root of the vertical scale, and as far as could be seen, the shapes of the layers were similar apart from the rollers. These experiments were conducted with the surface tension difference balanced. Similar results at full scale were obtained without this adjustment but the reduced scale results were erratic. Sometimes the roller type of tip occurred and sometimes a faster moving and more pointed wedge developed either initially or after some travel. It appeared that the capacity for surface tension effect was present and whether or not this occurred was dependent on the distinctness of the interface where it reached the surface.

7.4.2. The recordings for these tests are listed under 'Tests E' in Section 16. As comparisons were based on the plots of the advance of the top of the front, the only computations necessary were the finding of a 'general Froude law' time correction factor for each reduced scale test.

7.5 Simplified outfall experiments

7.5.1. It was thought that a comparison of scale effect, similar to that described in the previous section, should be made for a more general case. A coloured heated flow was introduced into the 7.25 ft. wide tank along an 0.5 ft. wide introduction box set into the middle of one end of the tank, as shown in Fig. 7.18. The depth of water in the box was 0.165 ft. and the total depth 0.83 ft. After an interval the spread was photographed through a grid suspended close to the water surface. The experiment was repeated with the surface tension balanced, first at full size, then at one third size, and finally at one third size horizontally with vertical distortion of 1.55 and density difference increase, both according to the process described for forced surface currents. Results are shown on Fig. 7.19 having been brought to the full size basis for comparison. Surface tension variation seems to have had little influence on the spread during the larger scale experiments. Otherwise the natural one third size test shows failure to achieve similarity and the distorted case appears slightly over corrected. A small error due to relatively varying rates of rise of water level was present as the same tank was used throughout.

7.5.2. Further tests were made using a one-fifth size model of the tank, formed by cutting off a short length of the flume, and basing the comparison on the rate of advance of the foremost point of the front up the tank. This was influenced by the sides after about 9 ft. of travel and by 14 ft. the middle of the front was only slightly in advance of that at the sides. Results are shown in Fig. 7.20. The failure in the natural reduced scale tests is marked. Although a distortion of 2.1 was obtained from Fig. 7.12, this was found to overcorrect and the best results were obtained with 1.95 distortion. Fig. 7.12 was adjusted on this basis. The general sequence of events appeared similar to the full size tests. Considerable mixing took place near the entrance; with temperatures of 63.8°F. and 83.6°F. the surface temperature at the full scale equivalent of 2 ft. from the entrance was about 71°F. during the test; and mixing swirls were noticeable.

7.5.3. The recordings are listed under 'Tests G' (Section 16.)

7.6 Heat Losses

7.6.1. Apart from the extreme circumstances dealt with in 7.7, heat losses to the atmosphere were not thought to be material. The effect of heat losses on models and small scale "studies" is dealt with in Section 11, with reference back to the tests in this project. But it should here be said that actual tests lasted a very short time after the final temperature check and that most thermal tests were carried out with the air temperature rather above the colder water temperature.

7.7. Effect of non-linearity of thermal density variation

7.7.1. Tests at temperatures around the density reversal temperature of fresh water (Fig. 2.1) were difficult to investigate quantitatively:-

(i) The laboratory had a high air temperature which could not be controlled in isolation from the rest of the building. Undoubtedly the best way to conduct low temperature model experiments is, as with the Kincardine investigation, during a cold winter in an isolated building. In the College the air temperature made reduction of water temperature difficult. More especially water in the flume tended to heat during the stilling period. Finally there was the probability of a material effect during a test.

(ii) Two cwt. of ice (carried up a ladder in buckets) were required to reduce one mixing tank (larger) of water to around 35°F, even in winter, when the tap temperature was about 50°F.

(iii) The small density differences involved made it impossible to obtain more than faintly turbulent conditions at the scale of the experiments which could be achieved in the apparatus. Temperatures of, say 34°F and 50°F, which might be thought suitable to investigate the effect of non-linearity, give a density difference of only 0.0002 gm./ml.

7.7.2. A few tests of the general type of forced surface density currents were made, but with the introduced water causing a rise in the general water level. The point of inversion was between the warmer (47 - 49°F) introduced water and the basic water (34 - 36°F). A slowly moving advance was obtained from which dropped 'streamers' (the introduced water being coloured). Eventually the overflow tip was diluted to the extent where no density difference existed and thus come to a halt. An underflow caused by the build up of the dropping 'streamers' continued along the flume.

7.7.3. For less severe non-linearity there will no doubt be some effect - e.g. shape of roller - due to variation in density difference after a certain amount of dilution as between hot and cold and fresh and saline water.

7.8. <u>Discussion and preliminary conclusions</u>

7.8.1. The circumstance of 'Density currents' having been selected as a Topic for the Eighth Congress of the International Association for Hydraulic Research, Montreal, August, 1959, led to a paper being rather hurriedly prepared. It was thought that certain conclusions could be drawn from the experimental work so far described and it seems reasonable to summarise these here.

7.8.2. It had been shown that, unless the correct vertical exaggeration and density difference exaggerations are adopted, similarity even between one horizontal scale and another could not be expected. It was intended to examine the temperature distribution in experiments such as those described under "Simplified outfall experiments". Lacking these, it could be said that the heated water did appear to take up the same general orientation in the different scale tests when agreement as regards the chosen criterion was achieved. Of course, with density difference exaggeration the recorded temperature increase during a test would be proportioned in the ratio of the initial temperature differences. Near $40^{\circ}F$ this would introduce a slight error.

7.8.3. In a small scale model, surface tension variations could cause considerable modifications of the flow patterns, perhaps differing between one test and the next. It would seem advisable to carry out some of the tests of a particular investigation with the surface tension differences balanced out and compare the results with others obtained without this adjustment. While a fresh water flow into a saline body to represent heated water into colder water would largely avoid surface tension differences there might be objections to this:-

(a) The salinity-density variation can only reasonably approximate to the temperature density variation above about $50^{\circ}F$. (But whether this is material or not is difficult to say.)

(b) With care heat losses could be simulated if the air temperature were controlled,[1.4] but not, of course, with saline density variations.

(c) The small salinity differences involved would be more difficult to record than the corresponding temperature differences, whether the comparison is between titrations and thermometer readings or between the appropriate automatic multi-point recording methods.

7.8.4. A slight scale effect may be present in models when a broad fronted overflow approaches a shore line and receives the check described earlier, caused by the slightest traces of dust on the water surface.[1.1]

7.8.5. It should be noted that the simplified outfall experiments were designed to be little affected by the correctly scaled entrance velocities, but were intended to show the effect of the interfacial drag. In some, at least, of the investigations listed in Table 1.1, similarity was doubtless much more dependent on the entrance velocity. For example, in the Kincardine investigation[1.4] the main interest was in the low slack water condition in a shallow tidal river and the flow from the outfall under these conditions extended down to bed level for a considerable distance away from the outfall. Thus the heated water was quite far from the outfall before being subject to true overflow conditions. In other of the listed investigations the slack water condition was not the point of interest.[1.4a]

7.8.6. Some discussion of the reasons for the variations observed in the flows during 'lock' experiments was attempted in the paper mentioned. However, as further tests were carried out with observations of the mixing processes, (Section 9) this will be combined with the later discussion. The tests described in Section 8 were interspaced in order to gain experience with the thermopile recording system and because it was hoped to learn something of the nature of interfaces under steady conditions before studying transient conditions.

8. STEADY STATE MIXING IN STRATIFIED FLOW

8.1. Introductory

8.1.1. The initial stages of the project were oriented, as regards actual heat dissipation and recirculation circumstances, towards the slack water period in a tidal river or estuary. In considering either the ebb or the flood, the circumstance of a relatively wide band of heated water flowing with and over a general flow comes readily to mind. It can be imagined that the sides are spreading by eddy dissipation or, more likely, by internal gravitational advance, or a combination of these, while vertical mixing takes place over the whole of the area.

8.1.2. In pursuance of the intention to isolate the various phenomena involved in heat dissipation and recirculation studies, as far as possible, it was thought that the effect of scale on vertical mixing might be studied if a layer of identifiable water was superimposed on a main flow of 'basic' water in a flume. Such an experiment had been intended from the start of the project. Normally, the approach would be to consider previous work, then to try some experiments so as to obtain familiarity with the operation of the apparatus and find the range of variables which could be covered. Having learned as much as possible from observational runs, a series of experiments might be designed to try to correlate with such theoretical predictions as could be made. In fact, the experiments were commenced while a student doing a very restricted period of full-time research, in order to obtain material for an A.R.C.S.T. thesis, was working with the Author. This tended to make the observations hurried and the recording apparatus, being an attractive feature for that type of thesis, was brought into use practically at once. However, the work done during this period was not wasted. Snags in the procedure were found, some of which could be put right later. It should be appreciated that though the studies were steady state, the length of run possible was very restricted due to the relatively small size of the header tanks. Thus, final results for a selected condition, if more than merely characteristic, would have to be composite. Although flows could be readily repeated, density differences were difficult to repeat exactly; the main body of water heated up slowly during a day's work and temperature differences were always varying for a selected density difference. Fortunately, it transpired that the early tests could be combined with later recordings in making up composite results.

8.1.3. Because of the short periods of the tests there was a tendency not to observe as calmly as is desirable, during the early instrument recording tests. The next stage was to run a fairly long series of observational tests; but modifying these as seemed logical in the light of the results obtained earlier. While the tests for this part of the project were in progress, it was learned that similar tests were being, and had been, carried out elsewhere. In the first case, Dr. Keulegan said that he was starting similar saline experiments, but oriented towards salinity intrusion in rivers. Then it was learned that experiments concerned with the mixing of methane with air in mines, but based on saline and fresh water, had been undertaken at Manchester University. Only brief details, as given in a letter, were available. It is thought best to first describe the early instrument recording experiments and the observational runs, and then go on to what was attempted as 'finished' experiments:

8.2. Initial tests

8.2.1. The introduction box was suspended in the flume facing downstream (edge at + 0.5 ft.) with its bottom 0.5 ft. above the floor of the flume (Fig. 8.1). A fairing was attached to the upstream end. With 0.625 ft.

depth of water in the flume (configuration A) it was found that with a basic flow of 0.357 cusecs and an introduced flow of 0.0894 cusecs (flows 1) at a higher temperature so as to give a density difference of 0.0015 gm./m.l., a reasonable amount of turbulent mixing took place. (The various combinations of box depth, total depth and overfall or underflow withdrawal at the end of the flume are given letters for 'configuration'. The various flows are given numbers. These codes are shown in Section 16, as are total Reynolds Numbers for the combined flows in the flume.) The flows were in direct proportion to the cross sectional areas of flow at the introduction box and the basic temperature was in the region 60 - 65°F.

8,2,2. When the characteristics of mixing were examined using the thermopile probes, the recording system was found to be sufficiently sensitive to pick up small eddies. A pattern of recordings was obtained for a range of depths and of distances from the entry box, as shown in the recordings for tests H.1. a - e. Two points emerged from these first recordings. Firstly, the persistance of the molar nature of the mixing, and secondly that, except for the middle of the mixing zone, mixing tended to the form of penetration of either of the base fluids by dissimilar eddies. Comparison of the recordings shows a tendency to an irregular but overall repetitive form. It was also noted that at the fringes of the mixing zone the pattern was very intermittant, with random departures from the base. The widely fluctuating nature of the recordings in general could not be readily analysed even so far as to obtain mean values. Also, though thin, the probes were observed to cause mixing eddies. It was therefore thought advisable to try damped probes and to avoid the chance of disturbance of the flow.

8.2.3. Eight waxed probes were set in a line across the flume 1.5 ft. from the introduction box, seven of them ranging uniformly from 3 in. mean depth of bulb to $\frac{1}{2}$ in. mean depth and one as close to the surface as possible. A series of tests at 0.625 ft. total depth was run, covering the range of density difference given by temperature differences of about 2^{o}F to 30^{o}F from a base of 65^{o}F, and a range of flows from 0.357 and 0.0894 cusecs (Flows 1) to 0.047 and 0.0112 cusecs (Flows 4). The recordings are given under tests H.2 - 17. Fig. 8.2 shows an example of turbulent mixing, the upper layer of introduced water being coloured. From the recordings, there was obviously a wide range in the amount of mixing, even after only 1.5 ft. travel.

8.2.4. For the second of the flows (Flows 2) a further number of tests were carried out with the eight probes at the same range of depths as previously, but positioned in turn at 0.5, 1.5, 2.5 and 4.5 ft. downstream of the entry box. Five density differences were used, 0.00299, 0.00153, 0.00087, 0.00032 and -0.00067 gm./m.l. (the negative sign indicating that the bottom layer was the less dense. The recordings are shown under Tests H.18 - 22. With the density difference 0.00299 gm./m.l. a clear interface was observed and virtually no mixing took place. With density difference 0.00153 and 0.00087 gm./m.l., mixing was very slight. For these three cases virtually the same recordings were obtained for all positions of the probes. The final two tests certainly show the extreme sensitivity of amount of mixing to very small density differences.

8.2.5. All the tests described above were carried out with flows proportional to the areas at the entry box. Prior to the last series of tests, however, the surface of discontinuity between the two flows was studied with the upper flow greater and then smaller than that given by proportioning the flow to area. In these cases the eddies arising from the interfacial waves had a definite direction of rotation, turning from the general direction of flow towards the slower moving layer. At the flows actually used in the experiments the waves could still be observed but the eddies did not fall into a distinguishable general direction of rotation.

8.2.6. Some flow measurements with the miniature current meter were carried out for flows 2 with no density difference. The recordings as given in Section 16 and the vertical velocity distributions obtained are shown in Fig. 8.3.

8.3. <u>Mainly observational tests</u>

8.3.1. The additional V-notch described in Section 4 was fitted (Fig. 47) and the introduction box moved back to have its edge at - 2.0 ft. in the flume, and again suspended 0.5 ft. above the flume bottom. A large number of observational tests were run, eventually using the small flume as a model of the large (with appropriate introduction box and with the drop floor sealed to form a normal flume). Observations were made by viewing the coloured upper flow, by timing the travel of surface floats and by viewing the relative speeds of the upper and lower flows as shown by dropping a 'splotch' of strong potassium permanganate solution into the flume. A few Ott and miniature current meter recordings were made. The original recordings and notes are shown in Section 16; the results as they throw light on the phenomena being summarised here.

8.3.2. With flows 1 and zero density difference the coloured water reached the bottom (apart from the thin laminar layer) at about 4.0 ft. from the box. As observed during the initial tests, there was not a clear cut diverging mixing zone; separate eddies could be distinguished and the 4.0 ft. represents the typical point of contact of an eddy; the point might then clear momentarily prior to the arrival of the next eddy. Mixing continued down the flume being fairly complete vertically by 11.0 ft., from the box, but never being quite complete and not changing much from 11.0 ft. As density difference was introduced and increased the divergence lifted somewhat; at 68.7°F - 78°F (0.00119 gm./m.l.) the bottom point of contact was 5.0 ft. downstream from the box, and stratification was clearly visible. At 687°F - 84°F (0.00214 gm./m.l.) it was noted that streamers only reached the bottom and the surface temperature at the end of the flume (15.0 ft.) was 81°F. This condition, growing more distinct, persisted till the greatest possible density difference (governed by the softening point of the perspex sides) of about 0.0035 gm./m.l.). Fig. 8.4. shows plots of the travel of surface floats for zero density difference. The results for the maximum possible density difference (about 0.0035 gm./m.l.) show the slightest trend towards a faster surface velocity, but, within the accuracy of the method of observation and allowing for natural scatter of successive tests of the same condition, cannot be said to show that a meaningful divergence would be obtained on plotting and drawing a comparable best line.

8.3.4. The flows were halved (Flows 2) and halved again (Flows 3). Figs. 8.4 and 8.5 show plots of the travel of surface floats, again with comparisons with the mean velocity about mid-travel. At the maximum possible density difference (about 0.0035 gm./m.l.) there was still no clear cut change in velocity, as determined by the float measurements, although, for Flows 3 at least, some signs of surface speed up just before the end overfall could be detected by the 'splotch' method. Otherwise, the velocity remained remarkably constant in the vertical direction to within an inch or so of the bottom and the curves of Fig. 8.3 as well as agreeing perfectly at the surface with the comparable estimate of velocity by the float method, seemed to typify the velocity distribution in general. Obviously this was affected near the weir but the divergence could only be observed for about 1.0 ft. back. The range of distribution of the heated water varied considerably from that observed during tests with flows 1 being completely stratified by the stage when maximum density at flows 3 was reached with only a slight 'hazing' of the interface. No signs of laminar velocity distribution were observed, in the layers or in the box.

8.3.5. At zero density difference the point of contact with the bottom was still 4.0 to 4.5 ft. for both flows 2 and 3. The complete lift of the heated upper water, as occurred in both cases, was at successively smaller density difference. Salient runs were as follows: Flows 2, 68.3°F - 72.0°F (0.00045 gm./m.l.); streamers only reached bottom of flume;by 0.00078 gm./m.l., the streamers had been suppressed. Flows 3, 67.5°F - 69.5°F (0.00024 gm./m.l.); when reduced steadily from this temperature difference to zero temperature difference, the mixing zone moved steadily down to touch the bottom.

8.3.6. Once again halving the flows (Flows 4) the awaited divergence in surface velocity as between zero density difference and about 0.0035 gm./m.l., density difference was clearly observed (Fig. 8.6.) Again there is considerable scatter between similar runs, but no doubt about the overall picture; allowing for scatter, the intermediate runs would more or less fit in between the extremes. Splotches of dye now disclosed a clear speed up of the upper flow, which therefore thinned. The velocity distribution in it was of the laminar type. Observing the zero density difference case, large distinct slow moving waves or eddies broke each way from the interface and top water again reached the bottom about 4.0 ft. By now a slight temperature difference, 66.0°F to 67.8°F was sufficient to practically suppress mixing.

8.3.6. On stopping the upper flow with a larger density difference and flows 4, the upper layer persisted for a considerable time, lying as a laminar layer above the turbulent lower flow, which was, however, insufficiently turbulent to 'break through'. The upper layer was slowly thinned till only

$\frac{1}{4}$ in. or so in thickness after several minutes. At flows 2 there was little tendency for this; the lower flow breaking through and sweeping the upper layer downstream.

8.3.7. Some tests were run with bottom withdrawal at the end of the flume. With zero density difference, there was little change in the velocity distribution to within a foot or so of the weir for all flows. Changing to 67.0°F to 82°F density difference there was again little effect in velocity distribution for flows 2; with flows 4 the usual speed up of the surface water, lifting away from the bottom of the box occurred, but the top water was not swept under the weir but built up a wedge which travelled back towards the box.

8.3.8. The subsidiary flume was $4\frac{1}{2}$ in. in width as compared with the 18 in. of the main flume. Using the small flume as a $\frac{1}{4}$ horizontal scale model of the large flume on a normal Froude law basis, a vertical exaggeration of 1.8 was found necessary, by the method described in Section 7, to maintain similarity of the advance of fronts. Although such advance was not involved in the present experiments it seemed logical not to ignore the exaggeration which would be necessary in a practical investigation. In the results, configuration B refers to the 1.8 vertical exaggeration model and flows 6 and 7 to normal Froude law simulation of flows 2 and 3. Throughout the smaller scale experiments the dimensions used are the equivalent prototype dimensions for the particular horizontal and vertical scales in use at the time. Times had, of course, to be adjusted.

8.3.9. For zero density difference the points of contact of the eddies from the upper flow with the bottom were noted as 4.5 ft. and 4.5 to 5.5 ft., for flows 6 and 7 respectively. Otherwise no distinct lack of similarity could be observed. This was typified by a demonstration run during a visit. With flows 6 and 2 in model and prototype respectively, both were run with the same supplies. Initially, the upper flow was made a degree or so colder and in both the point of contact approximated to 1.0 ft. The hot water feed to the header tank was opened and the supply temperature to the upper flows rose gradually. Model and prototype behaved very similarly, but the effect of the incorrect time for the changes of temperature in the model (which should have been around .7 of the prototype times, showed up as a quicker clearing of mixing down the flume in the model compared with the prototype.

8.3.10. Again the surface float recordings showed no distinct difference as between zero density difference and around 0.0030 gm./m.l. density difference. Figs. 8.4 and 8.5 show plots of typical runs connected to correspond with the full size runs. There was a scale effect in starting the chip of wood used as a float in model and prototype, which could clearly be seen using coloured water to show the 'slip' between the accelerating float and the water, and which shows up in the plots. But the velocities once the float is moving are in good agreement; and considering the relative difficulty of making the observations in the small flume, especially at flows 6, it was thought that the comparisons were extremely satisfactory.

8.3.11. The small flume was adjusted for simulation of the larger on an unexaggerated vertical scale and normal Froude law basis (flows 8 corresponding to flows 3 and the configuration noted as C). This test was approaching the limiting value of Reynolds Number for turbulence to exist along the flume, even allowing for the nature of the entrances (R.N. was 445). At zero density difference some of the upper flow still reached the bottom by 3.5 to 4.0 ft, though there seemed to be less mixing along the flume than would correspond to flows 3. The surface floats still gave fair correspondence with the large flume; two runs out of four giving almost perfect agreement allowing for the initial scale effect. At full density difference of about

0.0030 gm./m.l. there was an increase in velocity of about 8%, still far short of that for full size flow 4 (34.5%) despite the decrease in Reynold's Number (445 c.f. 1,775).

8.3.12. With the small flume and flows 8, the effect, on the surface velocity increase, firstly, of roughening the bottom of the flume by scattering gravel ($\frac{3}{8}$" mesh and down) on the floor of the flume to cover about 25% of the area and, secondly, of driving a pattern of nails into the bottom, was investigated. The pebbles, especially, seemed to prevent this surface layer from increasing its velocity, though it should be remembered that the increase without the pebbles, amounted only to 8%.

8.3.13. Using the larger flume, some tests were run with the entrance box placed, as before, 0.5 ft. above the flume bottom, but with a total depth of only 0.5416 ft. Again proportioning the lower and the introduced flows to the cross sectional areas, it was possible to run tests with a larger total flow since the introduced flow was the limiting factor. With flows 9 (Section 16) with average velocity about twice that for flows 1, the coloured introduced flow again reached the bottom about 4.5 ft. from the edge of the box with zero density difference between the flows. Ott current meter readings were just possible with flows 9 and these showed a distinct change in vertical velocity distribution between 4.0 ft. and 11.0 ft., the more typical type of distribution occurring at 11.0 ft. (Section 16). When the upper flow was heated to 90.0°F (lower flow 66.5°F; density difference 0.0043 gm./m.l.), some of the upper water still reached the bottom by 4.5 ft. but some layering persisted to the end of the flume. At 13.0 ft., the surface temperature was 75°F and the temperature 2 in. above the bottom was 68°F.

8.3.14. Halving flows 9 in the larger flume (flows 10), at temperatures of 665 and 88 °F the upper flow reached the bottom between 4.5 and 5.5 ft. At 13.0

feet the surface temperature was 78°F and 2 inches above the bottom the temperature was 67°F. These temperatures are mean values of the fluctuating reading on a thermometer held with its bulb at the required position. Flows 10 were simulated in the smaller flume using a 1.8 vertical exaggeration (Flows 11). With temperatures of 66.5°F and 87°F the coloured upper flow reached the bottom by 5 to 6 ft. (Equivalent prototype distance). At 13.0 ft. the surface and the 2 in. from bottom temperatures (equivalent prototype depth) were 77°F and 68°F respectively, in good agreement with the prototype. With zero density difference the point of contact of the upper water moved back to about 4.5 ft. in both model and prototype.

8.3.15. Returning to flows 3 and configuration A in the larger flume, temperatures of 66.4°F and 83.3°F gave a surface temperature of 82.5°F at 140 ft; comparatively little mixing having taken place. Two common bricks were placed in the flume so as to form a 3 in. wide by 4½ in. high block across the flume at 9.0 ft. With the same temperatures and flows, the average surface temperatures were 82.7°F, 78°F, 74°F and 73°F at 9.0 ft., 11.0 ft., 13.0 ft., and 14.0 ft., respectively. The bricks were moved to 2.0 ft. from the introduction box. With temperatures of 680°F and 842°F for lower and upper flows respectively, the average surface temperatures at 2.0 ft; 4.0 ft; 6.0 ft., 8.0 ft., 11.0 ft., and 14.0 ft. were 83.4°F., 80°F., 77°F., 75°F., 74°F, and 73.5°F. respectively. With a coloured upper flow it was observed that the increase in velocity to surmount the bricks was apparent for a short distance only on the upstream side. Downstream, the mixing was most marked between 4.0 ft. and 5.0 ft. and was more or less completed by 8.0 ft. The slight vertical stratification still visible at 8.0 ft. did not thereafter noticeably diminish.

8.3.16. It was obvious that more could be done with a thermometer ony, and that this method of comparison might have been used earlier. But it now seemed appropriate to consider the evidence available, and to design a short series of experiments using the recording system. It was decided to concentrate, for the time being, at least, on the simulation aspect of the phenomena rather than the analytical prediction aspect. The further the studies went, the more it was realised that the various aspects of flow and mixing in heat dissipation models were nearly all particular cases of the basic phenomena which were studied by hydro-dynamicists. Nevertheless, heat dissipation models had been used in the past and would doubtless be used again, without a detailed understanding, from the hydro-dynamic point of view, of the factors involved.

8.3.17. The recordings for this sub-section are listed as test series J, in Section 16.

8.4. <u>Further tests using thermopile recording apparatus</u>

8.4.1. In order to allow a speedy coverage of the whole length of the larger flume downstream of the introduction box, a 'traveller' was made which could be slid along the tops of the flume sides. It was stable, without fixing, and the recording probes were mounted on it. The "cold" junction probes, and both 'reference' probes were immersed in water contained in a bucket, which could be lifted along the flume as the traveller was moved. Fig. 8.8 shows the new arrangement of the probes.

8.4.2. From tests J, it was known that with flows 1, configuration A and the maximum thermal density reduction conveniently possible in the upper flow, little mixing would occur in the flume length. Changing the configuration to E and F by placing a $4\frac{1}{4}$ in. by $2\frac{7}{8}$ in. cross-sectional barrier across the flume bottom two feet downstream of the edge of the introduction box, conditions of partial and of almost complete mixing, by the end of the flume, were obtained with the longer and the shorter sides of the barrier horizontal respectively. These changing patterns of mixing are shown in Fig. 8.9 on a percentage temperature difference basis. To maintain the same general Froude number for flows 2, 3 and 4 (successively halved) it was necessary to successively quarter the density differences. This meant that the temperature difference for flows 4 was only about half a farenheit degree. However, even at this stage some evidence was found that the same patterns of mixing obtained.

8.4.3. Considering first configuration A, Fig. 8.9 shows that with flows 1, the surface temperature dropped to about 90% of the upper flow introduction temperature by the end of the flume, but that relatively little mixing occurred. For flows 2 and 3, tests M6 and M23 showed a very similar maintenance of stratification, about 90% of the original temperature difference remaining at the surface by the end of the flume in both cases. (N.B. M23 was example of test where there was a relatively large temperature difference between the lower flow and the reference bucket - about 20% of the flows temperature difference - and allowance should be made accordingly in examination of the recordings). The desired density differences for tests M6 and M23 were 0.00084 and 0.00021 gm/m.l. and those attained were 0.00088 and 0.00021 gm/m.l. (as obtained from the large scale plot of the temperature-density relation previously mentioned)

8.4.4. Configuration E and flows 1 led to considerable mixing (Fig. 8.9), the top and bottom temperature differences being about 59% and 10% of the starting increment by the end of the flume. Tests M11 (c.f. M7 as check on consistency) and M24 showed comparable results for flows 2 and 3; 63% and 7% being the approximate spot checks for M11 and about 62% for M23 at the surface, with the pattern of decrease of the recording being of more significance than an attempt to measure the small bottom deflection on the recordings.

8.4.5. Configuration F and flows 1 led to practically total mixing, largely accomplished by 8 ft. Tests M12 and M25 fell into line, the mixing at 8 ft. being perhaps slightly less for these tests of flows 2 and 3.

8.4.6. With flows 4 the desired temperature difference at 62°F was 0.5°F. During the tests the amplifier was switched to A.C. which gives a boost of three in the deflection of the oscillograph 'spot' over that with full gain D.C., but tends to cause fluctuations. At the end of each test a normal D.C. recording of the 14 ft. position was made. In general the same pattern of mixing for the three configurations (A, E and F) probably occurred, as shown in the recordings for tests H38, H39 and H37 respectively. Visual observations gave no indication to the contrary.

8.4.7. A fair range of tests was covered in the larger flume, some of which will be referred to later and some of which have not so far been used. It seemed reasonable to cover a range greater than that described in the immediately preceeding paragraphs while the apparatus was available, and for example, tests M25 - 29 illustrate the effect of increasing density difference (0.00021, 0.00042, 0.00084, 0.00168 and 0.00336, gm/m.l. aimed at) on the amount of mixing with flows 3 and configuration F.

8.4.8. In pursuance of the check on the applicability of the general Froude law, some tests were carried out in the smaller flume. First configurations A, E and F and flows 2 were simulated (configurations C, H and J and flows 12) to a natural $\frac{1}{4}$ scale. To obtain the same general Froude number, having maintained the normal Froude number for simulation without consideration of density difference, the density difference was kept at that for flows 2. Using the same spot checks for configurations A - C and E - H as previously, (but assuming 12 ft. similar to 14 ft.) 90% compared with about 90% and 60% and 11% compared with 63% and 7% were obtained for C compared with A, and H compared with E respectively. (Tests M43 and M44 for smaller flume compared with M6 and M11). For configurations F - J the degree of mixing in the smaller flume was perhaps slightly less complete by 12 ft., (Test 45 compared with Tests 12 and 30) but there was not much in it.

8.4.9. When a 1.8 vertical exaggeration was used in the smaller flume (configurations A, E and F and flows 2 simulated by configurations B, K and L and flows 6), the degrees of mixing at 12 ft. were hardly affected as compared with the unexaggerated smaller scale tests. (c.f. M43 with M48, M44 with M49 and M45 with M50)

8.4.10. It should be noted that Fig. 8.9 shows temperatures flux, and not density difference flux. Also because of the varying velocities in the vertical direction, especially near the barrier, the area of the temperature difference plot should not be constant.

8.5 Theoretical considerations and discussion

8.5.1. From consideration of the inhibition of turbulence by a density gradient, Richardson[8.1] suggested a ratio (later known as Richardsons Number, Ri) as a criterion for the correlation of observations of such occurrences. Following Prandtl's explanation[2.7] of the reasoning leading to the formulation of the ratio: the order of magnitude of the vertical velocity fluctuations in turbulent motion is proportional to l.du/dz where l is the Prandtl mixing length, in the mean velocity in the x direction, and the z axis is vertical. The kinetic energy of the vertical motion of an 'eddying' molar ball of fluid of volume V is thus proportional to

$\frac{1}{2}\rho V\ (l.du/dz)^2$. For a uniform density gradient in an incompressible fluid the work done in raising a ball of fluid a distance l is

$$\frac{1}{2}\ gVl.\ d\rho/dz.l\ =\ \frac{1}{2}\ gVl^2.\ d\rho/dz$$

If the quotient of the work done upon kinetic energy is greater than one, turbulence may be damped out, i.e. when $\frac{1}{2}\ g/\rho.d\rho/dz$ upon $(du/dz)^2$ is greater than one. Various attempts to estimate critical Richardson's numbers have been made. For the present purpose it is the relevance of the Richardson's number as a criterion of similarity, that is primarily of interest. Ri is of the same form as the inverse square of the general or internal Froude number and if it is assumed that dynamic similarity in momentum transferring turbulence exists, between model and prototype, the ratio could be regarded as a particular case of the general Froude number derivation, thus being applicable to characteristic lengths and density differences. Ellison and Turner[B.2] have confirmed the applicability of the ratio in this way; "as a parameter specifying the overall state of a cross section of a layer" of saline solution plunging down a sloping rectangular flume and entraining the ambient fresh water above it. They have described experiments which confirm that the rate of entrainment depends on the Richardson's number, and have evaluated the constant of proportionality for a range of values of the number. Because of the slope of the floor, the stabilising effect of density difference is decreased:-

$$R_i = \frac{\Delta\rho/\rho\ .\ g\ .\ \cos\alpha\ .\ h}{V^2}$$

where α is the slope. For the present purpose where the interest is in simulation rather than prediction, the experimentally evaluated coefficients are not of direct interest. It would, perhaps, have been preferrable to keep the term general, or internal, or densimetric Froude number for overall state evaluation, particularly where the mixing originates from wave like interfacial conditions and to use the term Richardson's number for local 'gradient' conditions, for which it was originally intended.

8.5.3. If a particular case of the simple two dimensional mixing phenomena studied in the flumes is thought of as a prototype and as a vertically exaggerated model, with the exaggeration equal to the inverse of the scale, it is obvious that similarity cannot be initially attained. However, if the mixing dies away fairly quickly and a more or less stable stratification continues down the flume, similarity by the criterion of this state of stratification might be approached where the model distance (and thus the prototype distance) is beyond the primary mixing zone. This is illustrated diagramatically in Fig. 8.10(a). Suppose a feature is now placed in the flume, for instance a thin vertical wall. The same configuration can no longer represent prototype and model, but again it might be that eventually similarity as regards stratification would be approached (Fig. 8.10(b)).

8.5.4. Thinking now of a prototype and a natural scale model where dynamic similarity is attained with homogeneous water; the energies lost in prototype and model in surmounting an obstacle will be proportional to $\frac{1}{2} MV^2$ where V is the change in velocity of a characteristic mass M and since

$$M_m = M_p \times \frac{L_m^3}{L_p^3} \quad \text{and} \quad V_m = V_p \times \sqrt{(L_m/L_p)}$$

the ratio of energy available will be $\dfrac{L_p^3 \times V_p^2}{L_m^3 \times V_m^2}$

If stratified non-homogeneous water is involved and dynamical similarity in mixing is attained, the ratio work done between model and prototype will be

$\dfrac{L_p^3 . \Delta\rho_p . L_p}{L_m^3 . \Delta\rho_m . L_m}$ leading, of course, to the relationship, when available energy is equated with work done in mixing, $\frac{\Delta\rho_p \times L_p}{V_p^2} = \frac{\Delta\rho_m \times L_m}{V_m^2}$

again a variation in the method of derivation of the Froude number law. This could have been obtained by direct substitution in Ri $= \frac{1}{2}\, g/\rho \,.d\rho/dz$ upon $(du/dz)^2$ of d /dz by $\Delta\rho/L$ and $(du/dz)^2$ by $(V/L)^2$ to give

$$F = \frac{1}{2}\,\frac{\Delta\rho \,.\, L}{\rho\, V^2} \quad \text{or} \quad \frac{\Delta\rho . L}{V^2}$$

for the purpose of model simulation using water.

8.5.5. If the model is exaggerated vertically, by reduction of the horizontal scale, and still thinking of the obstacles as definite, the distances between the obstacles are reduced but the mixing zones are not, and the same flows obtain. (Fig. 8.10(c)). With the passing thought that in intermediate cases it is just possible that scale effects may occur because of loss of 'venturi' recovery with the changes of slope, (Fig. 8.10(d)) consider the other extreme where resistance to flow is largely from general bed resistance. The concept of mixing after acceleration and deceleration of the flow is largely lost. However, the ratio of energy available for mixing to amount of mixing will still be on a general Froude law basis if similarity is attained between model and prototype both in surface slope and in mixing characteristics. Some attempt was made to examine this case in the larger flume (over a rough bottom) but it was found impossible to obtain conditions where mixing would occur, but where the entry mixing was not predominant.

8.5.6. There seems little evidence that scale effects are likely in vertical mixing phenomena, other than the obvious effect of vertical exaggeration. This seems to warrant individual study in any practical model experiment as its worst effects may well be local. The work done may seem of relatively little value but the experience with the surface tension scale effect in the previous group of studies illustrates the necessity of checking what may appear obvious, and this has been done within the limits possible with the apparatus as it is at present.

9. FURTHER NON-STEADY STATE STUDIES

9.1 Some experiments using the recording apparatus

9.1.1. An experimental study of the dilution pattern for extended flows in lock experiments seems desirable, with coverage of as large a range as possible of the infinite width and no reflected wave case. Such a study would best be combined with the observations of diminution of front velocity, already mentioned (Section 7) as being required. The present apparatus is not large enough for this, except for comparatively shallow depths, and even then only short developments of the underflow or overflow can be observed. Although a start could be made, there is plenty of other work still to be done which is more within the scope of the apparatus and single handed operation. A sustained study of the dilution of the extended flows has neither been attempted nor will be recommended for future work with the present apparatus, although some further work might be worth while.

9.1.2. A considerable amount of relevant work has been carried out by Keulegan, and described by him in unpublished reports.[1.9,3.15] He has dealt with the reflected wave case in comparatively narrow channels,[1.9] as referred to in Section 7, and also the case of a narrow channel separated initially from a limitless 'sea' by a removable barrier, the sea containing the fractionally heavier liquid.[3.15] Both these are affected, as compared with the case for which details are required, by important "configuration" circumstances; in the first the side effects and the reflected wave; in the second the side effects and a much greater initial difference in shape between the overflow and underflow, because of the lack of constraint of the overflow as it spreads over the basin representing the sea. The average coefficient of proportionality for the underflow into the channel from the sea as found by Keulegan was 0.57 compared with 0.46 for his lock experiments. It would also be expected that the subsequent rate of diminution of the initial velocity of the 'sea' underflow would be less than that for the 'lock' underflow, apart from the effect of any reflected wave on the latter, since the total interfacial and side resistance is obviously much decreased. This appears to be the case (direct comparison for any given width to depth ratio is not possible since although underflow tip velocities to a length to depth ratio of 280 along the channel from the 'sea' have been observed by Keulegan, no such measurements exist for the non-reflected wave lock case).

9.1.3. Attempting to summarise the salient points of Keulegan's experimental findings; it is known that the velocity of any underflow front, V, is approximately $1.05\sqrt{(\frac{\Delta\rho'}{\rho_m} g d_1)}$ where $\Delta\rho'$ is the average density between the front liquid and the ambient liquid (measured on the floor and at a distance equal to the total depth from the tip of the front), and d_1 is the depth of the front immediately behind the initial bulb. It also appears that the coefficient of proportionality tends to vary with the densimetric Reynolds number in a similar manner to that found for the coefficient for the initial velocity. Below densimetric Reynolds numbers of 400 (where R_Δ' is defined as $\frac{Vd_1}{\nu_m}$) the coefficient of proportionality falls away rapidly. Keulegan has not attempted to measure the variation in density difference (or the dilution) at various points along the extended underflow for the case of a channel connected to a sea. Some data is available for the reflected wave 'lock' case, but this is far too much affected by the aforesaid wave for there to be any possibility of transformation of the data. However, it does appear from Keulegan's plots of the advance of the underflow along a channel connected to a sea, that even at fairly small densimetric Reynolds numbers, the underflow and overflow extension in the idealised lock case would continue without severe diminution (i.e. V greater than say 0.1 Vo) well beyond extension to depth ratios of 300 and that the front would be followed up by only moderately diluted flows ($\Delta\rho'$ greater than 0.4 $\Delta\rho$). The foregoing is quantitatively very vague, but there is no basis for a more definite statement.

9.1.4. It is also known[3.15,22] that the shape of the tip of the underflow, as it appears to the eye, is characteristic in form, and can be expressed non-dimensionally in terms of the depth of the bulb. Although the ratio of height of bulb to depth d_1 is nearly constant (approx. 2) for the types of flow studied by Keulegan[1.9,3.15] and Ippen and Harleman,[3.22] this ratio is in fact very much conditioned by the configuration and can be much greater in the case of sloping floors.[8.2]

9.1.5. A few experiments were carried out in the larger flume using the recording apparatus. The objects were influenced by three considerations: firstly the aforementioned lack of prospects of much useful work in the present flume length; secondly the shortage of time occasioned by slower progress than had been hoped for in the previous studies and the necessity to remake the thermopile probes (Section 5): thirdly, the great improvements in detail that could be made in the recording system (dealt with in Section 13) were by now appreciated. The objects were then to quickly run over the following for a restricted range of conditions:-

i) to illustrate the use of the recording system for this type of problem.

ii) to find whether local density differences existed within the bulb at the end of the underflow, and how density varied in the body of the underflow.

iii) to find whether the intense mixing previously observed in the bulb showed up in the recordings.

9.1.6. Recordings were made for five thermal density difference tests, the underflow proceeding along the longer length of the flume (13 ft.), and with the shorter length now increased to five feet. These are shown under tests N in section 16. The bare recording probes were positioned at intervals down the flume and the other probes of the pairs, and both reference probes, were placed so as to be in the warmer water (ambient to the underflow) for as long as possible.

9.1.6a. Tests N1 and 2 were for 0.400 ft. depth and K.RΔ approximately 4000. The recordings for N1, where all the probes were half an inch above the bottom, show a practically featureless trace, apart from the arrival of the front at successive probes. Although the front was diluted to about 0.75 by the time it reached probe 5 (10 ft. 6 in.), soon afterwards practically undiluted underflow water obtained at 3 ft. 6 in., 7 ft., 6 in. and 10 ft. 6 in. (just a trace of dilution), the extension ratio at 10 ft. 6 in. being 26. Test N2 shows that at the top of the bulb the underflow was much diluted compared with the bottom of the bulb, as probes 4 and 5 were reached.

9.1.6b. Tests N3 and 4 were for 0.800 ft. depth and K.RΔ approximately 11,000. Although the trace is much less uniform than for N1 and 2, the fluctuations are not as marked as during test H1, suggesting that the mixing had reached a stage where individual eddies were often small in comparison with the probe head. The trace where the front reached probe 5 in N4 indicates that the lower part of the bulb was hardly diluted.

9.1.7. With a depth of 0.20 ft. and K.RΔ approximately 1500, Test N5 illustrates a case where the general appearance of the underflow was distinctly laminar. Comparing this test with N1 one finds that the relative times to travel from probes 2 to 3, 3 to 4 and 4 to 5 ase 0.83:1 : 1.04 and 0.75:1 : 1.39 for N1 and N5 respectively (as an approximation to bring to 3.5 ft. intervals from start instead of 3.0, 3.5, 3.5 ft. from 0.5 ft.:- 0.83 x 3.5/3 = 0.97 and 0.75 x 3.5/3 = 0.89). Fig. 9.1 shows the comparative progress of the two fronts, it being assumed that no diminution of velocity had occurred in either case by 0.5 ft. The initial velocities were obtained from Figs. 7.6 and 7. In the case of N5, where the velocity was finally observed as about 0.4Vo, the underflow was, at that stage, markedly diluted for two thirds of its length; while in the case of N1, where the velocity is finally about 0.9Vo, there was, as previously noted, little dilution. Supposing that N5 had been intended as a Froude law simulation of N1, a vertical exaggeration of about 1.5 would have been required for a horizontal scale of 1/3, leading to 3.5 ft. in N5 corresponding with 10.5 ft. in N1. In so far as practically no dilution indicates correspondence, correspondence in respect to the part of the underflow nearest to the bottom was obtained, and again, as previous results would have indicated, reasonable correspondence was obtained in decrease of velocity. It should be noted that the correct density difference was not in fact quite attained in N5, but on the basis of divergence from the calculated initial velocities, the foregoing is basically true. Again the reflected wave would undoubtedly have affected parts of the underflow in N5 before the final dilution recordings were made. As a fairly close approximation, it can be said that the underflow was pursued by the reflected wave from the time it reached 5 ft., the wave starting from minus five feet and travelling at a constant velocity, that of the underflow at five feet. However, the wave would have no mixing effect on the bottom water and little transferring effect in this particular case.

9.1.8 It is immediately apparent that comparison of the N5 10.5 ft. recordings, where a dilution gradient extends back into the underflow, with the corresponding N1 recordings would be much more conclusive - either way. It is thought that these could be obtained in a 1.5 ft. wide flume, as side effects are still small at a width to depth ratio of nearly 4. But the flume length required is about 58 feet, and if the effect of the reflected wave is to be eliminated, about 80 ft.

9.1.9. The full scale and reduced scale simplified outfall tests as described in 7.5.2. were repeated (apart from a small increase in flow and an increase in density difference) with recording probes positioned at 3 ft. and 7.5 ft. from the outfall on the centre line of the tank at the surface and also at 2½ in. deep at 3 ft. only, full scale dimensions (the corresponding dimensions being used in the 1/5 horizontal scale, 1.95 vertical exaggeration reduced scale normal Froude law model.) The tests were run with surface tension difference balanced throughout and the recordings are given in section 16 under tests P1 - 3.

9.1.10. It had been established (as described in Section 8) that something close to correspondence in the immediate mixing pattern due to velocity discontinuity on emergence from the outfall could be expected, and, as described in 7.5.2., correspondence in the advance of the front had been observed. Runs P1 and P2 were with very closely similar full scale conditions, the marked divergence in the recordings being due to reduction in the oscillograph gain for P1 (it was not known to what extent the initial temperature difference would be reduced by 3 ft. travel) Over the distance 3 ft to 7.5 ft. the travel time for the front agrees to within 2%, and while the dilution recordings show considerable erratic mixing taking place, they agree fairly well. P3 and P4 were the simulative reduced scale runs, fairly close agreement in density difference with that intended being attained (average of 0.00217 gm./m.l. instead of 0.0023 gm/m.l. as intended). Again the front velocities were similar, 4% covering the divergence in the times to cover the distance between the probes, and the mean of the reduced scale tests travel time,when scaled up, is 65 seconds, compared with 61 seconds for the full scale tests, the divergence being in line with the recognised error in density difference. Turning to dilution it is interesting to note that the eddies are distinctly larger in proportion in the smaller scale tests. (The actual speed up of the strip (x 2.5) was rather less than that required by the time ratio (x 3.16)). While remembering that in both cases the sampled portion of the front was merely a fraction of its actual width, it appears that the introduced water was more stratified in the reduced scale tests. The effect of exaggeration of the vertical scale could not be expected to wholly account for this; there was only a slight tendency towards greater stratification with reduced scale in the tests described in Section 8. Until more repetitive testing has been carried out, it would be unwise to draw further conclusions from these tests.

9.1.11 It is suitable to here ~~to~~ refer to a circumstance relevant to the above. Suppose a small density difference (reduction) agency with more or less linear mixing characteristics is present, uniformly distributed horizontally, on the surface water of a body. Spread is prevented by a removable barrier, which in this case need not reach the bottom. The agency is uniformly distributed vertically though a distance H^1 from the surface. If the initial velocity of advance Vo, upon removal of the barrier, is taken as $K.\sqrt{(\frac{\Delta\rho}{\rho}.g.H)}$ where K is the constant of proportionality from 'lock' experiments, then Vo is practically independent of H^1 since $\Delta\rho$ is inversely proportional to H^1. The small variation in V is due to changes in densimetric Reynolds number which is proportional to $\Delta\rho^{\frac{1}{2}}.H^{\frac{3}{2}}$. So it appears that a small variation in degree of stratification will not materially affect the capacity of a front to advance further, assuming that the density difference flux is constant.

9.1.12. The foregoing is more applicable to forced density currents than to the modified lock case, given that the relationship assumption between these made and tested in section 7 holds, since it is obvious that the kinetic energy distribution in the modified lock case underflow will be more and more affected as compared with the normal lock case, the further the extension continues. However, right at the start of the experimental work, some tests (A8 - A11) of the modified lock case were made, unfortunately before the effect of surface tension on the overflow was appreciated. In these tests the flume was filled to $4\frac{1}{2}$ in. with cold water and heated water on either side of the barrier in the usual way. Cold water was then slowly run into the longer (colder) length and the barrier was 'cracked' open, allowing the heated water to be lifted until some predetermined depth was reached. A fair amount of mixing did take place and a temperature traverse was made at the middle of the smaller length before the barrier was lifted and the flow observed in the usual way. Fig. 9.2 shows the results of two tests. From plots of the vertical temperature variation, an equivalent no mixing interface depth has been calculated, assuming all the heated water to be at the surface temperature. The actual progress of the fronts is compared with the initial velocities calculated from these (no mixing) depths and temperatures and using the most reasonable value of K^1 the apparent coefficient of proportionality for the thermal overflow obtained from the many normal lock tests in the range of the aforesaid depths and temperatures and without surface tension balanced. The actual initial progress of the fronts is remarkably close to that predicted, considering the erratic results which are characteristic of surface tension assisted advance.

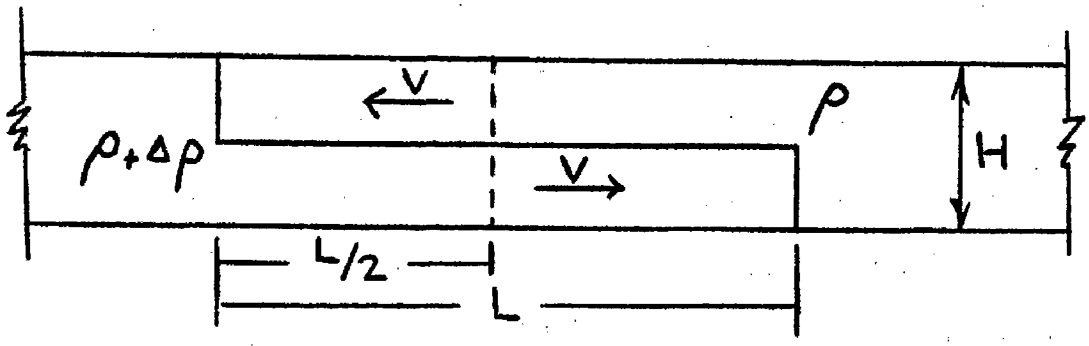
9.2 Theoretical considerations and discussion

9.2.1. The experiments described in this section tend to confirm the supposition of Section 7 that the variations in initial velocities and in decrease of velocity with travel length which occur during lock experiments appear to be, to some extent, applicable to more general non-homogeneous water movements. Without a great increase in the scale of models it is likely that, during slack water periods, movements on such magnitude as to have, broadly speaking, turbulent interfacial conditions would have to be simulated under more or less laminar interfacial conditions, assuming that the velocity scale is taken as, or is close to, the square root of the vertical scale. This assumption is based on the probability that tidal movements before or after the slack water would be simulated.

9.2.1. In 7.1.2. reference was made to attempts to obtain the initial velocities of the lock case fronts by analysis. There has been some disagreement on the conditions to be regarded as the idealised case prior to the start. If water, which differs in density, is at the same level on either side of a barrier in a flume, there is a nett resultant force on the barrier. If it is required that the nett force be zero, the less dense water must be at a slightly higher elevation and Shonfeld[9.1] and Schijf and Schonfeld[7.7] have started from that position, their theory being graphically illustrated in Fig. 9.3 (Taken directly from ref. 7.7). To better illustrate why the continuing identity of the surface wave phenomena with the internal phenomena is, in the opinion of the Author, fallaceous, consider the proposition of Linder.[7.6] He supposes that a globule of fresh water may be considered to rest momentarily upon and in the surface of a body of fresh water (Fig. 9.4) and then proceeds with the traditional 'iceberg' calculation, arriving at (due to his assumption of salt water specific gravity as 1.025) 40 times as much fresh water below the surface as above. He then says that the fresh water will flow out over the salt water because of its elevation, thus unbalancing the pressure at the bottom of the globule which will thus rise. But even the momentary existance of the globule implies interfacial surface tension to cause it to act as a unit, and there seems no reason to believe that this exists as between bodies of water with small density differences due to salinity or temperature differences. In fact, in the illustration chosen by Linder, the most compelling force on the globule would be that caused by the decrease in normal surface tension over its surface area. But neglecting this objection the proposition is still irrational. A globule of salt water resting on the bottom of a fresh water filled flume would spread over the bottom without a corresponding elevation to the 'iceberg' projection entering into the picture.

9.2.3. Shonfeld and Schijf[7.7] and Schonfeld[9.1] seem to have been actuated by a similar desire to explain the internal movements by external circumstances. The nett pressure distribution obtained from their diagram b on Fig 9.3 (Fig. 9.5a) seems initially more rational in terms of the observed movements than that on the basis of level surfaces (Fig. 9.5b). But starting from the latter as an unstable condition (once the barrier is removed) it can be visualised that the maximum reduction of potential energy commensurate with continuity requirements embracing equal flows and a logical transference pattern with minimum absorbtion of energy due to acceleration and the overcoming of viscous (normal and eddy) friction, is obtained from the flow pattern commonly observed, despite the necessity for the overflow to overcome the varying pressure difference appropriate to the depth. Figs. 9.6 - 8 show the development of the overflow and underflow at a somewhat later stage. As mentioned in 7.2.5, tests with differences in surface level did not suggest that these had any effect on the internal movements other than those which would have occurred with no density difference present. The surface disturbances caused by the sudden withdrawal of the barrier were of much greater magnitude but did not appear to affect the internal flows either. With regard to Figs. 9.6 - 8, it should be noted that the effect of dilution of the tip has a differing effect on the appearance of the overflow and underflow as the coloured water tends to show up even in great dilution. Thus the overflow in these cases actually extends somewhat beyond the point apparently indicated.

9.2.4. It is not thought that further consideration of the analytical prediction of the initial velocities would be profitable to the present study. Dr. Keulegan, an eminent hydro-dynamicist, has considered the matter over a period of twenty-eight years without finding a reasonably simple method which is not negativedby initial simplifying assumptions. Doubtless a step by step analysis could be programmed for a computer, but experimental observations are probably simpler. It is interesting to note that the following analysis' based on most obviously incorrect assumptions, yields the same result as that obtained by O'Brien and Cherno,[2.10] Keulegan[7.5] and Schijf and Schonfeld.[7.7]



Kinetic Energy = Work done

$$\tfrac{1}{2} L . H . \frac{\rho}{g} . V^2 = \Delta\rho \times \frac{L}{2} \times \frac{H}{2} \times \frac{H}{2}$$

$$\therefore \quad V = \cdot 5 \sqrt{\left(\frac{\Delta\rho}{\rho} . g . H \right)}$$

9.2.5. However, although absolute considerations are beyond the scope of this thesis, comparative considerations are of some value in the understanding of the observations of the lock phenomena. If it is assumed that at a particular ratio of total extension to depth in the development of a series of overflows and underflows there is geometric and dynamic similarity, the energy made available per unit width is proportional to $\Delta\rho H^3$ and the kinetic energy to $V^2 \frac{H^2}{g} \rho_{mean}$ giving $V \propto \sqrt{\left(\frac{\Delta\rho . g . H}{\rho_{mean}}\right)}$ if friction is neglected. The decrease in relative initial velocity can be observed very close to the barrier and cannot be explained by frictional losses, but is probably due to modifications in velocity distribution and interfacial shape at small values of $K.R_{\Delta}$ (which is approximately proportional to $\sqrt{(\Delta\rho . H^3)}$). There are indications in Fig. 7.6 that the coefficient of proportionality line flattens in the region $K.R_{\Delta}$ = 10,000 - 30,000. Further tests are required at large values of $K.R_{\Delta}$ but with a definite time taken to lift the barrier and the results corrected on the basis of comparisons made at small values of $K.R_{\Delta}$.

9.2.6. Supposing the total energy used in overcoming the interfacial and bottom drag, which decrease the velocities of the overflow and underflow, is proportional to L^2V^2 as between geometrically similar developments in the turbulent region, it would seem likely that the slope of the travel length to depth ratio line at a given proportion of initial velocity (Fig. 7.12) would also flatten in the fully turbulent region. This is largely proved by a series of the sea and channel case experiments described by Keulegan.[3.15] Fig. 9.9 shows his plot of the recordings and it can be seen that, even with the small channel used, the pattern of diminution of velocity up to a travel length to depth ratio of 280 reaches stability beyond $K.R_{\Delta} \doteq 25{,}000$. It should be noted that the method of plotting somewhat masks the effect of decreasing $K.R_{\Delta}$. At $K.R_{\Delta} \doteq 16{,}000$, the velocity ratio V/V_{Δ} at an extension of 40 is 0.8 compared with that of the fully turbulent case taken as unity, but by extension of 280 has fallen to 0.6 compared with that of the turbulent case as unity, plots of actual extension against time, where the divergence in velocity is cumulative, would more graphically illustrate the effect of partially laminar flow. Ofcourse, the justifiable use of the starting $K.R_{\Delta}$ instead of the local $K.R_{\Delta}{}^{l}$ depends on the extension envisaged; there is little divergence between runs ◊ and ■ in Fig. 9.9 so far as an extension ratio of 40. Neglecting the effect of mixing, the greater diminution of velocity as the phenomena comes into the laminar region can be partially explained as follows. The decreasing energy used to overcome friction up to the point of comparison would no longer be proportional to the square of the velocity but would, through decreasing (proportional to say L^2V or $H^{2.5}\sqrt{\left(\frac{\Delta\rho}{\rho}\cdot g\right)}$ assuming resistance proportional to V), become a continually increasing proportion of the more rapidly decreasing total energy available (still $\propto \Delta\rho H^3$ or $\Delta\rho L^3$). This would result in decreasing travel length to depth ratios at any proportion of the initial velocity. The foregoing would be modified by the probable changes in shape and more particularly in velocity distribution. These tentative considerations are, in the lack of the information on interface shape, on velocity distribution and on dilution required, merely an attempt to show that the variations observed are not irrational. The effect of dilution is not fully understood though it appears to be even more a feature of laminar advance than of turbulent advance.

9.2.7. It should be possible to achieve a fair degree of similarity in models during the slack water period by the use of moderate vertical exaggeration once a complete Keulegan type congruency diagram (Fig. 7.12) becomes available and the coefficients of proportionality diagram (Figs. 7.6 and 7) is extended. Since the variation between different travel length ratios probably alters from the laminar to the turbulent region it would be necessary to decide on a best compromise before making the calculation of vertical exaggeration. Care would be necessary in the selection of a representative densimetric Reynolds number ($K.R_{\Delta}$) for the prototype.

10 SPREAD IN MOVING WATER

10.1 Discussion of the problem

10.1.1. Consider two wide parallel flows of water moving horizontally at the same uniform velocity Vu and depth H, and with a slight difference in density $\Delta\rho$ between them, the flows being initially separated by a thin division. At the end of the division the flows are free to mix and for the lighter water to flow over the heavier and vice versa. In such an idealised condition it might be imagined that something close to the lock case overflow and underflow would take place as the flow continued beyond the end of the division. However, in practice the velocity distribution would not be uniform, either horizontally or vertically. Assuming turbulent flow the horizontal velocity gradient at the division would result in an initially horizontal mixing action beyond the division, similar to the initially vertical action beyond the bottom of the introduction box in experiments of the type described in Section 8. A variety of effects can be imagined for various combinations of $\Delta\rho$ and mean velocity Vm; the immediate mixing may prevent the formation of an underflow and overflow, which mode of flow appears to be much influenced by the interface conditions.

10.2.2. Neglecting for the moment the cross flow (from the point of view of the lock flows) consider the effect of partial mixing before removal of the barrier on the normal lock case. Fig. 10.1a shows the normal starting position; if the condition shown in Fig. 10.1b is substituted (with two barriers to be removed) there would at first be two separate lock exchange flows. We do not have precise information on the limits of movement in the simple lock case. It clearly extends some short distance beyond the fronts in the manner of Fig. 10.1c. With the double barrier the flows at some little time after the start would be as shown in Fig. 10.1d. Now if the normal lock case initial velocities were $V_{o(o)}$ and $V_{o(u)}$ equal to $K_o\sqrt{(\frac{\Delta\rho}{\rho}\cdot g\cdot H)}$ and $K_u\sqrt{(\frac{\Delta\rho}{\rho}\cdot g\cdot H)}$ respectively, the double barrier case initial velocities would start as $V_{o(o)}' = K_o'\sqrt{(\frac{.5\Delta\rho}{\rho}\cdot g\cdot H)}$ and $V_{o(u)}' = K_u'\sqrt{(\frac{.5\Delta\rho}{\rho}\cdot g\cdot H)}$ where Ko^1 and Ku^1 were only very slightly smaller than Ko and Ku. The linearity of the early extensions of lock exchange flows and the general shape of the phenomena (Fig. 9.8) suggests that the very simple concept of 9.2.4 may be of some use as a guide on a comparative basis; the assumption being that incremental reduction of potential energy is balanced by the incremental increase of kinetic energy. This is illustrated in Figs. 10.2.

10.1.2. With the double barrier case there would come a stage when the exchange flows would combine (Fig. 10.1e). Thereafter the nett rate of incremental reduction of potential energy, on a basis of extension, would remain approximately the same but the rate of incremental increase of kinetic energy would be halved, assuming maintenance of the front velocity. This would be, of course, unstable and there would in fact be a tendency for the fronts velocity to increase; the extent to which the comparable ($\Delta\rho$ and H) single barrier velocity would be approached depending on L_m and the principle considerations being the need to accelerate the already moving water occupying (approximately) the whole space between AA and BB on 10.1e and the increase of resistance, particularly as regards the continuing underflow and overflow tips, caused by the presumably greater dilution of them compared with the single barrier case. This might not be important as there seems to be a fair degree of replacement of the tip of the front during the early development of the overflow and underflow. But there certainly would be a destruction of potential energy involved in the mixing required to change from the single barrier to the two barrier case.

10.1.3. As the two barriers are brought closer together, the foregoing effects would decrease, eventually being interceptable and some extreme case of the foregoing in fact represents the practical single barrier case where the lifting of the barrier must cause a little mixing.

10.1.4. If now a multiple barrier case is considered, with the barriers close together (Fig. 10.1f) and equal increments of the total $\Delta\rho$ from the one outside barrier to the other, the combination of the series of exchange flows would be practically coincident with their initiation. It follows from 10.1.2. that the overall exchange flows would develop very slowly. If the simplifying assumption already used is adapted (however unrealistically) an expression for the velocity of the underflow (or overflow as both velocities are the same under the assumption) can be obtained in terms of L_d and L_s (Fig. 10.1f

$$K.E. = W.D.$$

$$\tfrac{1}{2}(L_s + 2L_d).H\rho V^2 = \Delta\rho.L_d.\tfrac{H}{2}.\tfrac{H}{2}$$

$$\therefore V = \sqrt{\left(\frac{\Delta\rho}{\rho}.g.\frac{H}{2}\left(\frac{L_d}{L_s + 2L_d}\right)\right)}$$

as L_d becomes large in comparison to L_s,

V tends to $.5\sqrt{\left(\frac{\Delta\rho}{\rho}.g.H\right)}$

In practice V would be decreased by frictional drag but would come closer to that for the normal lock case (also reduced from K_o (or K_u) $\sqrt{\left(\frac{\Delta\rho}{\rho}.g.H\right)}$ by drag) with increasing travel length.

10.1.5. If a continuous gradient of $\Delta\rho$ exists along a distance Ls which is rather great than H, it can be imagined that the development of an exchange flow would be very much retarded.

10.1.6. It might be difficult to perform experiments to fully verify the above, but starting with the relatively simple case of three or four barriers, fairly well spaced, some progress should be made and such experiments will be recommended for future work.

10.1.6. Now returning to the original problem, with a cross flow relative to the possible development of the exchange flows, it may be wondered to what extent inhibition of the exchange flows is likely. Suppose the average velocity in the parallel flows is of the order of 0.2 ft./sec. at a depth of 0.33 ft., and the density difference is 0.0023 gm./m.l.. The approximate angle obtained from $\tan^{-1} = .5\sqrt{\left(\frac{\Delta\rho}{\rho}.g.H\right)}/.2$ is 38°, a much greater divergence than the normal mixing zone which varies between 1 in 8 and 1 in 6, or around 8°.

10.1.7. An attempt was made to test the above conditions, by placing the introduction box on the floor of the main tank and facing downstream. The circulating flow was partially smoothed by dry brick baffle walls. However, there was insufficient absorbing capacity in the sump to allow the heated flow to continue long enough for steady conditions to be established. It appeared that the limit of the divergence, as viewed from above was around 1 in 3, falling between the estimates of the previous paragraph.

10.1.8. As well as the possibility of horizontal mixing partially inhibiting the development of the underflow and overflow, it seems likely that vertical mixing may affect such development as occurs. Although it was shown (in 9.1.12) that variations in vertical distribution of a density difference agency in a potential overflow may not affect its capacity to advance, particularly if its depths are small in comparison with the total depth, mixing during the actual advance in the case of an underflow and overflow implies both turbulent energy losses and decrease of potential energy, and, if the mixing is imposed by a cross flow, a decrease in the rate of development compared with that obtaining without the cross flow. It may be that the exaggeration in vertical scale needed to similate normal development of the underflow and overflow is no longer desirable since the resistance to the developments may be proportional to the square of the velocity over a greater range - but this is rather hypothetical and some experimental work is needed. For the present it can be said that, from the observations made during the previous tests, it seems that the vertical mixing resulting from the initially horizontal mixing action becoming random would predominate, in the basic configuration considered here, over bed induced vertical mixing.

10.1.9. An attempt was made to compare tests of an outfall projecting water into a moving stream at two scales, full size and $^1/_5$ size with 1.95 vertical exaggeration. (P5 - P8). For the full size tests the introduction box was set at the upstream end of the tank facing across it. Without the introduced flow, an extremely complex and unstable pattern of flows as set up and no consistency could be obtained in appearance or in temperature measurements downstream, when the introduced flow was started. Again the lack of sump capacity was inconvenient. These tests did, however, illustrate the need for a surface tension balancing agent which does not cause foaming, or alternatively a circuit without drops at the entry to test sections.

10.1.11. The idea of a continuous gradient of $\Delta\rho$ in the normal lock configuration is useful to further illustrate the fallacy of a non-level water surface.

11. HEAT LOSSES

11.1 Introduction

11.1.1. By 'heat losses' are meant the heat which is transferred from the water before it passes outside the limits that have been selected for consideration in either a full size or a small scale investigation. In general, and certainly for prototype conditions, by far the greater part of the 'heat loss' is to the overlying air, rather than to the containing solids.[1.2; 2.6, 11.1]

11.1.2. With regard to power station heat rejection with water as the agent, a circulating water system based on a cooling pond represents one extreme: practically all the heat must be transferred to the atmosphere at a definite location. Since evaporation is an important agency of the cooling process, make-up-water is required for a cooling pond and cooling towers are really a more compact and efficient form of the closed circuit system.

11.1.3. At the other extreme, one can imagine a power station sited on an exposed coastal promentary where the outfall water is rapidly swept away at practically all stages of the tidal cycle. For this case, as for other open circuit systems, the greater the dilution within chosen limits of consideration, the less the heat losses within the aforesaid limits.

11.1.4. Particularly for the case of cooling ponds, and for a variety of other cases, it may be desirable to calculate the heat losses for various conditions of station load and of weather. Apart from the actual heat loss calculations, it is necessary to predict the sequence of dilution and, depending on the circumstances, the heat loss or the dilution calculations can be of the greater importance and difficulty. For instance, if it is desired to calculate downstream temperatures in a non-tidal river where the total flow is only slightly greater than the circulating water flow and where there is little tributary flow within the distance in question, the heat loss calculations are paramount. On the other hand in a tidal river or estuary, the maximum upstream and downstream flows may be far in excess of the of the circulating water flow and the immediate diluting action may reduce the cooling potential. In assessing the chances of a build up of temperature the most important factor is the amount of replacement or interchange between the volume 'block' of water known to move up and down past the station and the adjacent blocks on either side.[11.1,2]

11.1.5. There are, then, three main points regarding heat losses which should be considered in the present circumstances:-

(a) How to predict heat losses in a prototype so as to find water temperatures after some period of time.

(b) Parallel with (a) is the question of heat losses in a small scale basic study. Normally it would be desirable that the density difference flux is essentially the same as that which would obtain with no heat losses.

(c) The effect of heat losses on model simulation.

11.1.6. At the time of the Kincardine investigation a method of computing heat losses given by Throne[11.3] was used for both model and prototype. Some experiments were carried out in the model to check on Throne's formula, and fair agreement was found. As heat loss was shown to be relatively unimportant in that study, the matter was not pursued. Since then conditional criticisms of Throne's method have been noted.[1.10; 11.4] As the question of heat losses was only very briefly mentioned in the final version of the Kincardine paper (Attachment 1, paragraph 21), these are now considered in more detail, remembering, however, that only a certain degree of accuracy is required in many heat dissipation circumstances because of the greater importance of dilution.

11.2 Heat losses from water surfaces

11.2.1. The energy transfer processes across the water air boundary are well known.[1.11; 2.6] Solar radiation strikes the water surface and the unreflected proportion heats the water below the surface, the distribution of the heating in the surface layers depending on the angle of incidence and the clarity of the water. There is an interchange of 'black body' radiation from the water upwards and from the atmosphere to the water.

11.2.2. Heat can be transferred from (or to) the water by conduction.

11.2.3. Evaporation from the water surface requires heat which is mainly drawn from the water. The reverse occurs, with condensation which is, however, improbable in heat dissipation circumstances.

11.2.4. It is convenient in heat dissipation studies to express heat gains or losses in BThU/sq.ft./hr. The energy budget per unit area of a body of water may be expressed:-[1.10]

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_x$$

Where Q_s is the solar (including sky) radiation incident to the water surface.

Q_r is the reflected solar radiation.

Q_a is the incoming long wave radiation from the atmosphere.

Q_{ar} is the reflected long wave radiation.

Q_{bs} is the long wave radiation emitted by the body of water.

Q_v is the net energy advected into the body of water other than that contained in evaporated water.

Q_e is the energy utilised by evaporation.

Q_h is the energy conducted from the body of water as sensible heat.

Q_w is the energy advected by the evaporated water.

Q_x is the increase in energy stored in the body of water.

It is agreed that, in most circumstances, ~~that~~ conduction of energy through the bottom and transformation of Kinetic energy into thermal energy can be ignored.[1.10; 2.6; 11.1]

11.2.5. For any combination of weather conditions and in the absence of added heat in the form of cooling water or the like, there will be a surface temperature at which there would be no heat flow between a body of water and the atmosphere. This is the equilibrium temperature (T_{we}) Throne's basic idea was the introduction of natural water temperature (T_{wn}) as the basis for comparison with industrial conditions, and the transference of the calculations from the absolute to the relative. The natural temperature is merely that temperature which would obtain at a particular time had a body of water not been used for heat dissipation. This may differ considerably from the equilibrium temperature; the range of mean temperatures[11.1,5] from the outer limits of an estuary to the non-tidal river during winter and summer illustrates the influence of the local conditions of depth, turnover and interchange on the tendency for a body of water to reach the mean equilibrium temperature. But at all places along the range, the temperature is always 'natural'. Throne's approach has been followed in later studies.[1.10; 11.1,4]

11.2.6. The nett solar and sky radiation, $Q_s - Q_r$, can be considerable, but is very erratic because of varying degrees of cloud cover. Up to the order of 200 BThU/sq.ft./hr. is possible in temperate climates.[11.4] The mean rates throughout March, June, September and December, for the British Isles are of the order of 31, 55, 33 and 9 BThU/sq.ft./hr. respectively.[2.6] But in comparing the heat balance of a natural and an industrial body of water, the nett incoming solar and sky radiation is the same in either case and can be ignored.

11.2.7. Q_{bs}, the black body radiation, would be $0.171 \times 10^{-8} (T_w + 460)^4$

BThU/sq.ft./hr. for an emissivity rate of 0.97[1.10], where T_W is the surface water temperature. Fig.11.1 shows a plot of this for the range of T_W from 32°F to 80°F, the variation from the linear assumption of Throne[11.3] and Lang haar,[11.4] being slight, but not negligible when water temperatures near freezing point are considered. Sverdruup, Martin and Fleming[2.6] have given a figure showing effective back radiation $Q_{bs} - Q_a + Q_{ar}$, which is reproduced as Fig.11.2. This is for a clear sky, assuming that air and surface water temperatures are equal. For cloudy conditions the value should be multiplied by (1-0.083C) where C is the cloud cover on the scale 1 to 10.

11.2.8. Throne[11.3] adapted Rohwer's[11.6] evaporation formula (inserting latent heat of evaporation) to give:-

$$Q_e = 70.6\,(1.0 + 0.268V)\ (l_w - l_a)$$

Where V is the wind velocity just above the water surface (m.p.h.)

l_w is the vapour pressure of water at the water surface temperature. (in. Hg.)

l_a is the partial pressure of the water in the air (in. Hg.)

and sea level conditions are assumed.

This result is similar to that which would be given by the Meyer formula for evaporation.[11.4,7] Penman,[11.8] after investigations in England, concluded that the empirical Rohwer formula was superior in use to results given by more theoretically correct approaches.

11.2.9. A relationship between the amounts of heat given off to the atmosphere as sensible heat and used for evaporation can be obtained as follows (vide "The Oceans"[2.6]). The amount of heat carried from the sea surface in unit time through unit area is $Q_h = -C_p A \left(\frac{d\,Ta}{d\,z}\right)$ (neglecting the adiabatic lapse rate)

where C_p is the specific heat of the air, A is the eddy conductivity and

$-dT_a/dz$ is the temperature gradient near the water surface (°C/cm). Again the transport of water vapour, F, through unit area in unit time is $-A df/dz$ where df/dz is the vertical gradient of the specific humidity. This leads to

$$Q_e = -L.A.0.621/p.de/dz$$

where L is the latent heat of vaporisation at the surface temperature of the water, p is the atmospheric pressure and de/dz is the vapour pressure gradient (millebars/cm). R, the ratio of Q_h to Q_e is equal to

$$C_p/l.\ p/0.621.\ dT_a/dz.\ dz/de$$

$$= 0.66.p/1000.\ d\,T_a/dz.\ dz/de$$

$$(c_p \doteq 0.240 \text{ and } L = 585 \text{ calories/gm.})$$

Remembering that air must pass several miles over water before any perceptible change in air temperature and humidity is noted, because of the constant interchange of the lower stratas, this leads to

$$R \doteq 0.66.p/1000.\ (T_w - T_a)/(e_w - e_a)$$

which is known as the 'Bowen ratio'.

11.2.10. If it is accepted that the relationship between the heat used for evaporation and that transferred by conduction is given by the Bowen ratio:- 1.10;2.6;11.4

$$R \doteq 0.012\ \frac{(T_w - T_a)}{(l_w - l_a)}\ \frac{P}{30} \quad \text{(transferring to in. Hg and °F)}$$

Where T_w is the surface water temperature °F

T_a is the air temperature °F

P is the atmospheric pressure in. Hg.

This leads to Throne's combined formula, in this case assuming an atmospheric pressure of 30 in. Hg. :-

$$Q_e + Q_h = 70.6\ (1.0 + 0.268V)\ [(e_w - e_a) + 0.012\ (T_w - T_a)]$$

11.2.11. Hence Throne obtains H, the heat flow from the water surface occasioned by the raising of the temperature from 'natural' to 'industrial' as

$$H = 1.04 (T_{wi} - T_{wn}) + 70.6 (1.0 + 0.268V) [(e_{wi} - e_{wn}) + 0.012 (T_{wi} - T_{wn})]$$

Solar and sky radiation is ignored, being unaffected by the change from 'natural' to 'industrial' conditions, and the air temperature and partial water vapour pressure are cancelled. The first term is an approximation for the differential black body radiation (more or less correct about 60 - 70°F water temperatures - see Fig. 11.1)

11.2.12. As mentioned earlier, Throne's formula was used for both model and prototype to assess the effect of heat losses on simulation in the Kincardine model. The tests (briefly described in paragraph 22 of Attachment 1) consisted of trapping the heated water which had gathered over a sheet of thin glass by placing a wooden frame on the glass. The glass was supported on four thin columns and lay horizontal and centred at 3,300'E., 1,350'S. (Fig. 2 of Attachment 1). By the time the frame was positioned, all flows had been stopped and the subsequent loss of heat was studied. Table 11.3 shows the results and how the heat loss differed from that predicted by Throne's formula.

11.2.13. It was thought that the divergence at the larger temperature differences might be due to the Bowen ratio assumption being inapplicable for the limited area involved. An alternative approach to the conduction loss can be made by considering the water surface as a flat horizontal heated surface and following a method given by C. W. Rice.[11.9] The conditions over a model in a building are neither truly 'free convection' or 'forced convection'. The assumption of free convection with, perhaps, some allowance for wind velocity seems more reasonable. The free convection heat flow from a flat horizontal surface, as given by Rice, is

$$Q_h = 0.83 (T_w - T_a)^{1.25} \text{ BThU/sq.ft./hr.}$$

11.2.14. An alternative to Throne's approach for indoor conditions is therefore:-

$$H = Q_{bs} (T_{wi} - T_{wh}) + 70.6 (1.0 + 0.268V) (e_{wi} - e_{wn}) + 0.83 (T_{wi} - T_a)^{1.25} \text{ BThU/Sq.ft./hr}$$

The results with this method are again shown on Table 11.3 under "New Formula loss". There is some improvement over the original formula, especially in the case of the highest temperature test, using a Thermos jar. This test corresponded more closely to the laboratory conditions during the later basic studies.

11.2.15. For average conditions during the basic study tests where heat losses are thought most likely to be perceptable, it is reasonable to assume a natural water temperature of 60°F with an air temperature of 70°F. The heat content, above the reference provided by basic temperature, at the start of a 'lock' experiment with water at 100°F on the shorter flume length and at 60°F in the larger length (as described in section 7) at depth 0.25 ft. would be 4,200 BThU. The initial heat loss rate would be 198 BThU/sq.ft./hr. and if the heated area at half the available travel length combined with twice the time taken to reach the aforesaid half travel length is taken as sufficiently representative, the total heat loss is 115 BThU, without making any reduction for the effect of the mixing which would undoubtably take place. This is just under 3% of the original heat content. Again, if a half inch deep band of water is allowed to flow down the flume from the introduction box, the heat content per square foot (assuming the same illustrative temperatures) is 104 BThU. At 0.06 ft./sec. (the mean speed of flows 4 - see Section 8) the heat loss by the end of the flume, assuming again no mixing would be 13 BThU or about 13%. This would be more than desirable, but, in fact, such an experiment was never carried out, the nearest approach being with $1\frac{1}{2}$ inches depth of water at a smaller heat difference, which would lead to about 3% heat loss for the most extreme heat loss circumstances met with in the stratified flow studies.

11.3. <u>Heat losses and model simulation</u>

11.3.1. For most investigations it is sufficient to check that the heat losses are likely to be small in both model and prototype within the appropriate limits of time and location. Throne's formula is suitable for the prototype and the adjusted formula for small scale models, though, if the temperature increment is small the difference between the results from the two methods is slight.

11.3.1. If it is desired to simulate heat losses in a model, it must be arranged that equivalent bodies of water have equivalent heat drops in equivalent time. Supposing that the same temperature increment is adopted in model and prototype, the ratio of heat loss rates required, for a normal Froude basis model, is $1 : Lm^2\,Hm / Lp^2\,Hp . \sqrt{Hm\,Lp} / \sqrt{Hp\,Lm} . Lp^2 / Lm^2$ as between prototype and model; i.e. $1 : (Hm/Hp)^{\frac{3}{2}}.\ Lp/Lm$ or $1 : Hr^{\frac{3}{2}}/Lr$ where L and H. refer to horizontal and vertical lengths and m p and r indicate model, prototype and model to prototype ratio (the scale). This means that for say a $\frac{1}{144}$ natural model the heat loss rate in the model should be $\frac{1}{12}$ that in the prototype. Now it is normally found that minimum prototype heat loss rates are about 2 to 3 times that in models operated with the same temperature increment. This was so for Kincardine and has recently been stated to be the case for some river recirculation models in the United States.[3.13] Thus great difficulty would be found in simulating heat losses in a natural scale model, a difficulty increasing with decrease of the scale. Partial substitution of saline density difference would seem the only solution.

Only one model where close heat loss simulation is necessary has so far been described.[1.7] The scales adopted, $\frac{1}{480}$ horizontal and $\frac{1}{60}$ vertical, lead to a model heat loss rate requirement of 1/1.45 of that of the prototype. This seems sufficiently near ½ to ⅓ to present no undue difficulty. If it were desirable to increase a model's heat loss rate, the use of overheated but slightly salted outfall water would be much easier to arrange and control than salting of the main body of water, which was suggested earlier in this paragraph as the remedy should the heat loss rate be too great when thermal density differences only were used.

11.4. <u>In conclusion</u>

11.4.1. A further search of the literature might well provide information on which a better approach to heat losses could be based. The presently described method is thought to be adequate for the present purposes and it has been sought to demonstrate this. There is, at present, considerable interest in the effect of heat dissipation on the temperature of rivers and estuaries and on the biological effect of temperature changes,[2.15-19; 11.1,10,12,1] and it is probable that, when the results of current investigations are published, an improved method for the prediction of heat losses will be available.

12. ECONOMICS OF HEAT DISSIPATION

12.1 Introduction

12.1.1. Considering only temperate climates and conventional methods of heat dissipation, it is normally found more economic to base the circulating water system of a coal or oil burning steam power station on a convenient naturally occurring body of water than on cooling towers. The relationship of this advantage to fuel transport costs and transmission losses is such, however, that many power stations have been, and are being, constructed so as to be close to coalfields and load centres although this necessitates the use of towers. As illustration of the basic economic disadvantage of towers, it has been shown[12.1] that where insufficient flow is present at an otherwise suitable inland riverside site for all or part of the year, a system which uses the river water available augmented by towers is preferable to a system depending entirely on towers for heat dissipation. This compromise, involving a certain amount of duplication of equipment, has been adopted for several modern power plants.[12.2-6] Because of the lower initial steam temperatures and pressures, the circulating water flow required for the type of nuclear station currently under construction is nearly double that of a conventional station for a given output and temperature rise and the nuclear stations so far announced are all sited beside natural sources of cooling water. 10,000 and 6,000 BThU/KWhr for nuclear and conventional stations respectively have recently been quoted as typical figures for the surplus heat to be transferred to the circulating water.[12.7]

12.1.2. The economic design of circulating water systems based on cooling towers has attracted rather more attention than that for systems based on natural bodies of water, perhaps because of the initial disadvantage of the former type, but the economics of the latter type are not without interest.

In this section an attempt is made to review this subject in the light of recent developments in steam power plant and from the point of view of the civil engineer. However, for the civil engineer to understand the basis of economic design of the circulating water structures with which he may be concerned as regards layout, hydraulic design, stress design or construction, it is necessary for him to have some little knowledge of matters which are primarily the concern of the mechanical engineer. Some terms, which may be unfamiliar to the civil engineer, are briefly explained in an Appendix.(12.9)

12.2 Design considerations - 1 Effect of exhaust pressure on turbine output

12.2.1. For given rated initial (and reheat) steam conditions and throttle flow and a given final feed water temperature the output of a central station steam turbine is affected by the exhaust pressure and by the total annulus area of the last stage of the low pressure section or sections, assuming an equal standard of design and manufacture throughout the turbine for varying last stage annulus areas. Keller and Downs[12.8] have described how the minimum heat rate for a given steam input and annulus area is attained at the exhaust pressure where the following effects resulting from a small decrease in pressure are equal:-

(i) The varying increase in output due to increase in used energy per pound of steam flowing through the last stages (the used energy tending to a limit where sonic velocity is reached at the last stage).

(ii) The decrease in output due to the reduction in steam flow through the stages beyond the first feedwater heater, at which additional steam is withdrawn to compensate for the reduction in condensate temperature corresponding to the small decrease in exhaust pressure.

The relation between steam flow to the condenser and the last stage annulus area determines the optimum exhaust pressure (so defined) at which the minimum heat rate is attained and Keller and Downs have given the following empirical rule:-

$$\frac{\text{Steam flow to condenser (lb/KWhr)}}{7.9 \times \text{Annulus area per MW (sq. ft.)}} = \text{Optimum exhaust pressure (in. hg. absolute)}$$

They have further shown that the curve relating percentage increase in heat rate from the minimum obtaining at optimum exhaust pressure to the ratio of exhaust pressure over optimum exhaust pressure is more or less constant in form and if known for any turbine and initial steam conditions and flow can be modified to apply to any generally similar turbine and varied conditions by its multiplication by two factors, the first depending on the change in steam conditions and the second on the characteristics of the last stage buckets of the turbines. Fig. 12.1 shows part of this curve as given by Keller and Downs.

12.2.2. Miller and Sidum[12.9] and Morgan and Fulton[12.10] have shown how output increases with increasing annulus area for constant initial reheat and final (exhaust) conditions and flows, giving examples from ranges of annulus areas available from two of the principal turbine manufacturers in the United States. The effect of variations in annulus area on cost and on floor area is also discussed and comparative figures given. Together with other contemporary papers[12.11,12] these immediately preceding references are cited because of the lack of comparable published studies dealing with British practice. They are mainly of interest for the information given on the effect of variation of exhaust pressure on output and as illustration of the problem of optimisation of power plant component selection in conditions where standardisation is much less operative than in this country, but may also give guidance as to the economic effect of any departure from the normal range of circulating water temperature increment.

12.2.3. The foregoing tends to under emphasise a factor to which increasing attention is being given in this country as the basic unit size of turbines increases rapidly. That is the 'quality' of the annulus area. In the various stages through a turbine the required flow area for the steam increases greatly, as the steam expands from the initial conditions to an exhaust pressure of 1 or 2 in. hg.absolute, despite the abstraction of steam for feed heating of the order of one third or more of the initial flow. At the first stages of a modern central station turbine, the quotient base radius/blade height is large, of the order of 10 to 15. The practical assumption can be made that the blade velocity is constant along its length, leading to a uniform section. At one time this assumption was continued through to the last stage,[12.37] but with the continuous search for greater efficiency and greater unit size, this phase has long past. The 30 and 60 MW turbines of the post-war years had last blade quotients of the order of 1.3 to 1.5, with one and two exhausts respectively. For the larger turbines now being installed, a quotient of 1 may be considered standard and, for the largest last stage yet announced, that for the English Electric 275 MW turbine, the quotient is 0:89 (36 in. blade on 32 in. base radius). Table 12.3 shows details of typical British turbine designs, concentrating on the last stage details.[7] It will be realised that the particulars published by the various manufacturers vary greatly in detail. Regarding the last stage annulus, for example, the English Electric Co. and the General Electric Co., give considerable details;[7] Messrs. C.A. Parsons & Co. and the Metropolitan-Vickers Co. are much less inclined to disclose overall sizes. Some idea of the last stage annulus can sometimes be gleaned from the sectional drawings published in various papers and books. These are sometimes named, but can otherwise usually be identified by the characteristic design features of the various makers. The use by the Metropolitan-Vickers of 'Bauman' multi-exhausts (indicated B) complicates comparison. So the table is rather fragmentary. Designs of The British Thomson-Houston Co., are included, although the turbine manufacture side of this A.E.I. subsidiary have recently been integrated with those of The Metropolitan-Vickers Co. For the computation of Keller and Downs, optimum exhaust pressure on Table 12.2, exhaust flows were taken from Table 12.3 which lists the salient features of the C.E.G.B. standard steam cycles.

12.2.4. Considering, then, the last stage of a modern turbine of quotient about 1, the stage is designed for some selected exhaust pressure. From the cycle characteristics, the exhaust flow is more or less known. The root blade speed is $50 \times 2\pi R_r$ ft./sec. where R_r is the root radius in feet, (3,000 r.p.m. is the shaft speed used for 50 cycles/sec. generation) and the tip blade speed is about twice that at the root. The designer must attempt to produce a blade which will 'throw out' the steam axially at a uniform velocity over its length; the desired axial velocity being determined by the volume flow and the annulus area. This determines the ideal blade exit angle. Agreement between the nozzle angle and the blade entry angle, so that a variable degree of reaction through the stage fits logically into the design in general and compensates for the centrifugal pressure increase due to vortex flow through the stage, must also be achieved. The number of blades must be chosen as a compromise between tending to obstruct the base flow and being able to effectively control the flow at the tip, without widening the blade more than can be held by the root area. Once a best compromise has been found, changes in the exhaust pressure will modify the degree of axiality of the exhaust flow. The difficulty of design increases both with the mean radius of the blade and with decrease of the blade quotient. In a fairly recent discussion on turbine design, Mr. J. M. Mitchell,[33a] speaking for The

General Electric Com., attacked The English Electric Co., 275 MW last blade dimensions, not of course directly, but clearly illustrating a divergence of opinion between turbine designers in this matter.

12.2.5. The exhaust pressure-heat rate curves supplied by a manufacturer should be the manufacturers' best computation of the factors involved; but there is divergence of opinion on such computation. The curve is used, firstly, to a assess the economics of the choice of turbines and, secondly, to correct for differences from rated conditions during acceptance trials. It is a curve agreed between the manufacturer and the buyer and is not based on actual tests. These may come later and are used to re-assess the basis for the computation of later curves. For a particular curve, similar to the generalised Messrs. C. A. Parsons drawing (Fig. 12.4), supposing that the heat rate is correctly assessed at the design point, the effect of over optimistic computation of variations due to changes in exhaust pressure, particularly reduced exhaust pressure, would be to reduce the true rate of curvature of the curve.

12.2.6. Kennedy and Margen[12.1] have also given a set of curves showing the effect of changes in exhaust pressure which are reproduced here as Fig. 12.5. These authors, writing about cooling tower economics, made statements about the 'inevitable' increase in annulus loading which have subsequently been shown to be completely misleading (Table 12.2). Their figure ignores the decrease in output which occurs with reduction in exhaust pressure below optimum, but is otherwise probably quite useful so long as 'exhaust heat-loadings' can be obtained for the turbines; a simple process, but ignored in the paper apart from the statement of typical figures for 30, 60 and 100 MW sets. These loadings are included for some of the turbines in Table 12.2.

12.2.7. Thus, although standard steam cycles and turbine ratings have been adopted for conventional plants in this country, as shown in Table 12.3, standard heat rate to exhaust pressure curves for full load running are far from realisable, principally because of variations in the low pressure stages of equivalent turbines by different makers. It is suggested that for circulating water system design the most useful form of the heat rate - exhaust pressure relationship is the curve of percentage change in full load output per degree change in equivalent exhaust temperature. Ideally, such a curve for a particular case can be prepared relatively simply from a percentage change in heat rate against exhaust pressure curve as computed by the turbine maker on the assumption of direct correspondence between exhaust pressure and temperature, although in certain cases it might be necessary to make some constant adjustment.[12.15] These curves are not, however, readily available. Figs. 12.4A and 4B show information received from two manufacturers. The British Thomson Houston curves for 120 MW or 200 MW sets are for designs only, made prior to the integration referred to earlier. For purposes of general study, the Kennedy and Margen or the Keller and Downs curves might be used. Unfortunately, the part of the Keller and Downs curve relevant to British practice is reduced to a small size in the original paper and some error is likely in both the preparation of the enlarged section shown in Fig. 12.1 and in the interpolation needed to bring the curve to the required stage for a chosen case. However, this method should give results of the correct order and the approximation for optimum exhaust pressure is thought to agree fairly well with British practice. For practical use, some assessment of the characteristics of the turbine 'in mind' would be necessary with recourse to the paper to make allowance for the differences thereby made from the writer's company's Turbines, as instructed in the paper.

12.2.8. It should here be emphasised that the effects of both variations in last stage annulus area chosen within economic limits and variations in exhaust pressure during operation on the output of a modern turbine are relatively small and are decreasing as higher initial steam temperatures and pressures are adopted. Both effects are proportional to the steam flow through the last stages of the turbine. This steam flow with the most recent C.E.G.B. standard steam cycle (2300 lb./sq. in. 1050°F with 1050°F reheat) is only 63% of that of the immediate post war cycle[12.14], the flows corresponding to about 6,500 BThU/KWhr and 4200 BThU/KWhr heat rejection respectively. A 5000 lb./sq. in. 1200°F with 1050°F reheat 325 M.W. set, for Eddystone power station in the United States is expected to have less than 4000 BThU/KWhr heat rejection.[12.16] Generally speaking total last stage annulus areas per MW have tended to decrease in proportion to the steam flow through the last stage as larger turbines for improved throttle conditions have been designed; the English Electric 275 MW turbine is one notable exception to this trend.[12.17] More detailed study of the effect of these variations is made later in this section.

12.3 Design considerations - 2 Relationship of exhaust steam temperature to intake water temperature.

12.3.1. The amount of heat passed to the circulating water in condensing exhaust steam is little affected by the exhaust pressure within the limits likely to occur in power plants. (Latent heat of steam 1060 BThU/lb. at 0.5 in. hg. and 1036 BThU/lb. at 2.0 in. hg. absolute). Thus the temperature rise through the condensers is determined by the circulating water flow, and the exhaust pressure in a well designed condenser closely corresponds to the temperature necessary to cause the rejected heat to pass to the varying temperature circulating water. The resistance to heat transfer depends on the material and construction of the condenser, on the water velocity in the tubes, on the intake water temperature and on the state of cleanliness of the condenser. Fig. 12.6 shows the relationship between intake water temperature and exhaust steam temperature for a wide range of circulating water increments and is based on the following empirical equation after Guy and Winstanley[12.18]

$$\frac{H \times \log_e [P/(P-R)]}{S \times C_c \times \sqrt[2]{\frac{V_t}{5}} \times \sqrt[4]{\left(\frac{T_i + R/2}{100}\right)} \times R} = 1$$

Where

H = Heat flow per KWhr (B.Th.U./hr.)
P = Exhaust steam temperature - Ti (°F)
T_1 = Intake water temperature (°F)
R = Condenser increment (°F) ($\frac{Ti + R/2}{100}$ is dimensionless)

Vt = Water velocity in tubes (ft./sec.) (Vt/5 is dimensionless)
Cc = Characteristic of condenser (B.Th.U./sq.ft. x hr. x °F temperature difference)
S = Condense surface area per KW (sq. ft.)

12.3.2. If the rated exhaust pressure at a given intake water temperature and condenser increment is known, exhaust pressures at selected intake water temperatures representative of the annual variation can be obtained as shown on Fig. 12.6 for a typical case. Positioning of the curve of percentage change in full load output per degree change in exhaust steam temperature above the condenser relationship graph enables the effect of changes in intake water temperature on output to be readily appreciated. Such a figure could also provide guidance in the comparison of condenser increments. Although written some 25 years ago, the paper by Guy and Winstanley[12.18] is regarded as a standard reference.[12.19] In it 650 BThU/°F temperature difference is suggested as the value of C_c for average conditions. While the authors stated that the use of the Grasshoff mean temperature difference may be incorrect in condenser calculations, they showed it to be reasonably accurate for cases where little pressure drop occurs through the condenser as is assumed for Fig. 12.6. As the figure is intended as a basis of comparison only, starting from rated conditions or from some modification of rated conditions, and not for the evaluation of precise conditions, further refinement is not thought to be justified.

12.4. Design considerations - 3 Effect of circulating water released into rivers, lakes and estuaries

12.4.1. Circulating water abstracted from a natural body of water is usually returned, after being heated in passing through the condensers, to the same body, the distance between the points of intake and discharge varying with the circumstances. Exceptions to this can be found where site configuration has been especially favourable.[12.20-22] In the body utilised for heat dissipation, whether the source or not, variations from the natural temperature, which would have obtained at particular points and times had the station not been in operation, can sometimes be recognised at considerable distances from the station.[12.23] Neglecting for the moment the complication of other circulating water systems which might be based on the body, any sequence of variation of temperature from natural at the intake of a system using esturial or tidal river water may be regarded as having two varying but separable components, a long term or inherent recirculation increment and a short term or configuration recirculation increment. The first component is likely to be largely independent of the relative placing of the outfall and intake and of the combination of flow and temperature rise chosen to remove a required amount of heat from the condensers, but is strongly influenced by the mixing and flushing characteristics of the particular body on which the station is sited and by the nature of the tidal cycles and of the output of the station for some days previous to the time in question. Although in relatively shallow waters the actual water temperature is closely affected by the weather, the inherent increment over natural temperature is much less affected since it is unlikely to exceed a few degrees. The second component will vary with the state of the tide, the design of the system (orientation of intake and outfall and the design flow) and the output of the station just previous to the time in question. The natural water termperature may also affect this increment because of the non-linear density-temperature relationship in water. In open waters there are occasions where the inherent recirculation increment is imperceptible and the configuration increment inapplicable, but in many cases stations are built on more enclosed tidal waters where both increments may reach several degrees farenheit, though probably not concurrently.

12.4.2. In this country lakes have not so far been used to any extent to provide circulating water but separation between the two increments could again be envisaged. With non-tidal rivers the inherent increment does not apply but the configuration increment, though much more easily avoided than in tidal waters, may be a factor to be considered where economical design is attempted for cases of fluctuating river flow.[12.24]

12.4.3. Limitation on the use of river or estuary water for cooling purposes is commonly stated as a maximum allowable temperature increment for the outflow over the natural temperature together with an absolute maximum outflow temperature.[12.25] In the case of a previously unaffected non-tidal river site, the base for assessing the condenser increment plus the recirculation increment, if any, for comparison with the allowable increment is easily definable during operation from the upstream temperature. Even with a series of stations a basis of comparison is available somewhere, but for a site on tidal waters the natural temperature may be difficult to define due to an inherent recirculation increment, whether caused solely by the station under consideration or not, being superimposed on a natural temperature subject to semi-diurnal tidal cyclic variations and irregular variations caused by the weather. Thus for practical design purposes a condenser increment must be selected which allows for any configuration increment, possibly allows for special circumstances which may be envisaged and either allows for an estimated inherent increment or ignores this aspect of recirculation. On a non-tidal river site the closeness of the condenser increment to the allowable increment may determine the total heat rejection which can be accepted at low flows but for tidal waters this is unlikely to be the case because of the vastly greater flows involved. For example, the River Forth has an average flow of about 1,500 cusecs at the tidal limit but 18 miles downstream at Kincardine power station the average flow, up river and down river, is about 40,000 cusecs although the drainage flow has only increased to 1800 cusecs.[12.26]

12.4.4. In industrial regions waterways are increasingly used to dispose of sewage, sewage works effluent, industrial wastes and even radio-active material[12.27] while, at the same time, the natural drainage flow is increasingly abstracted. The dissipating capacity of such waterways is being widely studied (innumerable references can be found in the monthly D.S.I.R. Water Pollution Abstracts) and attempts made to formulate rules for the best use of the available resources so as to combine reasonable facilities for the disposal of waste with the maintenance and, where possible, the improvement of amenity and of the marine and river life environment. Waste heat disposal is really a form of pollution and it has been shown that the combination of temperature rise and oxygen deficiency resulting from bacterial pollution can have a more severe effect on fish than oxygen deficiency alone.[12.28] Certain toxic impurities also become more harmful to fish with increasing water temperature.[12.29] Although fish can be comfortable at a wide range of temperatures, sudden changes in temperature may be harmful even in unpolluted water.[12.7] Such considerations may lead to a more accurate determination, perhaps a more restrictive determination, of how much use can be made of natural bodies of water for heat dissipation without undue interference with their other functions. In this country river boards and similar bodies are already less willing to accept such large increases in the temperature of rivers as has been customary in the past[12.25,30] and this is helping to make suitable river, estuary or lakeside sites for conventional power plants difficult to find, and where found, to secure. Even in the United States with its apparently limitless resources there is a tendency in this direction.[12.31,32.] A recent article on the siting of a nuclear power plant[12.33] (where the requirement of especially favourable foundation conditions as compared with a conventional station adds to the difficulty of finding a suitable site) shows that despite negligible fuel transport costs, the need for isolation and the relatively greater circulating water requirement, the open sea may not always be the most economic source of cooling water. Here an inland body of water at much the same distance from the load centre was found preferable, attractive though the open sea would have been as a means of heat dissipation unlikely to result in recirculation or to meet strong opposition for reasons of amenity or conservation. This points to to the continuing pertinance of the study of heat dissipation in enclosed waters.

12.5 Design considerations - 4 Theoretical optimum full load increment

12.5.1. For a particular site and circulating water system layout the cost of providing some design flow of circulating water will be related to the amount in some fairly complex manner; the proportions of the minimum annual cost for any chosen flow attributable to capital expenditure, to providing power for pumping and to maintenance, including efficiency losses caused by servicing and cleaning, varying with the flow. The power required for pumping will not even be proportional to the design flow because the design head loss to give minimum costs will change with varying flows.[12.34] Because of the vastly different conditions between one site and another, no rule for costs could be given. If leading details of costs, design flow and head loss for various recent circulating water systems could be obtained, it is thought that broadly representative curves of full load annual cost per cusec against full load design flow could be drawn. It is this information that has been sought from the project design staff of the C.E.G.B. The request has not been rejected out of hand, but whether the information will be given is not known. With such information the economic comparisons to follow could be expanded and more firmly based and it might be possible to make a paper out of this section.

12.5.2. For a selected turbine type and number the full load condensing heat flow is largely independent of the condensing steam temperature. Assuming that the problem of recirculation does not arise and that there is no restriction on circulating water outfall temperature, a theoretical optimum full load circulating water temperature increment can be envisaged, for any selected orientation of outfall and intake, with which the sum of the following annual costs is a minimum for full load running assuming that no increase in the condenser increment is allowable at any time:-

(i) Cost of condensers.
(ii) Cost of providing the circulating water flow.
(iii) Cost of loss in efficiency occasioned by the difference between the seasonally varying intake water temperature and the condensing steam temperatures appropriate to the circulating water flow, the condenser design and the aforesaid seasonally varying intake water temperature.

12.5.3. This optimum increment would be expected to be at a minimum when the total circulating water route length through the station and between suitable points of intake and discharge is the shortest feasible. Just as the technically possible optimum output as affected by the total last stage annulus area is rarely economically justified, the increase in output which could be obtained with relatively large circulating water flows and proportionally low temperature increments is hardly ever found economic. At a particularly favourable site a design circulating water increment of 4°F and condensers giving condensing steam temperatures 11°F above intake water were adopted in 1937 in the United States.[12.35] This represents a limit which is unlikely ever again to be approached because of progress in turbine design.

12.5.4. Although the invalidity of the assumptions made in paragraph 12.5.2. rules out the automatic adoption of the minimum theoretical optimum full load increment as the design increment, there may be considerable benefit in knowledge of the relation of the theoretical optimum full load increment, for the layout selected, to the design increment chosen. Choice of layout and design increment (or the design flow) may be influenced by various factors including:-

(i) The type of loading envisaged for the station. (As the load factor decreases and the proportion of part load running to full load running for a given load factor increases, the most economic value of both the design head loss and the design flow tend to increase and the economic capital outlay on circulating works tends to decrease.)

(ii) The restriction, if any, on heat rise in the source of circulating water.

(iii) The amount of recirculation, if any, thought likely with various layouts on flows and the comparative ease or difficulty in decreasing the configuration recirculation by expansion of the layout, e.g. foundation conditions, availability of deeper water, limits of land available, etc.

(iv) If no restriction on heat rise arises, or if such restriction is not fully taken up, the relationship of the intake water temperature corresponding to minimum heat rate to the expected annual cycle. (The case for increase in increment with saving of pumping power at low temperatures has been stated.[12.15, 36, 36a])

(v) The effect of departure from standardised practice on price and delivery of components.

(vi) The necessity to guard against unlikely but feasible isolated combinations of conditions where considerable damage might be done to marine life.

(vii) Arbitrary decisions which may be made as factor of safety because of lack of knowledge of (iii) or as concessions to parties interested in the source body of water.

12.5.5. Again it is hoped to eventually prepare curves of annual costs for varying increments and selected representative ranges of intake water temperatures based on the curves mentioned in 12.5.1., on Fig. 12.6. and heat rate - exhaust temperature curves. Minimum costs and the corresponding increments would be obtained from these curves and would be compared with design increments as recently adopted in the United Kingdom. For the present, some such increments are given in Table 12.7. linked where applicable to turbines listed in Table 12.2.

12.6. Economic comparisons - 1 - Values of possible changes in circulating water arrangements at Kincardine

12.6.1. This and the following economic comparisons are made in terms of annual value, or of capitalised value, for selected typical cases. As similar comparisons can readily be made for other cases by the methods outlined, it is thought that the disadvantages inherent in attempting to typify a fairly wide range with a very restricted selection are more than balanced by presenting the comparisons on the basis of stations which can be readily visualised, and in a form which has an immediate meaning to the civil engineer in terms of costs of works. Indeed there are so many possible combinations of equipment and situation that any other course might well lead to confusion.

12.6.2. Kincardine Power Station was originally intended to have six 120 MW sets; it was later decided to substitute two 200 MW sets for the final three 120 MW sets, G.E.C. sets with four flow low pressure stages being chosen (14 on Table 12.2). However, details of the cooling water flow for the 200 MW sets have not been issued. Considering, for simplicity, a 720 MW station sited at Kincardine with six 120 MW Parsons sets (29 on Table 12.2). The condensers are rated to give 28.9 in. vacuum (1.1 in. hg. absolute exhaust pressure) at 55°F intake water temperature and with a flow of 160 cusecs. This corresponds to 15.8 F temperature rise through the condensers assuming 95% dry steam. (At the time of the Kincardine investigation 15°F was the assumed rise). Unfortunately, the last stage annulus area of the Parsons 120 MW turbine has not been given. However, the annulus area of the Parsons 60 MW set is about 70 sq. ft. with two flows (information received from Messrs. C. A. Parsons & Co. Ltd.). The cost of developing a new last blade is considerable,[12.14,39] and since the 120 MW set has triple exhausts, it seems reasonable to assume that the same last stages were used. Allowing for the improved initial steam conditions and the reheat, compared with the 60 MW sets steam cycle, the relative annulus area (taking 1 as representing 70 sq. ft. for a 60 MW, 900 lb/sq. in., 900°F non-reheat set) is about 0.97 and the Keller and Downs optimum exhaust pressures are 0.67 and 0.69 in. Hg. absolute for the 60 MW and 120 MW turbines respectively. Now the rated condenser performance for the Parsons 120 MW sets at Kincardine is 1.1 in. Hg. absolute pressure (or 82°F saturation steam temperature) at 55°F intake water temperature. The typical Parsons heat rate-intake water temperature curves (Fig. 12.4A) were stated to cover most of the machines designed by them in recent years for the Central Electricity Generating Board and the South of Scotland Electricity Board. The annulus area of the 120 MW set is relatively large and the leaving loss would be expected to be nearer 1% than 1½% at the design point. Curve A on Fig. 12 would reach a minimum at about 13°F below the design point intake water temperature and at a saturation steam temperature of 69°F (or 0.71 in. Hg. absolute exhaust pressure). This is in reasonably good agreement with the Keller and Downs optimum exhaust pressure.

12.6.3. Curve A (Fig.12.4A) has been transposed into percentage full load output increase per degree decrease in saturation steam temperature and placed 12.40 on Fig. 12.6. Representative average natural water temperatures at Kincardine are 38, 43, 48, 53, 58 and 63°F for sixths of the year. Suppose 2°F is taken to cover the inherent and 3°F for six hours per day, the configuration recirculation increments. Taking 38 + 2 + 1½, etc., as the mean actual intake water temperatures during periods of recirculation, the developed Parsons curve A is placed with the design point rate of change at 82°F saturation steam temperature. A horizontal line is drawn on the condenser relationship part of the figure so that it passes through the point on the 55°F intake water temperature and 15.8°F increment line (interpolated) which is vertically below 82°F on the saturation steam temperature scale, thus agreeing with the rated condenser performance. Output changes are then read from above the appropriate temperatures on the horizontal line. The mean output change for 3°F temperature drop is thus + 3/6.(0+0.035+0.085+0.11+0.145+0.160) % or 0.27%, and at 80% load factor, 0.6d per unit and remembering that the saving is for only 6 hours per day, the annual value of the saving is £8,500. Capitalising at 10%, the result is £85,000 for the capital value of the configuration recirculation losses. As no value has been placed on the increased capacity, because of the extremely marginal nature of the case, it would be reasonable to spend nearly this amount to avoid configuration recirculation at Kincardine. That is assuming that the model results were reasonably accurate.

12.6.4. When the configuration at Kincardine is studied, (Fig. 2 of Attachment 1) it is difficult to see any way whereby the configuration recirculation could have been completely prevented at such a low cost. The obvious expedient of increasing the distance off-shore of the intake so that the heated water would pass entirely behind the intake during the ebb, would have been impossible because of interference with the navigation channel. If it had not been for this, a considerable improvement might have been made at a cost of the order of £85,000. But detailed study would have been necessary before such an extension of the intake culverts could have been firmly decided upon. Nevertheless, the point is made that the order of possible savings is far in excess of the order of the cost of the further development and running of the Kincardine model (Kincardine Paper - Paragraph 45); had this been undertaken £1,000 would have covered the further work.

12.6.4. Considering now the output loss that would have been occasioned had the condenser increment been increased by 1°F from 15.8 F. Fig. 12.6 can be used to give the change in saturation steam temperature to sufficient accuracy for the present purpose; about 0.8°F increase assuming no change in condenser conditions. Using the same annually representative intake water temperatures as previously, this leads to a capitalised loss of £91,000. Against this must be placed the savings in pumping and capital expenditure. Firstly the pumping; at 0.6d. per unit, 960 cusecs full load flow for 15.8°F increment, 30 ft. average head loss, 80% load factor and 90% pumping efficiency, the capitalised saving in pumping is about £30,000. Secondly, the saving in capital expenditure on the total circulating water arrangements. Only a rough estimate of this can be made, say one third of the direct proportion of a total cost, of the order of £2,000,000 given by the ratio 1 to 15.8, i.e. £42,000. The total saving on this basis is £72,000. These figures mean no more than that it appears that the increment of 15.8°F is pretty close to the optimum increment for the 'imaginary' six 120 MW sets station at Kincardine. There would thus have been little scope for the model results to have been used to save overall expenditure by the proportioning of condenser increment and maximum configuration recirculation increment to come just below some critical or agreed figure. If, however, the optimum increment had not been approached, valuable information might have been obtained in this context.

12.6.5. Table 12.7 shows that for stations such as Kincardine and Blyth A and B, on the Northumberland cost, it has not been thought worth while to provide particularly high performance condensers; a rated intake water-saturation steam temperature difference of 26 - 29°F is rather greater than that for most cooling tower stations. It was probably found that with the higher initial water temperature of the latter, more is to be gained by reducing the back pressure. Certainly intake water temperatures at Kincardine will sometimes be sufficiently low to bring the back pressure down below optimum (i.e. intake water temperatures below 42°F) and thus cause loss of output unless the increment is temporarily increased by reducing the circulating water flow.[12.15] Such a step would not be acceptable to the Conservancy Board in this case. Had the representative two month periods used in 12.6.3., been further divided, the cost of circulation would have varied slightly, but not materially. However, it is interesting to find what would have been the capitalised value of the increase in output had the rated intake water-saturation steam temperature difference been cut 7°F to be 20°F. On a similar basis to the previous calculations, the sum of £450,000 is obtained, allowing for the loss at lower intake water-temperatures (below 48°F) which would in this case obtain for a material portion of the year. Parsons curve A was used directly for the above computation and it was assumed that the curve was symetrical about the minimum heat rate point. The extra condenser area per set to obtain 28.9 in. Hg. vacuum at 62°F instead of 55°F is 45,000 sq. ft. The cost for the station would be about £600,000 at 45/-. per square foot total extra cost. Again there is no economic justification for improvement in the station efficiency by modification of the circulating water arrangements, if anything, the reverse appears to be the case.

12.7 Economic comparisons 2 - General

12.7.1. In 12.6 an attempt was made to use the original design of Kincardine Power station to illustrate economic considerations which might have a bearing on the model study programme. Recapitulating, the points already brought out are as follows:

(a) If a model investigation shows how the same, or less severe, recirculation conditions can be obtained at a reduced capital expenditure, its worth is obvious, and no consideration of economics is necessary.

(b) Given knowledge of the cost of loss of output caused by recirculation, the economics of various alteratives, resulting in differing recirculation circumstances, might be studied in conjunction with model results. While this applies mainly to new stations, it is not impossible, or indeed, unlikely, that simple modifications to existing circulating water intakes might be proved worth while. Going no further than Braehead Power Station, on the Clyde near Renfrew, one finds the intake and outfall sited in short canals leading from the river, and at a spacing of quarter of a mile or so. It seems likely that a fair amount of recirculation occurs on the ebb, and a simple baffling arrangement might help.

(c) Should the case arise where the limiting of condenser increment plus maximum recirculation increment to some agreed limit results in a condenser increment materially below optimum, a model might show how economy could be affected by keeping the condenser increment as large as possible.

12.7.2. To what extent could models be used effectively in the future to investigate these various aspects of economic design, if greater confidence were felt in predictions obtained from this type of model than in the past? As mentioned in 1.2.2., whenever a circulating water system is elaborated beyond that necessary to deliver some predetermined flow of sufficiently clear water to a station and to allow of its disposal without consideration of the intake temperature, there must be some method of deciding upon the amount of elaboration necessary to avoid recirculation. For stations of the capacity of Kincardine, or for nuclear station of about half its capacity as are now being built and which have about the same circulating water flow, the basic cost of elaboration is of the order of £60 to £100 per foot of culvert length on land and very much more where under sea tunnels or culverts are concerned. Most published descriptions of new stations mention briefly the need to prevent excessive recirculation and the elaboration of the circulating water systems at stations such as Hunterston is considerable. It is undoubtedly much more likely that an arbitrary decision involving the odd £100,000 of additional expenditure will occur somewhere in the process of design of the basic layout of a system than that £5,000 will be spent on a model investigation. It is realised that, taking an overall view, it may be just as well for a prosperous body, such as the Central Electricity Generating Board, to spend more on civil engineering construction than can be justified on the basis of strict 'economic' design, but that is a question beyond the scope of this thesis. If rational calculations for the avoidance of configuration recirculation in estuarine conditions can be made, they are certainly not publicised, and the Author's experience with the Kincardine model did not lead the belief that such calculations could yet be made. The probability is rather that a basic layout of intake and outfall is arbitrarily drawn up very early in the planning stages of most stations and that although much careful design is carried out on the details, it is practically impossible for anyone to bring themselves to change the overall configuration. The method of tendering foo nuclear stations; design and price for the reactors and principal equipment and cost plus for the civil engineering works where local conditions are relevant; again does not lead to the economic design of circulating water works. As regards the first use of heat dissipation models, then, it does seem that if the accuracy of the results would be established, economics far in excess of the cost of such models would be likely wherever any elaboration of a circulating water system were examined. Furthermore, this type of study, as typified by the Kincardine investigation, may be of use with less than full quantitative similarity, and at its simplest could be merely a demonstration that distance is not necessarily the criterion of safety as regards freedom from recirculation.

12.7.3. The next stage, the design of some feature in a circulating water with expenditure balanced against cost of output loss rather than the cancellation of expenditure, would require quantitative assessment of amount of recirculation. At this stage the characteristics of the station generating and condensing equipment might also have to be considered. With rise of the intake water temperature at which optimum back pressure is attained, the importance of preventing recirculation decreases. At the present time, the swing seems to be in the reverse direction. Three illustrations come to mind; at Kincardine the 200 MW sets are to have a relative annulus area of 1.17 compared with the 1.0 of the 120 MW sets. Moreover, the successful tenderer could also have offered a more compact design with a relative area of 1.07, but this was not considered sufficient. (Table 12.2) At Blyth A the 120 MW sets have a relative annulus area of 0.90, while at Blyth B the 275 MW sets have 1.41 relative annulus area. Robson[12.14] has explained how nuclear power station turbines must have relatively large exhausts because of the great decrease in the total heat drop. Two turbines for nuclear stations have been illustrated, one of 80 MW,[12.4] and one of 60 MW.[12.37] Both have triple flow low pressure sections.

12.7.4. It thus seems that the cost of recirculation at Kincardine would be a reasonable basis for estimates, if better information were lacking. The cost per °F of recirculation will apply roughly to both the improved steam cycles for conventional stations and to nuclear stations as long as the design condensing water flows are used as a link. For example, the cost per degree of recirculation at Hunterston is approximately the same as that at Kincardine since the circulating water flows are approximately equal and this allows for the difference in steam cycles and installed capacity, which, at Hunterston is approximately half that at Kincardine. Prevention of recirculation by additional expenditure will thus continue to be on much the same economic basis as at present and should be worthy of study wherever appreciable recirculation occurs.

12.7.5. The third possible approach to economy by model study, that of preventing an undue allowance for recirculation from forcing down the condenser increment below optimum, seems unlikely to be applicable in the future. The building of large stations on small estuaries seems to have been completed, if only because of lack of sites, and the sites being investigated for nuclear stations are mostly on the open coast.

12.8. In conclusion

12.8.1. An attempt has been made to review the economics of heat dissipation and to provide a method whereby a civil engineer can get an approximate idea of the effect that differing circulating water arrangements can have on output. Tables 12.2 and 12.7 have been drawn up to show the trends of present British practice and it is thought these have been made more meaningful for the civil engineer by the use of comparisons of relative annulus area and rated exhaust temperature - intake water temperature difference.

12.9 APPENDIX I TO SECTION 12 - GLOSSARY

The standard turbine terms, and other terms used in Section 12, are briefly explained here. Bartlett's[12.41] Glossary was taken as a basis, but was very considerably curtailed, and reference has been made to Kearton[12.37] and Salisbury[12.42] for other definitions.

ANNULUS AREA:- The area of the annulus occupied by the blades. Usually refers to the last stage of the low pressure section and to the total area if more than one flow is involved in the particular turbine.

BLADES, BUCKETS:- The rotating vanes which convert the Kinetic energy and heat energy to work. In an impulse stage no expansion of steam occurs through the blading and only kinetic energy is used. In a reaction stage the steam expands while passing through the blading and both kinetic energy and heat energy are used to directly drive the blades.

BLADE QUOTIENT:- The root radius divided by the blade length.

CIRCULATING WATER FLOW:- The flow of cool water through the non-steam side of the condenser.

CONDENSATE FLOW:- The flow of condensed steam from the condensers. Due to feed heating this is only a percentage of the steam flow to the turbine from the boiler.

CONFIGURATION RECIRCULATION INCREMENT:- That part of the temperature rise of the intake water, compared with the temperature had the station not been operating, which can be attributed to the selected configuration of outfall and intake.

DESIGN, RATED:- A turbine is designed to most economically meet a certain capacity requirement when supplied with steam at rated conditions of temperature and pressure (and perhaps with steam at some reduced pressure being reheated to approximately the original temperature). A rated exhaust pressure is chosen for the design stage and the design process leads to steam flows for various turbine arrangements and for changes from the rated exhaust pressure, which is chosen to be typical rather than optimum.

EXHAUST LOSS:- Energy losses which occur between the last stage and the condenser. Mainly leaving or velocity loss (the kinetic energy of the steam leaving the last stage) and hood loss (the frictional and eddy losses between the last stage and the condenser).

EXHAUST PRESSURE:- The steam pressure at exit from a turbine section. Often used as a synonym for condenser pressure.

EXHAUST TEMPERATURE:- The saturation steam temperature corresponding to the condenser pressure.

FEED WATER TEMPERATURE:- As the condensate is pumped back to the boiler it is heated by steam bled from the various extraction points. The steam makes up the volume and, at the final extraction point, the final feed water temperature and the initial steam rate flow are reached.

HEAT RATE:- The heat supplied to the turbine per KWhr output (BThU/KWhr).

HEAT REJECTION:- The heat flow carried away by the circulating water, again per KWhr output.

INCREMENT:- Temperature difference from some variable starting temperature.

INITIAL STEAM PRESSURE AND TEMPERATURE:- The steam conditions at the turbine stop valve. Also called throttle conditions.

INHERENT RECIRCULATION INCREMENT:- That part of the temperature rise of the intake water, compared with the temperature had the station not been operating, which is unavoidable within the broad limits of the various configurations of intake and outfall which are feasible.

LOAD FACTOR:- The ratio of system or unit load to capacity load, normally averaged over a period.

MINIMUM HEAT RATE:- For a given turbine operating close to the rated output with rated initial and reheat steam conditions there will be an exhaust pressure where the required steam flow is a minimum. Hence the minimum heat rate.

OPTIMUM EXHAUST PRESSURE:- The exhaust pressure at which the minimum heat rate is attained.

NOZZLES:- The stationary blades or guides which direct the steam towards the moving blades.

RECIRCULATION:- The drawing of already heated water into the circulating water intake.

REHEAT:- The practice of removing partially expanded steam from a turbine, resuperheating it, and then returning it to the turbine to complete its expansion. Thus reheat pressure; the pressure at which the steam is removed, and reheat temperature, the temperature to which it is reheated.

RELATIVE ANNULUS AREA:- The ratio of the total last stage annulus area per lb./sec. steam flow to the area for a 900 lb. 900°F non-reheat 60 MW set with 70 sq. ft. total annulus area and on full load.

STAGE:- The combination of a single row of stationary nozzles and a row or rows of moving blades. This is the elementary turbine building block and in the type of turbine here described there are only single rows of moving blades for each row of nozzles.

STEAM CYCLE:- The sequence of steam conditions from the selected initial conditions to the condensing conditions at rated vacuum.

STEAM RATE:- Weight flow at a specified point divided by the generator output of the system. Hence initial or throttle steam rate or flow and condenser steam rate or flow.

USED ENERGY:- The amount of heat energy per pound of steam actually converted into work during a given expansion.

VACUUM:- The vacuum at the condenser is the assumed standard atmospheric pressure of 30 in.Hg. absolute minus the absolute exhaust pressure.

VORTEX FLOW:- The steam spirals through the turbine leading to an increase in pressure at the outside of the annulus due to centrifugal force. Where the blade quotient is small this can lead to uneven flow distribution unless corrected by varying the degree of reaction in the stage from inside to outside of the annulus.

13. CONCLUSIONS, GENERAL DISCUSSION AND RECOMMENDATIONS

13.1 Conclusions

13.1.1. If a thin vertical barrier initially separates two bodies of water contained in a flume and at the same level though slightly varying in density, then a pure density current exchange flow develops after the barrier is suddenly lifted (Fig. 7.5). In such experiments a study can be made of the coefficients of proportionality which relate the initial velocity of advance of the underflow and overflow to the densimetric velocity obtained from the general Froude law. These coefficients were found to increase slowly with increasing densimetric Reynolds number through the range likely in hydraulic models. Also the initial developments of the underflow and overflow are not, as commonly illustrated, symetrical; the overflow velocity exceeding that of the underflow by about 20%. Actual values are shown on Figs. 7.6 and 7.7.

13.1.2. Detailed observations of the coefficient of proportionality of the overflow were made for the first time and it was found that the slight variation in surface tension appropriate to a small thermal density difference has a pronounced scale effect on the mode of flow of the overflow. This is illustrated in Figs. 7.13 and 7.14. The scale effect can be obviated by balancing the surface tensions using wetting agent; the results of corrected tests being given in Fig. 7.7.

13.1.3. It has been shown that the conditions for similarity in diminution of velocity and in density difference flux in certain lock experiments are applicable to internal gravitational advance in open water. Also that for a heat dissipation model of small horizontal scale, some vertical exaggeration is essential and there is always a best value for this exaggeration. Any significant departure from the best value will result in failure to simulate the prototype advances. In Fig. 7.12 there is given a congruency diagram from which the vertical exaggeration may be obtained when both prototype and model are small, and Fig. 7.20 illustrates how critical is the determination of the exaggeration.

13.1.4. It appears that as the horizontal scale of a model of a full large prototype is increased there will come a stage when no vertical exaggeration is appropriate, but this size is outside the range of scales of models so far operated or contemplated. Fig. 13.1 shows a prediction of the trend of the congruency diagram (Fig. 7.12) as prototype conditions are approached.

13.1.5. Experiments were performed which confirm the applicability of the general Froude model law to vertical mixing of stratified water. The effect of vertical exaggeration was shown to make three dimensional simulation impossible immediately after a definite change in the mode of flow. After a stretch of more or less uniform flow from the overall standpoint, the degree of stratification will tend to be adjusted so as to give three dimensional simulation.

13.1.6. It appears that the importance of simulation of internal gravitational advance in heat dissipation models may have been obscured by the initial formation of partially mixed zones at the sides of an introduced stratified flow in the normal type of estuary model. Such a gradual change between the flows would slow down the development of the overflow and the underflow.

13.1.7. Heat losses can be simulated in a heat dissipation model with comparative ease using the information given in Section 11 and a thermal density difference is convenient to simulate the thermal density difference of the prototype, particularly if the recording system developed for the project and described in Section 5, is used.

13.1.8. There has been a tendency for the designers of the civil engineering aspects of thermal power stations in general and of heat dissipation models in particular, to be unaware of the economic implications of their work in relation to the overall working of the station. The information provided in Section 12 would allow a fairly accurate economic appreciation of the effect of heat dissipation circumstances on any chosen combination of site and generating plant to be made.

13.2 <u>Design of further heat dissipation and recirculation models, and the consideration of results from a model investigation.</u>

13.2.1. The programme of studies which has been described in this thesis followed from the Kincardine investigation and the approach which might in the future be made to a similar problem will now be discussed. It is emphasised that any divergence from the procedures followed during the Kincardine investigation does not imply criticism of these procedures, which were adopted in the light of rather less information than is now available.

13.2.2. It may be that in a relatively small model the ideal of three dimensional similarity of the velocity and density structure as compared with the prototype is not attainable, and certain aspects of this have already been discussed. However, if horizontal two dimensional similarity in density difference flux can be attained, much worth while information might be obtained; on the other hand if something approaching two dimensional similarity is not attained, model studies of the type listed in Table 1.1 are unlikely to be of much value.

13.2.3. The possibility of spread of heated water due to internal gravitational forces is inherent in heat dissipation and recirculation problems and the first concern of the designer of a model should be to assess the chances of such spread being critical in the prototype. By this it is not meant that the designer could predict the details of the advance - there would then be much less need for a model - but obviously the circumstances of the particular case would affect both the probability and the criticality of internal gravitational advance. As an extreme case one may envisage a situation similar to, but more involved than, that of the simplified outfall experiments which are described in sub-section 7.5. Here a model experiment carried out at some horizontal scale which would result in the same order of size of water movements as those during the reduced scale tests of the above mentioned series would be of little purpose without initial experiments to allow the completion of the lock congruency diagram for the infinite width, no reflected wave case. With such a diagram completed, the best compromise of vertical exaggeration would be chosen in the manner described in 7.4.1., and, if necessary, a density difference adjustment determined. The required extension of Figs. 7.6 and 7.7 would presumably also be available after the necessary experiments to allow a full congruency diagram to be drawn. These experiments are discussed in 13.4.3.

13.2.4. With increasing size of model and with decreasing importance of internal gravitational spread there would doubtless come a stage when an approximation to the best vertical exaggeration would serve sufficiently well. Fig. 13.1 shows a 'prediction' of the general trend of the congruency diagram, and was sketched using the related information available (i.e. Fig. 7.12 and Dr. Keulegan's results for relatively narrow channels). The Kincardine investigation is illustrative of the type of study where spread was of decreasing importance for the following reasons:-

(i) During the latter stages of the ebb, strong river currents were still operative, and indeed the illustration of the peculiarities of these currents and their effect on the outfall water distribution was probably the most important result obtained from the investigation.[1.4]

(ii) Once slack water conditions obtained, the outfall water itself formed a strong current reaching more or less to the bed during a considerable portion of its travel. Similarity in this depended more on normal model principles than on internal gravitational considerations.

(iii) Spread did eventually affect the intake, but only some time after the very conservative period allowed to cover the possible duration of a low water stand.

13.2.5. However, before deciding against the need for immediate large scale basic studies (assuming these had not been already carried out) any future investigator should consider the alternative benefits of increasing the scale and increasing the coverage. The experiments described in this thesis suggest that a breakdown of similarity due to completely laminar interfacial conditions, as described in 8.3.6., is unlikely except at Reynolds numbers (for the combined flow) of the order of 600 or less. Although the necessary design information is not at present available, it is reasonably certain that internal gravitational spread can be simulated fairly accurately. But insufficient introduction length before the portion to be studied in a river model is always a hazard. To illustrate directly, the Kincardine model might have been built at half the horizontal scale actually adopted. With an increase in vertical exaggeration of 1.5 (i.e. vertical exaggeration of 4.5 instead of 3), internal gravitational advances would have corresponded as between the alternative models. The following advantages might have been obtained.

(i) Using the same shed the whole of the isolated channel leading to the North channel could have been included in the model. This would have very considerably simplified, and probably improved, both calibration and operation.

(ii) Using the same pump the maximum river flow could have been simulated and the investigation would probably have been continued to the stage where a complete tidal cycle was simulated.

13.2.6. There would have been the disadvantage of slightly greater difficulty in control. However, as the present discussion is intended to illustrate what might be done in the future, this is not really a snag as it is unlikely that completely manual control would again be adopted.

13.2.7. Thinking of surface slope as a measure of the energy available for mixing, correspondence in this is also essential, with subsequent application of the general Froude law. (8.5.5.) For a full tidal model correspondence in surface slope is normally attained by application of the normal Froude law, but for a short length of river some departure from the velocities so determined might make correspondence in surface slope easier to attain. Where it is necessary to add roughness, it appears preferable to do so by treating the bed rather than by using vertical turbulence generators, since the mixing caused by these would be initially in the horizontal direction.

13.2.8. Having determined the scales, including the density difference scale which would necessarily be one in a normal Froude law model, apart from a special adjustment to give correspondence in initial velocities, and having calibrated and adjusted the model to give the correct profiles velocities and directions of flow, the agency of density difference has to be chosen. The obvious and commonly adopted choice of a thermal variation has been shown to have the disadvantage of a relatively large surface tension difference. Just as internal gravitational advance can be inhibited by initial mixing, the effect of surface tension on the overflow aspect of such advance is likely to be masked, again because of a gradual gradient rather than a clear cut interface. If in a model internal gravitational advance is of importance, it appears necessary to balance the surface tension difference if a thermal difference is adopted. Despite this, the advantages of a thermal density difference are such that it should always be used even if only as part of the total density difference:-

(i) The realism is convincing to those who may make use of the results in making a decision.

(ii) Heat losses can be simulated.

(iii) Thermal indication of mixing is very simple and precise at all levels from thermometers to recording systems such as that which was used for the present tests. A development of this system, especially suitable for model studies, is described later in this section (13.3.8.)

(iv) At lower basic temperatues, only thermal variations in the model could approximate to the thermal variations in the prototype because of the nature of the temperature-density relation.

(v) Already models have been run with the natural salinity variation of an estuary also simulated and as salinity is the obvious alternative to thermal variation, confusion might arise with this complication, if salinity were used for both density variations.

13.2.9. There is a probably a tendency for the following sequence of events to occur when a hydraulic model study undertaken. The model is designed and verified to the best of the investigator's ability; the required results are taken from it and in the light of the subsequent findings with the prototype the model is assessed as a success or a failure. It seems particularly important in heat dissipation studies that the degree of simulation of the various aspects of the flow and in varying positions should first be considered before any recordings are applied to the prototype. This will be the case even when a complete congruency diagram is available, it is even more so the case for any study that may be initiated in the absence of this diagram.

13.2.10. Briefly, what is meant is that after taking a considerable number of sets of vertically spaced measurements of density difference flux (normally of temperature), the model should be divided into zones, in terms of time and location, where two dimensional or three dimensional similarity is obtained - or where it is suspected that neither is the case. If a band of introduced water is carried with a main current, it is likely that two dimensional similarity will gradually merge into something like three dimensional similarity. Again, with incorrect vertical exaggeration, the aforesaid two and three dimensional similarities are likely to obtain until internal gravitational spread becomes operative - then neither will obtain.

13.2.11. Two other possible scale effects should be kept in mind:-

(a) A break down of similarity due to the formation of a completely laminar interface.

(b) Distortion of flows due to a stagnant surface.

Both of these have been observed ~~in~~ during the studies described here (8.3.6, and 7.3.3. respectively).

13.2.12. Taking just one concrete example of what the foregoing could involve, stratified water might be flowing past a model intake with only two dimensional similarity applicable. If the intake is well below the surface it is unlikely that actual measurements of the intake water would be reliable. But if a vertical temperature section at the intake is instead corrected for lack of two dimensional similarity in the light of the local conditions, a much better idea of the prototype intake temperature would probably be obtained.

13.3. <u>Comments on apparatus with suggestions for development</u>

(a) Hydraulic apparatus.

13.3.1. The hydraulic apparatus has so far, on the whole, served its purpose well, and it is thought that in the design a reasonable balance was struck between the sizes of the various parts and also between facility of use and cost of the apparatus. Although the main tank has not been used directly so much as the larger flume has, it was essential for its delaying and reducing effect on recirculation during tests such as are described in Section 8.

13.3.2. Two main difficulties in operation became apparent during the tests. Firstly, when wetting agent was added to the main body of water there was a tendency for foam to form at the various drops in the circuit; at the V-notch, at the entry into the main tank, and at the constant head tank overflow. This was inconvenient during some of the tests and it appears desirable to find a surface tension balancing agency which doesn't cause foam, nor, of course, is necessary in such strength as to cause an appreciable density difference. Failing the use of such a substance, it would be possible to design a circuit with bottom withdrawal after any drop. Such modification would involve considerable changes in the present circuit. This difficulty could not have been foreseen, as the necessity for surface tension balancing was discovered during the project.

13.3.3. Secondly, the small capacity of the sump above minimum depth (about 9 cu. ft.) compared with the capacity of the larger header tank (23 cu. ft.) reduced the possible duration of certain types of tests carried out in the main tank to far below the limit set by the header tank size. This could be overcome by placing a 20 cu. ft. tank at the pump end of the apparatus and leading a flow to it from the constant head tank, equal to the maximum flow from the larger header tank. The flow from this additional tank to the sump would be controlled by a float and lever operated valve, and the tank would thus provide a reservoir equivalent to an enlargement of the sump (such an enlargement being impossible).

13.3.4. The delay occasioned by the refilling of the header tanks (20 - 25 minutes in the case of the larger) was often inconvenient. A very useful development of the apparatus would be to fit a delivery from the pump to the larger header tank such that filling might be accomplished in 5 minutes or so. This modification, if combined with the provision of a fairly powerful system of electric water heaters in the header tank (15 KW or so) would allow the following mode of operation using salt as the density difference agency and temperature as the indicating agency. The water in the main circuit, of approximately known salinity, would be thoroughly mixed, then the header tank would be filled. A known weight of salt would be added and the water heated to some convenient temperature above that of the basic water in the main circuit. Thus water of a known density difference could be introduced into the circuit as required, and would be identifiable by what appears to be a very convenient indicating agency - a small temperature difference. The practicable range of density differences would be very much increased over that obtained from thermal variations only. Alternative to the heaters, salinity meters might be used, one in the main circuit and one in the upper tank. Though at first sight more direct, this alternative appears much less suitable for single-handed working, although one meter would be advantageous if placed in the main circuit.

13.3.5. The foregoing possible developments of the apparatus are basic; it is not necessary to deal with the minor pieces of equipment such as introduction boxes and the like which would be required for the further programme of tests to be suggested later. Nor is discussion of the possible construction of an actual model in the main tank necessary, except to note that the additional sump reservoir described in 13.3.2. would probably be advantageous.

(b) Recording apparatus

13.3.7. The thermopile temperature recording apparatus has functioned well, showing up best, in its present form, with the recording probes mounted on a traveller. There are, however, several possible developments in construction and technique which might be pursued:

(a) Neither method of fusing the junctions was really satisfactory and better methods could perhaps be found.

(b) It would be desirable to find a method of treating the probe junctions with a thin hard waterproof protective coating; perhaps a resin.

(c) More powerful oscillographs than the standard Pye model used are available. Although more screening would be necessary in order to take advantage of such an oscillograph, this development, if successful, would allow proportioning of mixing with a much smaller initial temperature difference.

13.3.8. In the form as used for the herein described tests, the temperature recording apparatus was suitable for mounting on a traveller, or for maintaining in a static state. It was not really convenient to move the probes, say from test to test, nor could individual probes be detached from the whole, making for clumsiness when re-arranging. There is another arrangement which would, in certain circumstances, give greater flexibility; it would, for instance, have been extremely suitable for the Kincardine investigation. This would be to pair the 24 in. probes, as used so far, with short probes set into a plug and with some two or three feet of flexible connection. Combined with the plug junctions would be the changes from thermopile metals to copper and the copper wires would end with some suitable proprietary connection. The plugs would fit into a P.V.C. pipe, the openings being closed by blanks when not in use. A flow of water, from the constant head tank, would pass along this pipe. The salient points are:-

(a) With the basic water temperature in the region of air temperature, the change in temperature along a 30 - 40 ft. length of $\frac{3}{4}$ in. bore pipe under 5 or 6 ft. head is imperceptable.

(b) The thermo couple metal to copper junctions would all be at the same temperature without being brought to the same point.

(c) Damaged probes could be easily replaced.

(d) The thermopile circuits would be shorter.

(e) The plug probes need not be in such a thin tube as the recording probes.

(f) With a series of spare holes in the pipe, and the possibility of adding holes if required, the system would be very flexible.

13.3.9. The basic system having been thoroughly proved, it would be worth while to incur the extra expense of press stud or similar connections from the probe-plug units to the wiring. While a system such as is envisaged would not be as quite as convenient as that under development at Wallingford [13.1] it is probably more flexible, has a quicker response, and is capable of further development. It can be built by one man in about a month (say 20 recording probes) at a cost of around £30 in materials. The amplifier, oscilloscope and camera are costly, about £350, but are basic equipment which could be used for many other purposes and which are widely available.

13.3.10. Reference was made in 5.3.12. to possible lines of development of velocity recording methods for non-homogeneity problems and no further discussion is appropriate since these lines were not pursued.

13.4. Recommendations for further studies

(a) In small scale apparatus

13.4.1. By small scale apparatus is meant apparatus of the size of the present apparatus or smaller, and most of the following experiments would be suitable for the present apparatus, developed where necessary. However, their value would be much enhanced if they could be related to basic studies in larger apparatus, as described later in this sub-section.

13.4.2. As far as simple lock experiments are concerned, without larger scale results being available there seems little prospect of further studies of diminution of velocity or of dilution in the present flume length being of much value. But if a few large scale tests were carried out, the situation would be entirely different as economy would suggest the use of a small flume where possible. One possibility with the present apparatus, in the absence of some definite assurance of correlation with larger scale tests, is its use to study the effect of a slow withdrawal of the barrier so that a suitable common procedure could be adopted.

13.4.3. As suggested in Section 10, some work might be done in the present flume on the case of the lock type experiment but with several barriers. This could be combined with experiments carried out in an additional piece of apparatus as follows. If a perspex sided rectangular conduit, with one end fixed and the other removable, were placed on end, it could be filled with any arrangement of density stratification present, such filling having been carried out in much more difficult circumstances. The conduit would then be quickly but smoothly laid flat and the overflow and underflow development observed. 8 ft. x 4 in. x 4 in. is the order of size envisaged for convenient handling, though a smaller example might be used as a pilot model. The apparatus could be used to study the development of the modified underflow and, presumably, mirror image of the underflow, in various circumstances, including that of a uniform variation from one end to the other, which might be expected to completely inhibit movement.

13.4.4. Turning now to the steady state studies described in Section 8, the use of saline water would allow a very considerable extension of the range covered. What is envisaged is that similar configurations to A, E and F, should be again examined while maintaining the same general Froude number. These have already been compared and found to illustrate stratification, some mixing and complete mixing respectively. It would be necessary to reduce the flume width in order to provide sufficient flow but the range of Reynolds number examined could be at least doubled. In isolation such tests would hardly justify the modifications to the apparatus required (i.e. pumping lead to header tank and salinity meter) but the modifications would also be desirable for the tests to be described below. In passing, it should be noted that tests of a similar nature to those described in Section 8 have been carried out at both Manchester University and the Hydraulics Laboratory of the National Bureau of Standards. In the second case it is possible that a sufficient flume length was used to continue the study into the uniform flow zone. No details are yet available but it would be foolish to devote much more time to these studies until more is known of what has already been done.

13.4.5. In Section 10 reference was made to the probability of inhibition of the development of an underflow and overflow by initial mixing. A start would be made to the investigation of this in the present flume. If the upstream part of the movable side were brought in to make a 12 in. wide length of flume and an introduction box was arranged at the projection so formed, the flow subsequent to the junction of a 12 in. wide band of basic water and a 6 in. wide band of introduced water could be studied. The depth could not, of course, be great; 2 - 3 inches would be best. However, it has already been shown that in similar circumstances the critical Reynolds number for laminar flow is very low, about 400 - 600, and a useful range of conditions should be possible. With saline density variations, but thermal indication, it should be possible to range from conditions where density difference would be unimportant to those where a clear cut underflow and overflow would develop.

13.4.6. It would be expected that the very small scale experiments outlined above would suggest the need for larger scale experiments. Some enlargement could perhaps be accomplished in the main tank, if an additional sump tank were fitted, although there is probably not sufficient introduced flow capacity available at present for completely steady conditions to be established, at least at larger values of introduced flow. This difficulty has already been mentioned in 10.1.7.

13.4.7. The main tank would be suitable for a small model of some river or estuary where a suitable small density difference flow occurs. Such illustration and confirmation of the results of the project would be the final stage - though it is possible that the building and use of some well verified ad hoc model elsehwere may make this course unnecessary.[8]

(b) In large scale apparatus

13.4.8. The need for extension of the 'infinite' width - no reflected wave Keulegan Type congruency diagram, which has been discussed earlier in this thesis, could probably be met by a few experiments in a 600 ft. long by 6 ft. wide flume and 11 ft. deep flume, together with more prolonged testing in a flume about 80 ft. long by 2 ft. wide. The first of these may seem rather large but the work could be done in any suitable channel or ship model tank so long as mixing tanks were available and the channel or tank could be drained reasonably quickly. Two 1800 cu. ft. mixing tanks with appropriate mixing devices and piping would be the main equipment, and probably the main difficulty in arranging the tests.

13.4.9. The other set of experiments which might be carried out in larger apparatus than is at present available, relates to vertical mixing in stratified flow once more or less uniform flow is established. That is beyond the effect of the entry or introduction conditions. Even at the scale of the experiments described in Section 8, a fairly long flume would probably be necessary; perhaps 100 ft. or so. However, considerable indication that similarity between model and prototype may be attained on a general Froude law basis is given by the successful tidal estuary salinity intrusion models,[2.37, 3.6-8] where general bed resistance presumably predominates over the resistance due to bends and where correspondence in a slight vertical salinity differential has been attained throughout tide runs which extend to several hundred of times the average depth in the prototype.[2.37] Consideration of such model prototype comparisons, and possibly of the results of the tests at present being undertaken at the National Bureau of Standards Hydraulics Laboratory, may obviate the need for further basic studies of this problem.

13.5. Miscellaneous

13.5.1. This thesis is a record of part of a continuing investigation. Despite the considerable attention that has been given to small density difference phenomena in open surface hydraulics, there is much that is not understood and which is worthy of attention. For example, it was stated by Inglis and Allen[2.37] in 1957 that the nett upstream bed flow observed in the Thames could not be simulated in the Thames model without the use of salinity whereas Allen[13.2] in his capacity of Director of Hydraulic Research stated in 1959 that it has been shown that the upstream bed flow in the Thames was independent of salinity variations.

13.5.2. Some comments are here made on some aspects of internal gravitational movements which are outside the main line of the thesis.

(a) The Mississippi salt wedge intrusion model

13.5.3. In 3.3.1. reference was made to Tiffany's[3.16] description of this model study, carried out at the Waterways Experimental Station, which appears to have been the only attempt so far made to simulate a distinctly wedge type salinity intrusion. Unfortunately, the details given were extremely sparse - the scales of the model were not even quoted. But after saying that some basic studies, presumably lock tests, had been carried out prior to the design of the model, the author stated as definite that a density scale of unity should be used and otherwise the normal Froude model law would give the correct flows. Although Dr. Keulegan's later basic studies were all carried out for the Waterways Experimental Station, he does not refer to any report on the Station's own basic studies. It appears that the Mississippi model was comparatively large and had a fair vertical exaggeration. Probably the length studied was progressed by the salt wedge at something corresponding to a uniform 'initial' velocity and the apparent ease with which simulation was obtained deceived both the personnel of the Station and those interested in density current simulation in general, as to the difficulty of the problem.

(b) Sewage disposal in Santa Monica Bay

13.5.4. The Author, in discussing the pattern of spread of fresh polluted water moving along the shore under a prevailing coastal flow, suggested that with a density differences of the order of 0.0003 gm/m.l. to 0.00009 gm/m.l. and a stratified layer of several feet in depth, an exchange flow would develop. This would have accounted for the much greater angle of spread which eventually developed than that found with dye streams in the open sea. However, the suggestion was not favourably received by the author of the paper who had ascribed the spread entirely to lateral eddy dissipation. The considerations leading to the possibility of inhibitance of internal gravitational spread, as dealt with in

Section 10, provide a further possible explanation of the type of spread pattern observed at Santa Monica where some considerable progress had been made along the coast before the spread became pronounced. This would fit in with an initially mixed interface eventually clearing after the coast wise flow had 'settled down', following the inflow of the sewage. Presumably, the rise of the boil from the deep out fall would cause considerable disturbance to the general flow. The further experiments suggested in sub-section 13.3 may elucidate this type of dispersion.

(c) Basic studies for heat dissipation models by Professor Allen and Dr. Allen.[1.4a]

13.5.5. The experiments described in paragraph 55 of Attachment 2 are wholly understandable in the light of the tests described here. But the value of Reynolds number found necessary in the smaller channel to maintain similarity suggests that the introduced flow was small in comparison with the basic flow. In Section 8 it was shown that similarity in vertical mixing can be achieved with much smaller Reynolds numbers so long as the velocity discontinuity is sufficient, i.e. that sufficient momentum adjustment has to be made.

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ASPECTS OF THE STUDY OF HEAT DISSIPATION USING MODELS

by

D.I.H. Barr, B.Sc., D.R.T.C., A.M.I.C.E., M.ASCE.

SUMMARY

(The reference numbers correspond with the Sections of the Thesis)

The Author had been engaged on a model study of the dissipation and the possible recirculation of heated water which was to be discharged from the circulating water system of a steam power station sited on a tidal river. He has described this investigation in a paper "A hydraulic model study of heat dissipation at Kincardine power station" (a copy is attached to the Thesis). It seemed that further work on the basis of design of such models would be worth while, and that the various modes of flow involved might be examined for scale effects in isolation (1).

Various aspects of small density difference phenomena which affect free surface hydraulics are reviewed (2), together with the present status of model simulation of these phenomena (3).

In describing the circuit of flume and tank which was built for the studies, the general requirements for apparatus for small density difference studies are discussed (4). A thermopile recording system was chosen from the various possible means of indicating the mixing and dilution of introduced water, and the construction (5), use (8) (9) and possible development (13) of the indicating probes is described. This system is thought to be very suitable for any future ad hoc or basic studies.

The first mode of flow to be studied was the pure density current exchange flow as found in idealised lock experiments. Some additional

information on the overall characteristics of the overflow was obtained, and a scale effect, caused by small variations in surface tension, was noted. This easily obviated phenomena might seriously impair similarity in heat dissipation models. It was found that the requirements for similarity in lock experiments are applicable to internal gravitational advance in open water, and some success was achieved in the simulation of small scale prototype phenomena in very small scale models (7) (9).

Vertical mixing was studied using the recording apparatus and the applicability of the general Froude model law was confirmed (8). Modified forms of lock flow are suggested as being pertinent to the spread of less dense water over more dense water, when both are combined as an external gravitational current (10).

The effect of heat losses on model simulation is considered (11) and the economics of heat dissipation are reviewed in some detail (12).

After summarising, the possible form of future <u>ad hoc</u> studies is discussed and recommendations made for future basic studies (13).

A comprehensive list of references (14), the tables and figures collect at the start of the second volume (15), the test recordings (16) and the notation (17) follow.

A subsidiary outfall scour model had been run in conjunction with the main Kincardine model and this also left some uncertainties which were partially elucidated in a series of tests, described in an appendix (18). In a further appendix some minor aspects of the Kincardine investigation are discussed (19).

ASPECTS OF THE STUDY OF HEAT DISSIPATION USING MODELS

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VOLUME II

The contents of both volumes are listed at the front of Volume I. Pagination in Volume II continues from that of Volume I.

15. FIGURES AND TABLES

(A full list of Figures and Tables is included in 'Contents' at the front of Volume I.)

Model	Hor. Scale	Vert. Scale	Size of model and details
At Manchester [1.1,4a]	1/150	1/150	Approximately 2.5 ft. wide with only part of ½ mile width of tidal river actually modelled.
Antioch P.S. [1.2] (U.S.A.)	1/100	1/100	30 ft. x 4 ft. with part width of tidal river modelled.
Kincardine P.S. [1.4]	1/144	1/48	30 ft. x 15 ft. with whole width of tidal river modelled.
Berkeley P.S. [1.5]	1/300	1/60	Rather smaller than Kincardine model but again whole width of body of water modelled.
Bradwell P.S. [1.5]	1/192	1/60	As for Berkeley P.S.
Thames Model (North fleet [1.3] and West Thurrock P.S.+)	1/600	1/60	Recirculation studies for two power stations to be sited on the Thames were carried out in the Thames model while it was being operated with normal tidal conditions and salinity distribution simulated.
Pt. Augusta [1.6] (Australia)	1/60	1/60 ?	Size not known. "Study of optimum location for flow cut-off walls between inlet and outlet ducting of condensate cooling water".
Severn [1.7]	1/60	1/60	Combined intake and outfall structure, operated with tidal flows simulated.
Severn [1.7]	1/480	1/60	Tidal model of large part of Severn estuary - 150 ft. long or so. Effect of heated discharge from several power stations to be studied.

Note:- So far as is known, all these models were run with thermal density variations to a scale of 1.1 and with the velocity scale given by the normal Froude law (i.e. the square root of the vertical scale).

\+ See Hydraulics Research 1955, page 23.

TABLE 1.1 HEAT DISSIPATION MODELS INVOLVING TIDAL FLOWS.

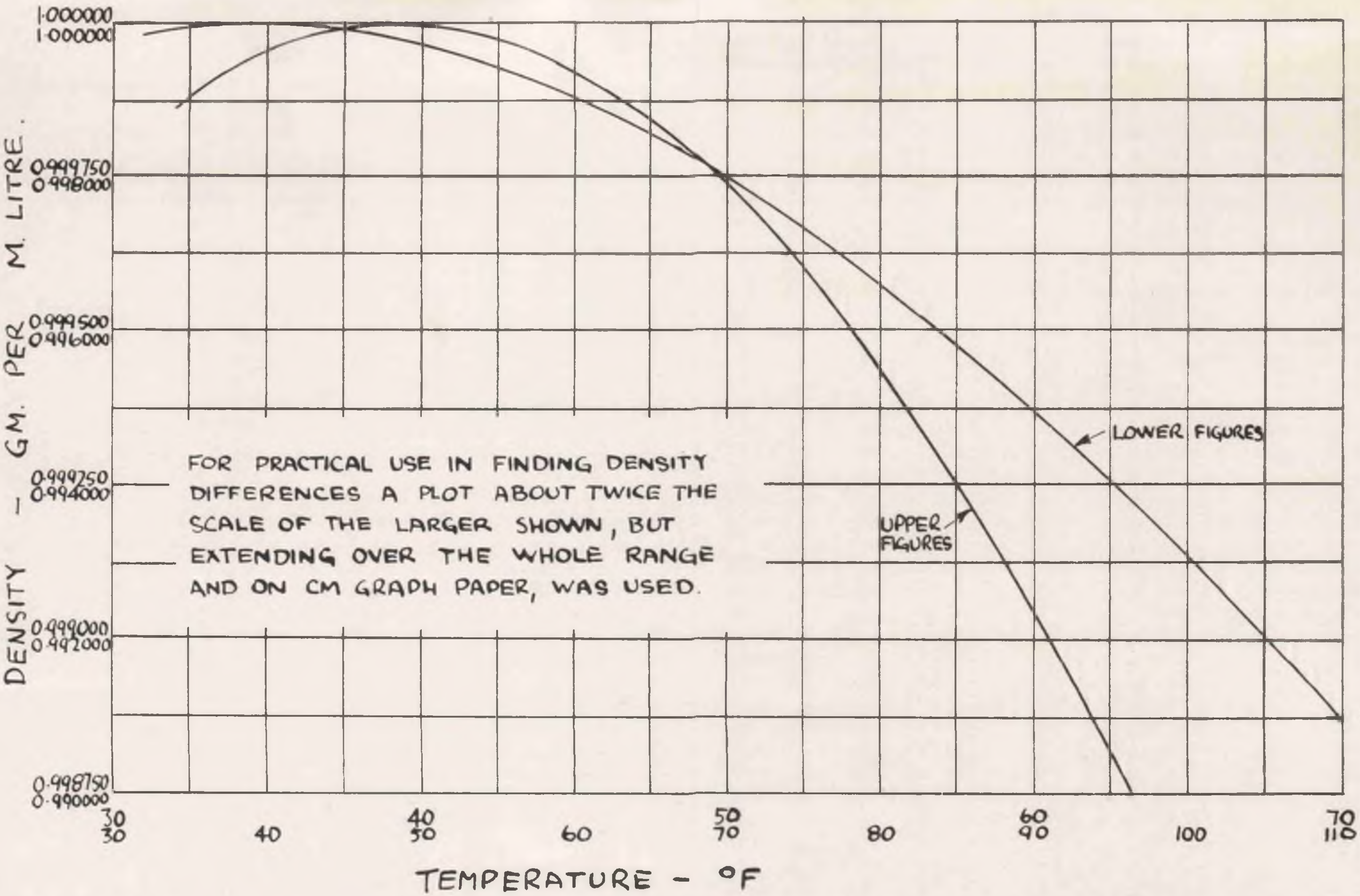


FIG. 2.1 TEMPERATURE - DENSITY RELATION FOR FRESH WATER

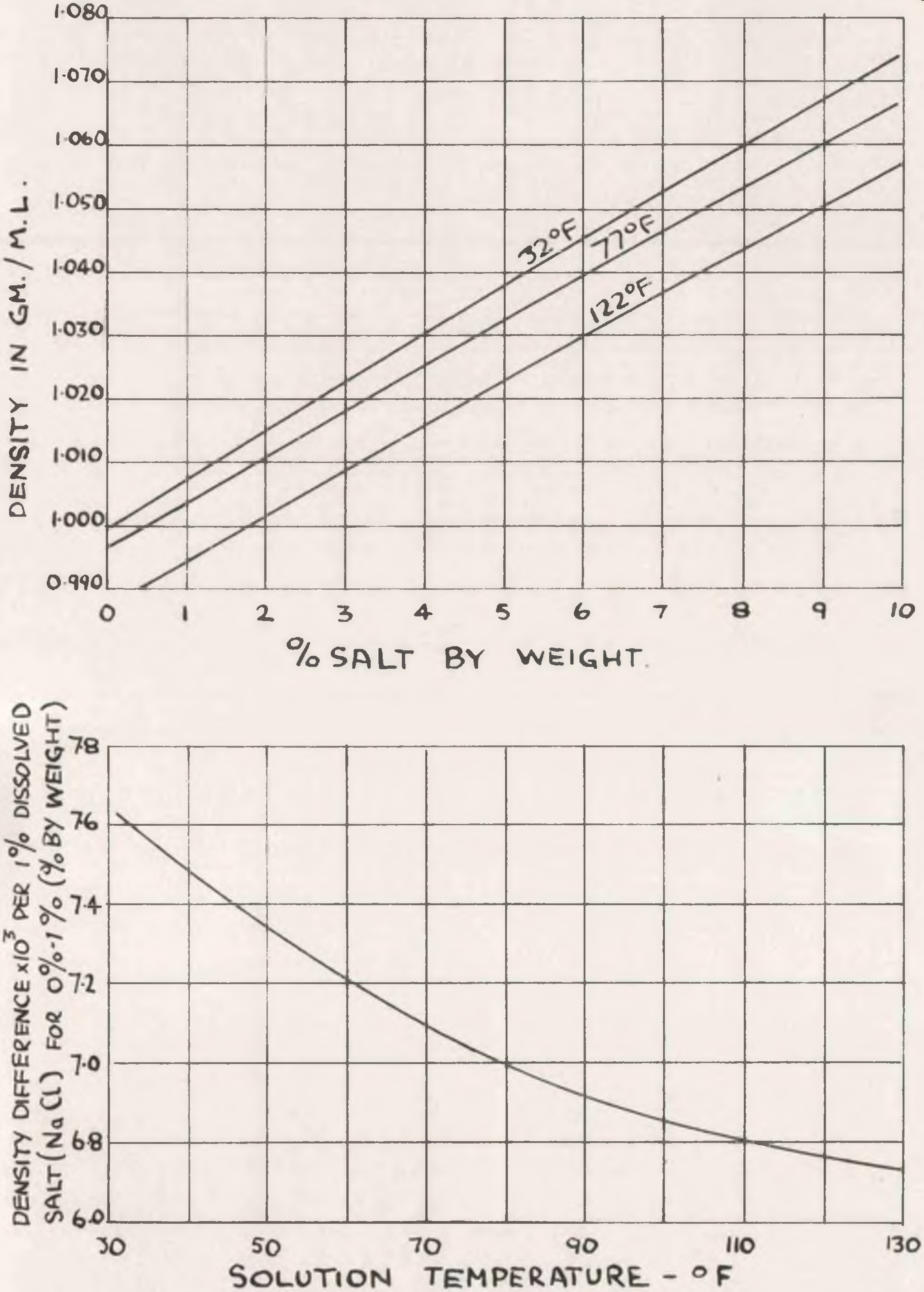


FIG. 2.2 CONCENTRATION-DENSITY RELATION FOR SALT SOLUTION (NaCl). VALUES FROM INTERNATIONAL CRITICAL TABLES.

Model	Hor. Scale	Vert. Scale	Notes
Castle Donington P.S.[3.1]	1/120	1/36	Length of River Trent modelled and recirculation studied using heated water.
Alden Hydraulic Laboratory[3.13]	-	-	At least three river model studies have been carried out. Vertical exaggeration 3 to 5 with normal Froude law basis for velocity and heated water at 1 : 1 density differences.
White River[3.12]	-	-	Purdue University - No details known
Crawford P.S.[3.11]	1/60	1/60	Model study of recirculation in Chicago Sanitary Canal.
Schylkill River+	1/45	1/15	Recirculation studied in river model - No details known.
Olosglany P.S.[x]	1/250	1/50	Model study for siting of baffle walls to give maximum cooling surface.

\+ Ref. 3.11, p.96.

x O. Gyorke "Scale model investigations of the cooling pond at a thermal power station." Report on the activities of the Research Institute for Water Researches in 1957. (Hungarian with English abstract)

TABLE 3.1 NON-TIDAL RIVER OR LAKE RECIRCULATION MODELS.

Model	Hor. Scale	Vert. Scale	Notes
Sacremento - San Joaquin[2.22]	1/4,800	1/100	Salinity distribution in horizontal direction was represented without density difference.
St. John River[3.6]	1/1,000	1/100	Density scale 1 : 1 (W.E.S.)
Savanah[3.8]	1/1,000	1/150	Density scale 1 : 1 (W.E.S.)
Delaware River[3.7]	1/1,000	1/100	Density scale 1 : 1 (W.E.S.)
Thames[2.37]	1/600	1/120	Density scale 1 : 1. Better results were obtained with 1/120 vertical scale than with earlier attempts with 1/60 vertical scale.
Mersey[3.17]	1/550	1/60	Density scale 1 : 1
San Francisco Bay[+]	1/1,000	1/100	Density scale 1 : 1. Very large model (1 acre and up to 4 ft. deep).
Alberni Inlet[x]	1/4,308	1/288	Density scale 1 : 1
Puget Sound[÷]	1/40,000	1/1,152	Density scale 1/2.

\+ J. A. Graf, "San Francisco Bay Model Study". Military Eng., V.49, No. 331, 1957.

x J. P. Tully, "Oceanography and prediction of pulp mill pollution in Alberni Inlet." Fish Res. Bd. Canada, Bull. 83. 1949.

÷ M. Rattray and J. H. Lincoln, "Operating characteristics of an oceanographic model of Puget Sound". Trans. Amer. Geo. Union, Vol. 39, No. 2, 1955.

TABLE 3.2 TIDAL SALINITY INTRUSION MODELS.

FIG. 4.2 PUMPING ARRANGEMENTS

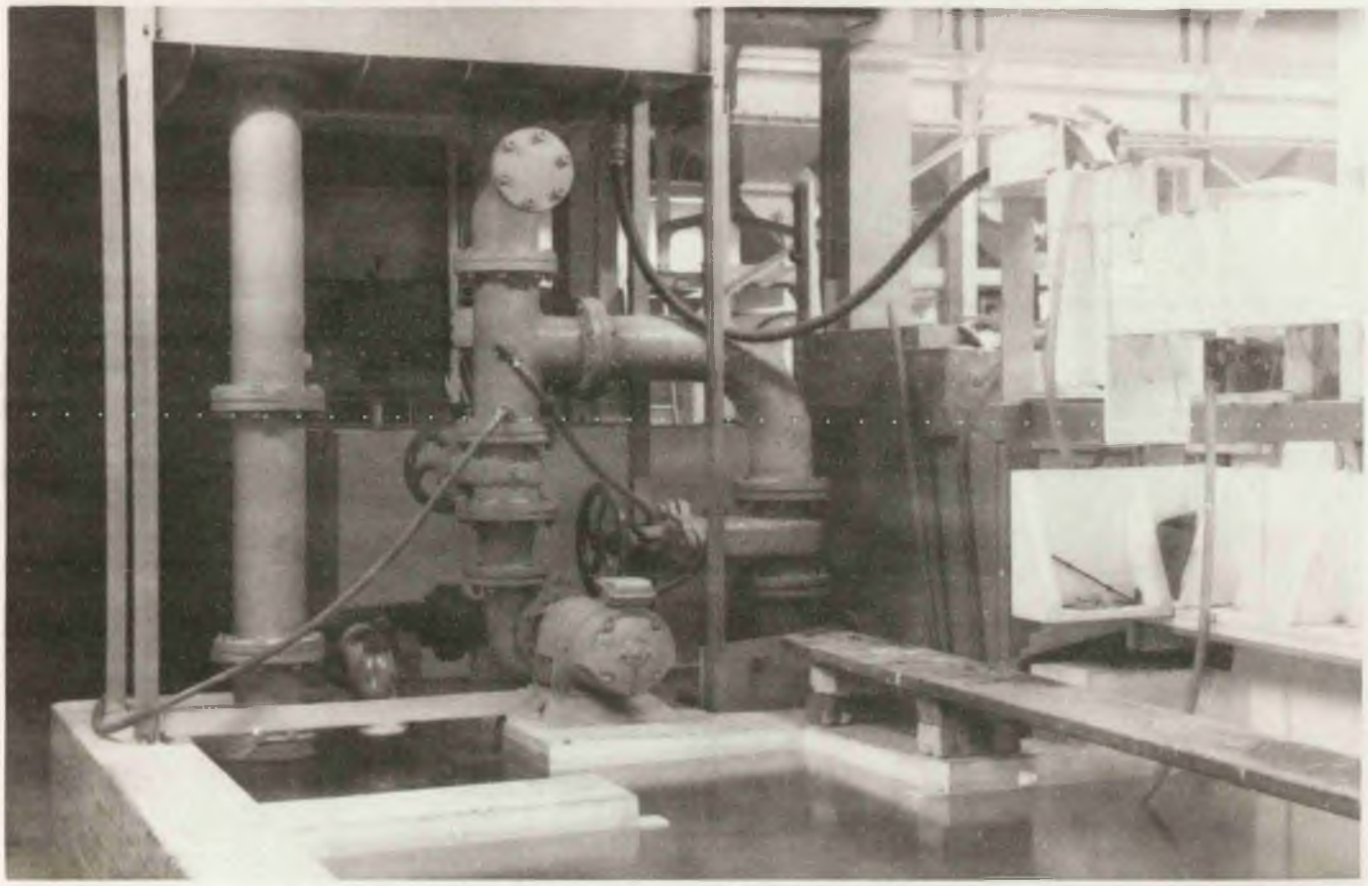
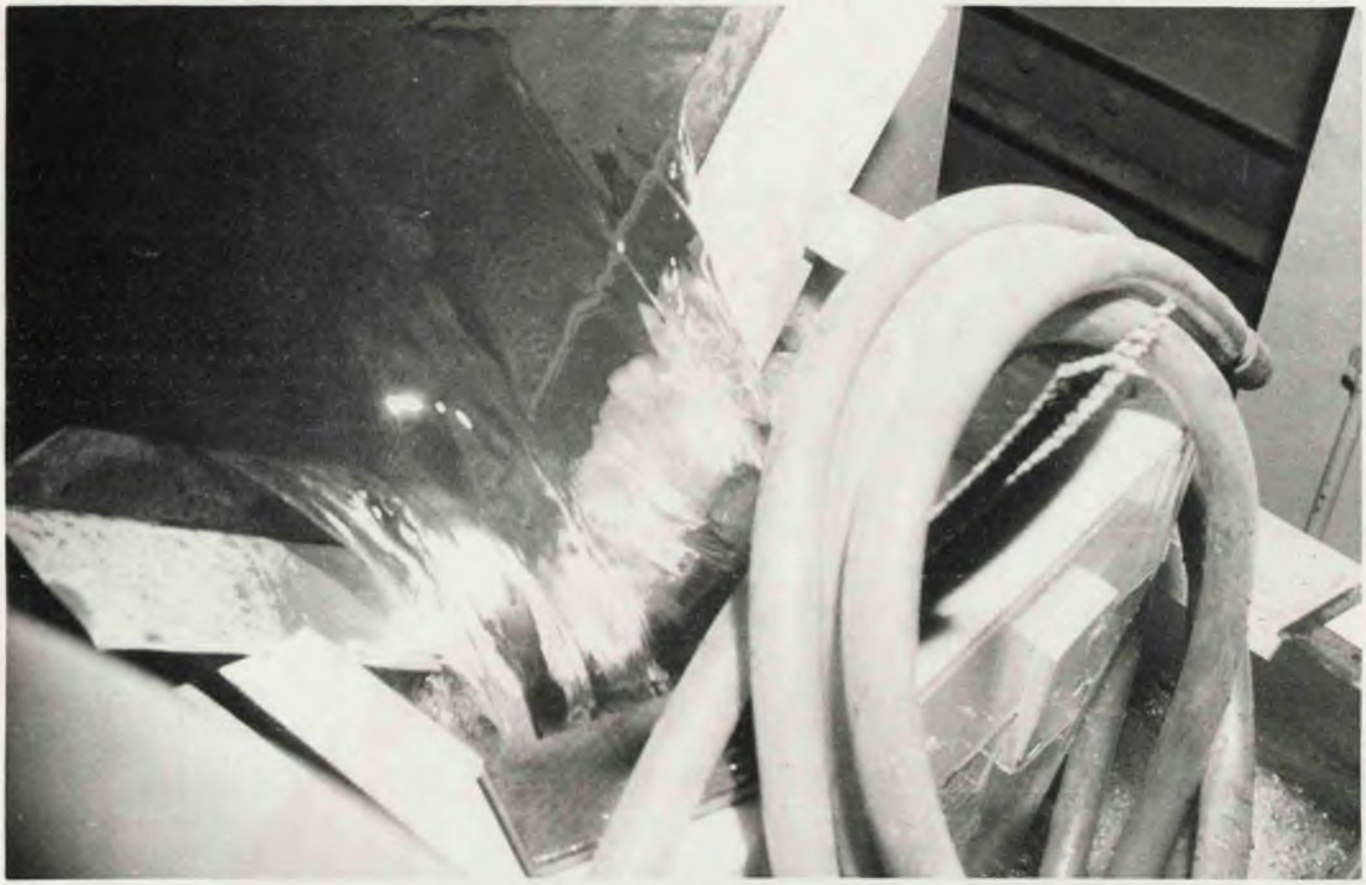


FIG. 4.3 VIEWS OF CIRCUIT - 1
Flow over main V-notch guided below
surface of stilling chamber of larger flume

FIG. 4.4 VIEWS OF CIRCUIT - 2
Downstream end of larger flume with
draft excluders in open position



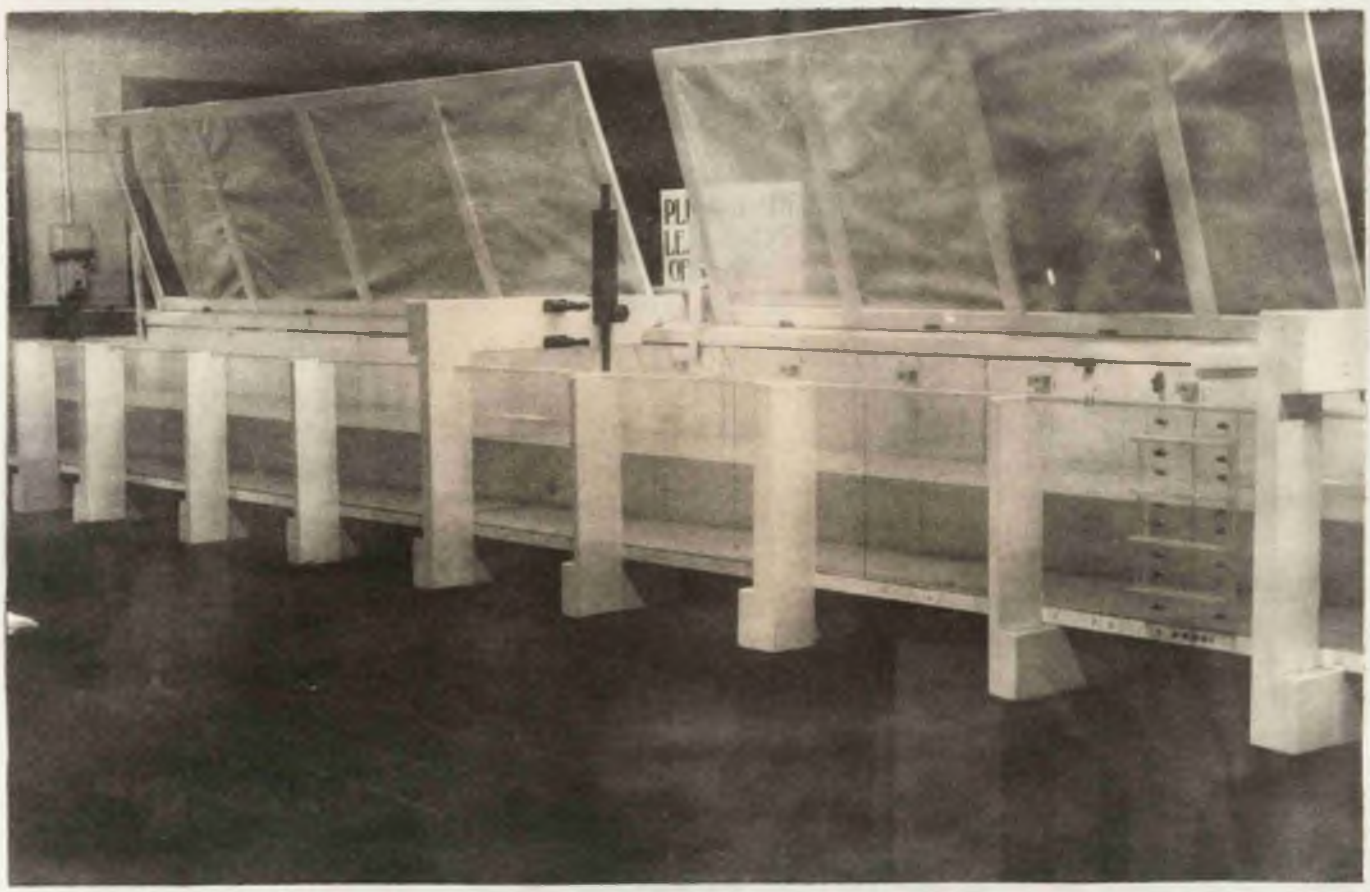
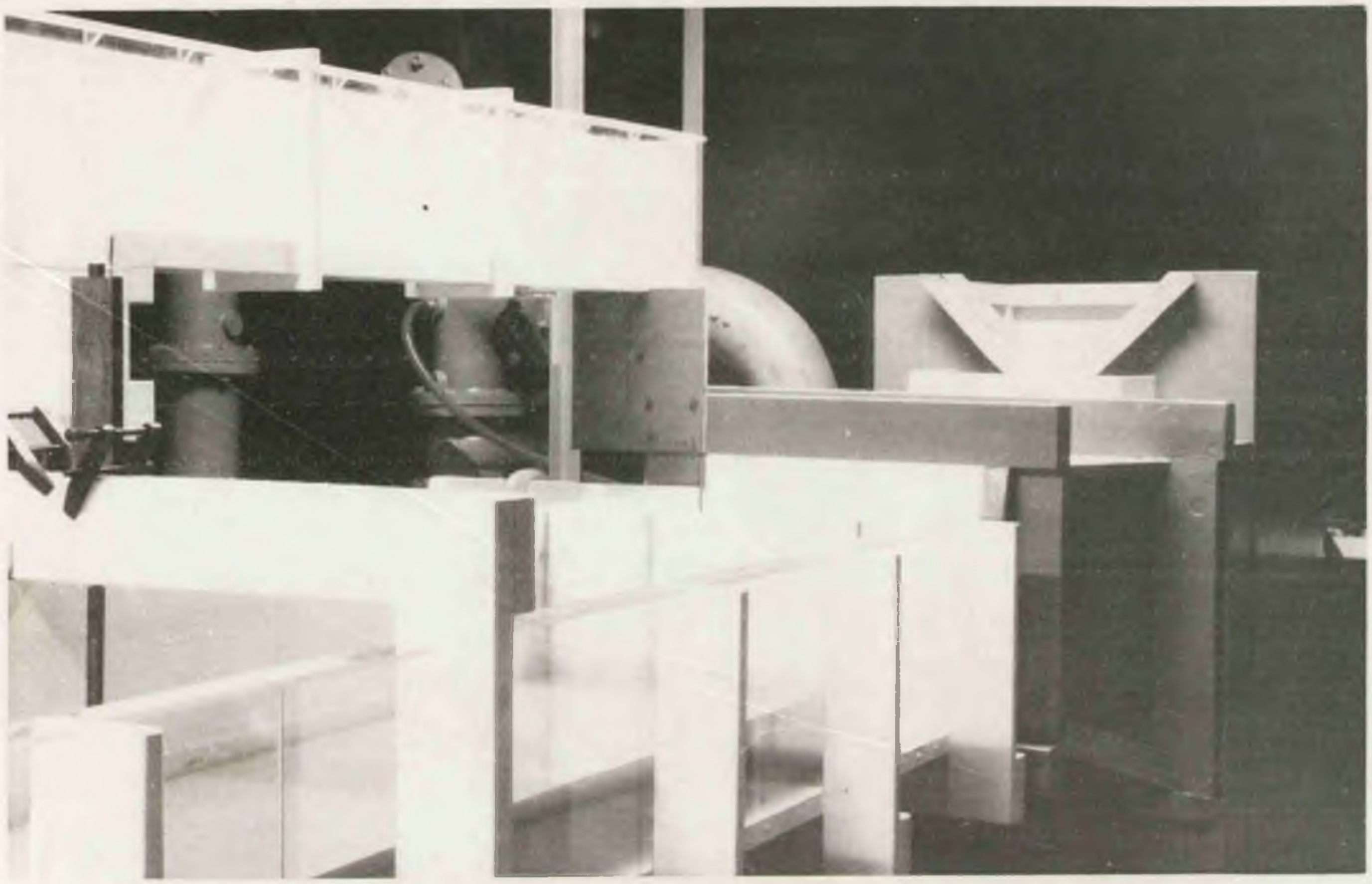


FIG. 4.5 VIEWS OF CIRCUIT - 3
Upstream end of larger flume with fixed 'cut-off' for lock experiments in position. Main V-notch in background

FIG. 4.6 VIEWS OF CIRCUIT - 4
General view of tank and rear of flumes



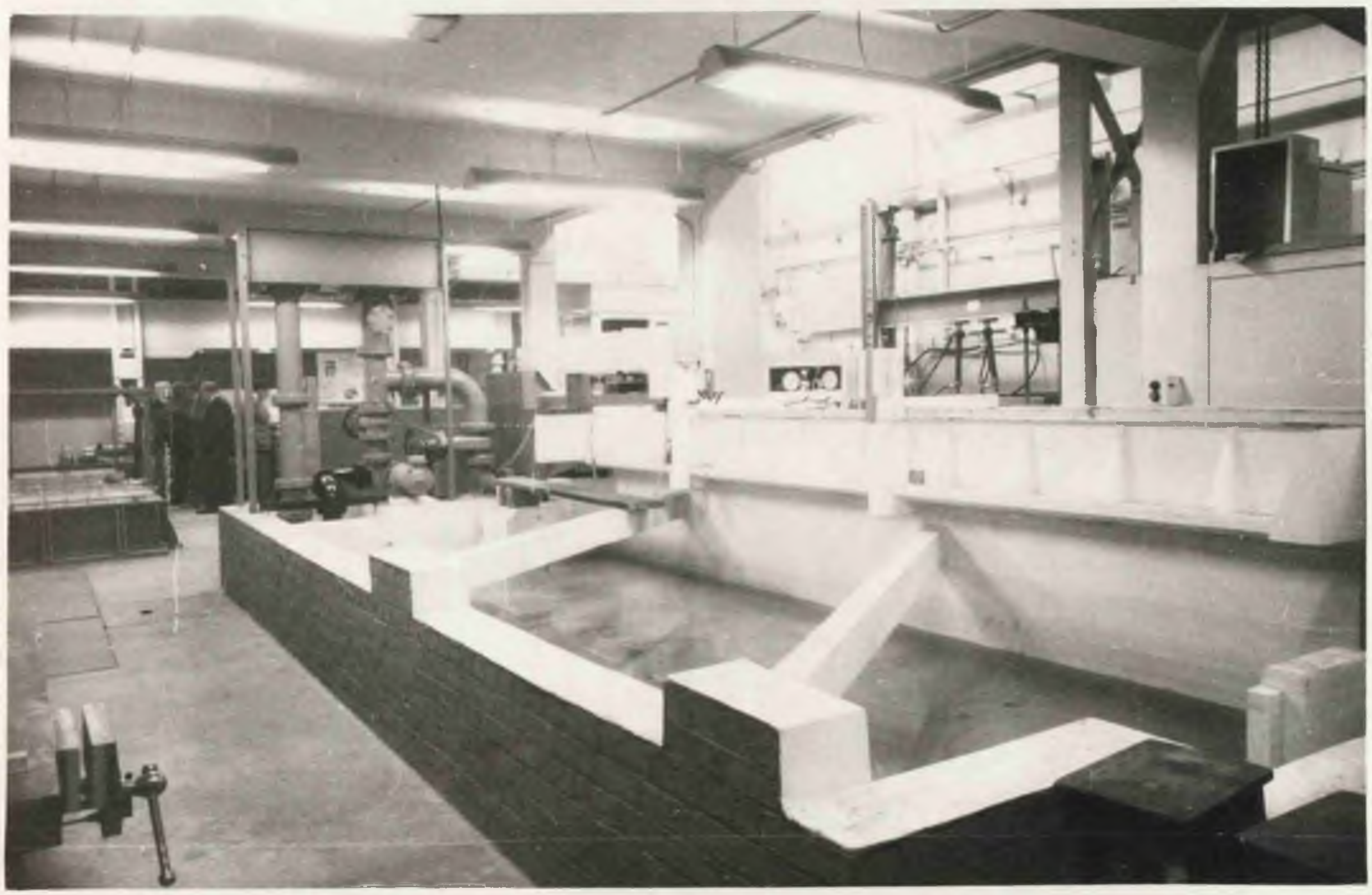
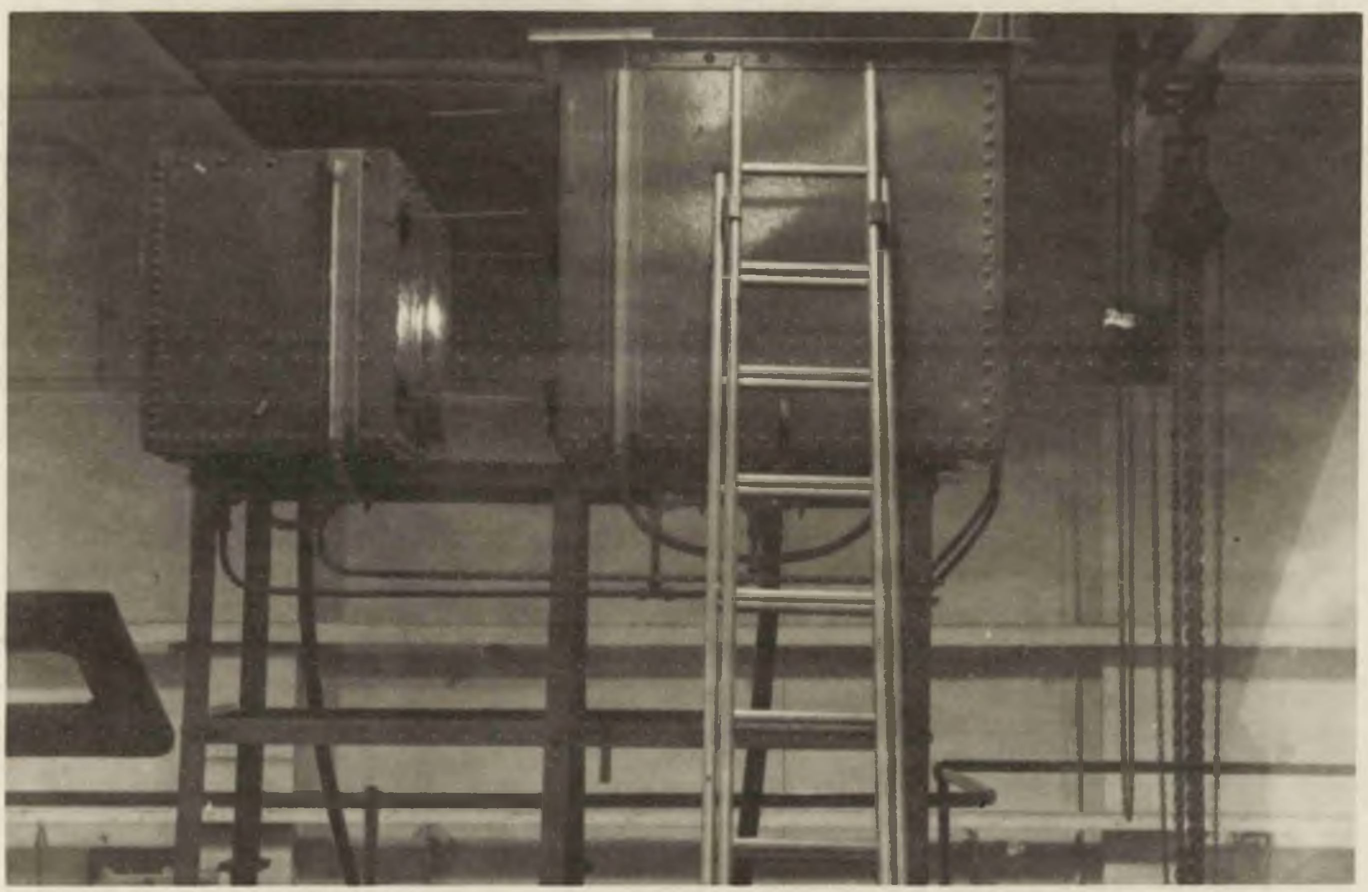
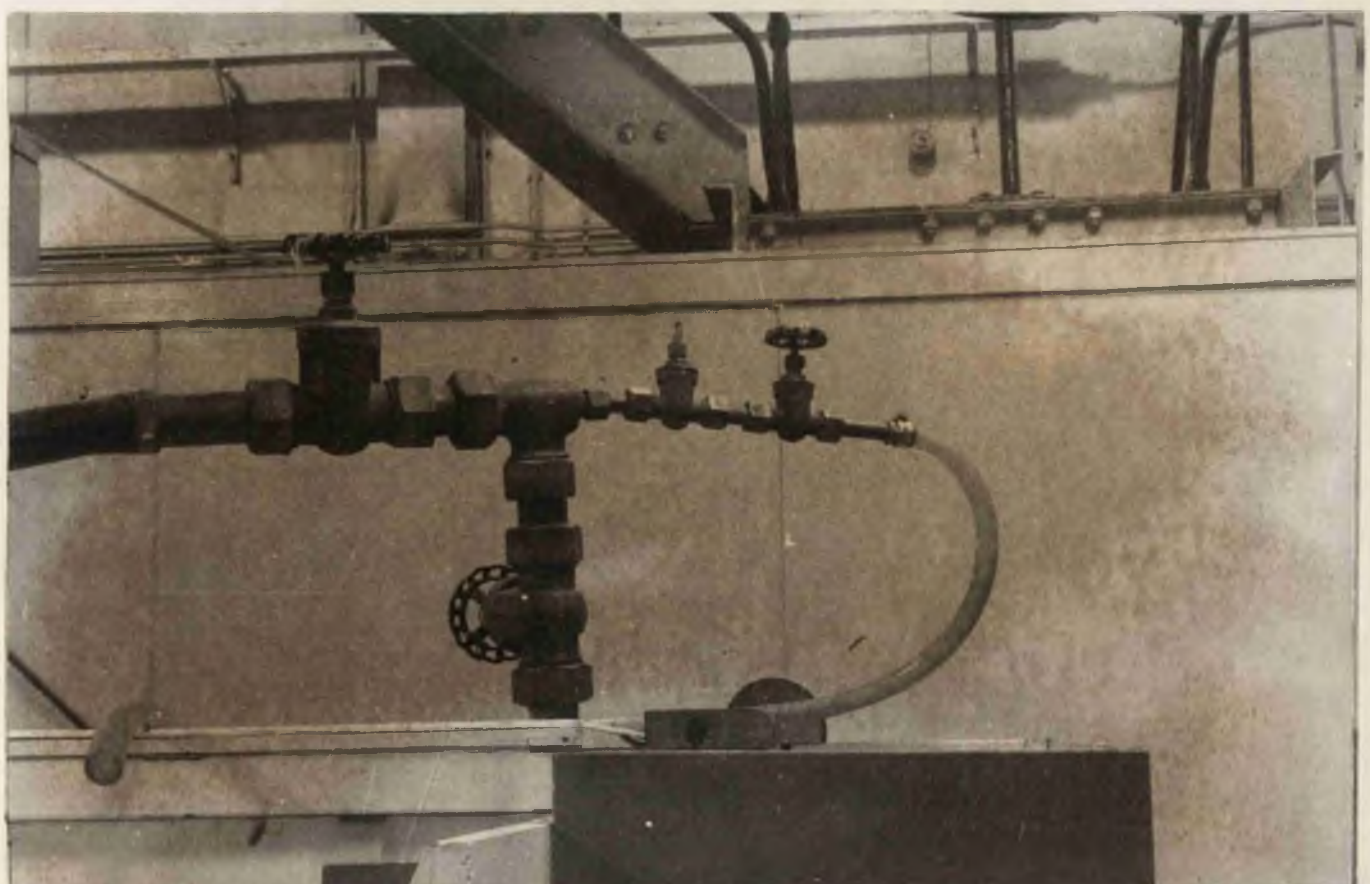


FIG. 4.7 UPPER MIXING TANKS

FIG. 4.8 DOWN-PIPE CONTROLS





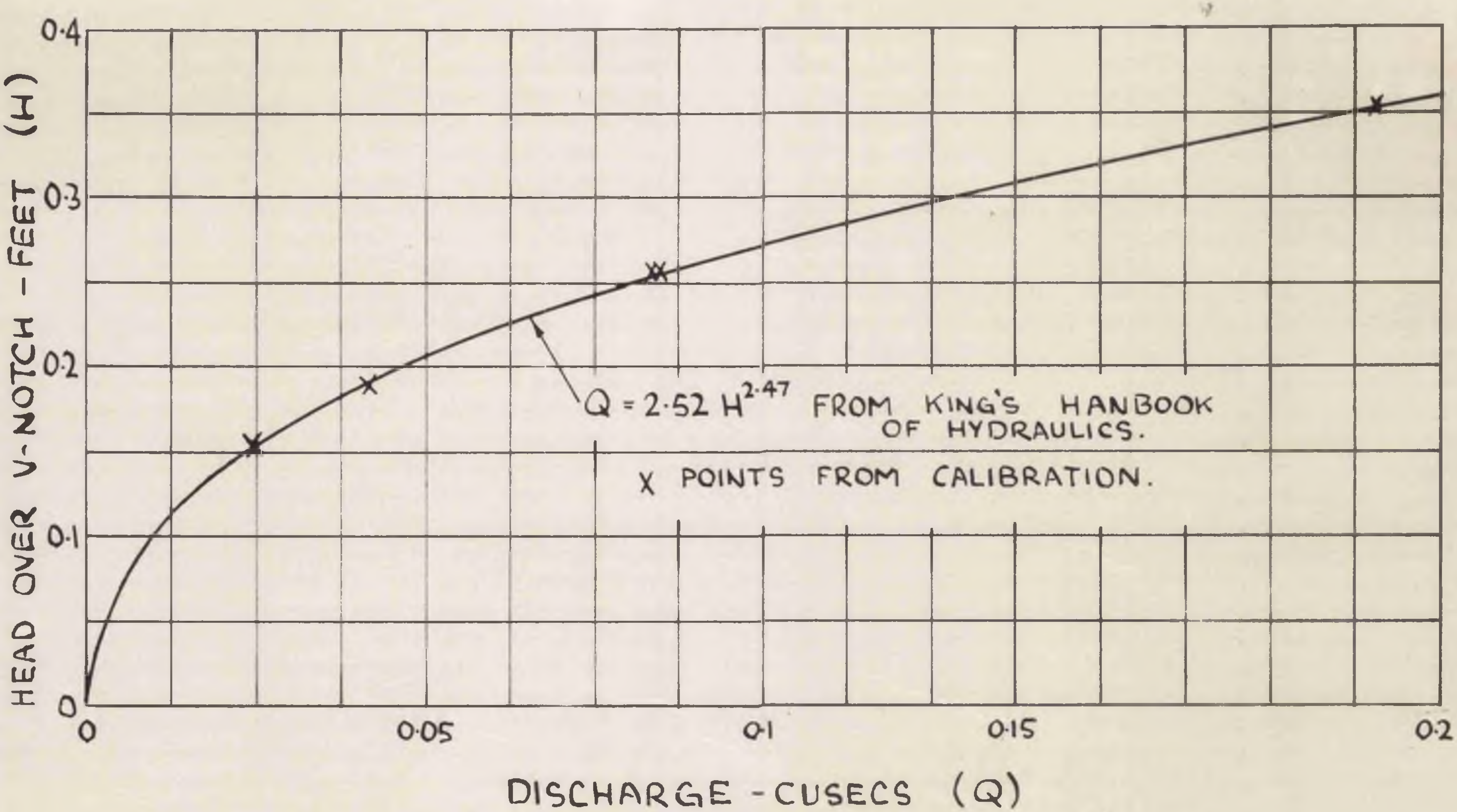


FIG. 4.9 CALIBRATION OF MAIN FLUME V-NOTCH.

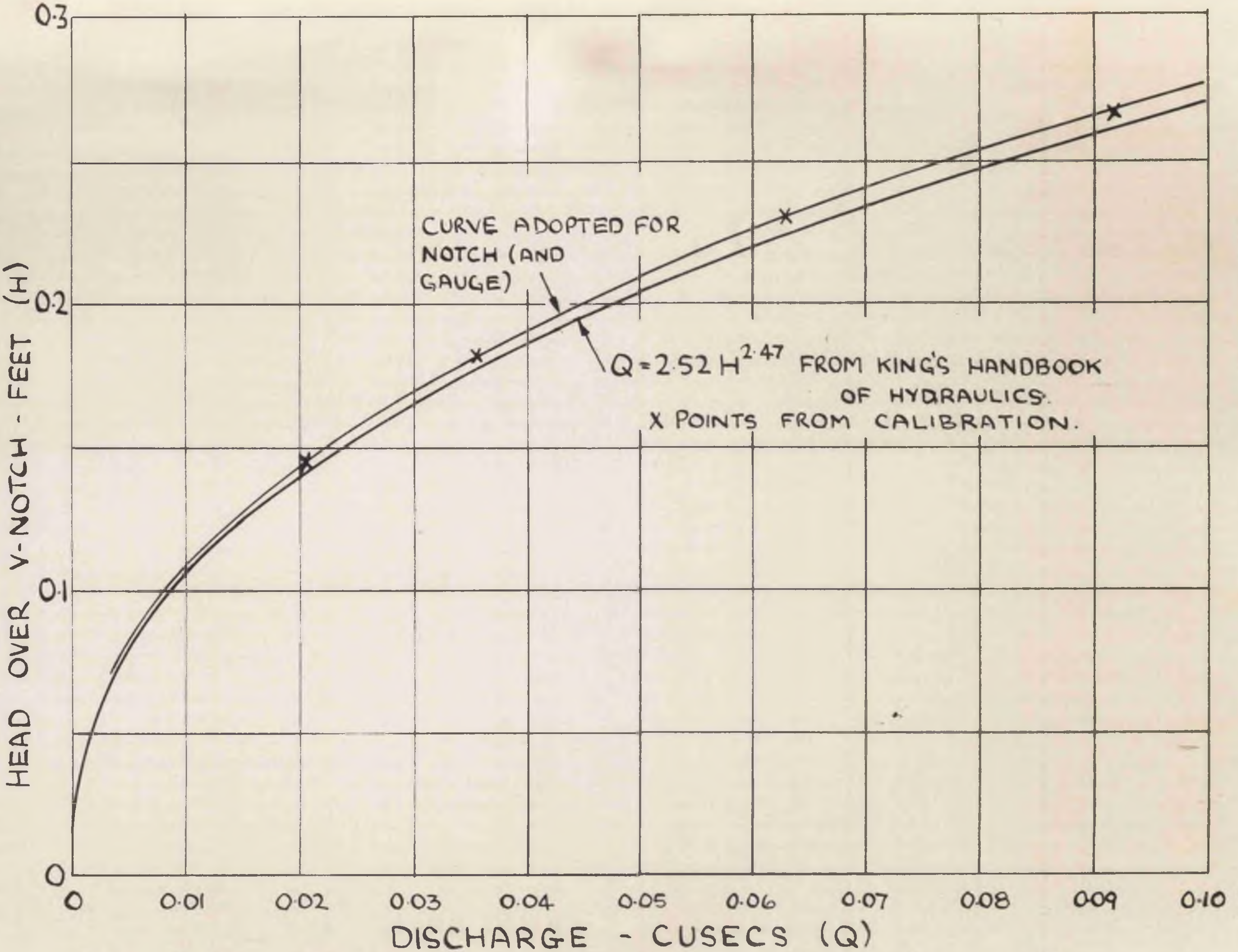
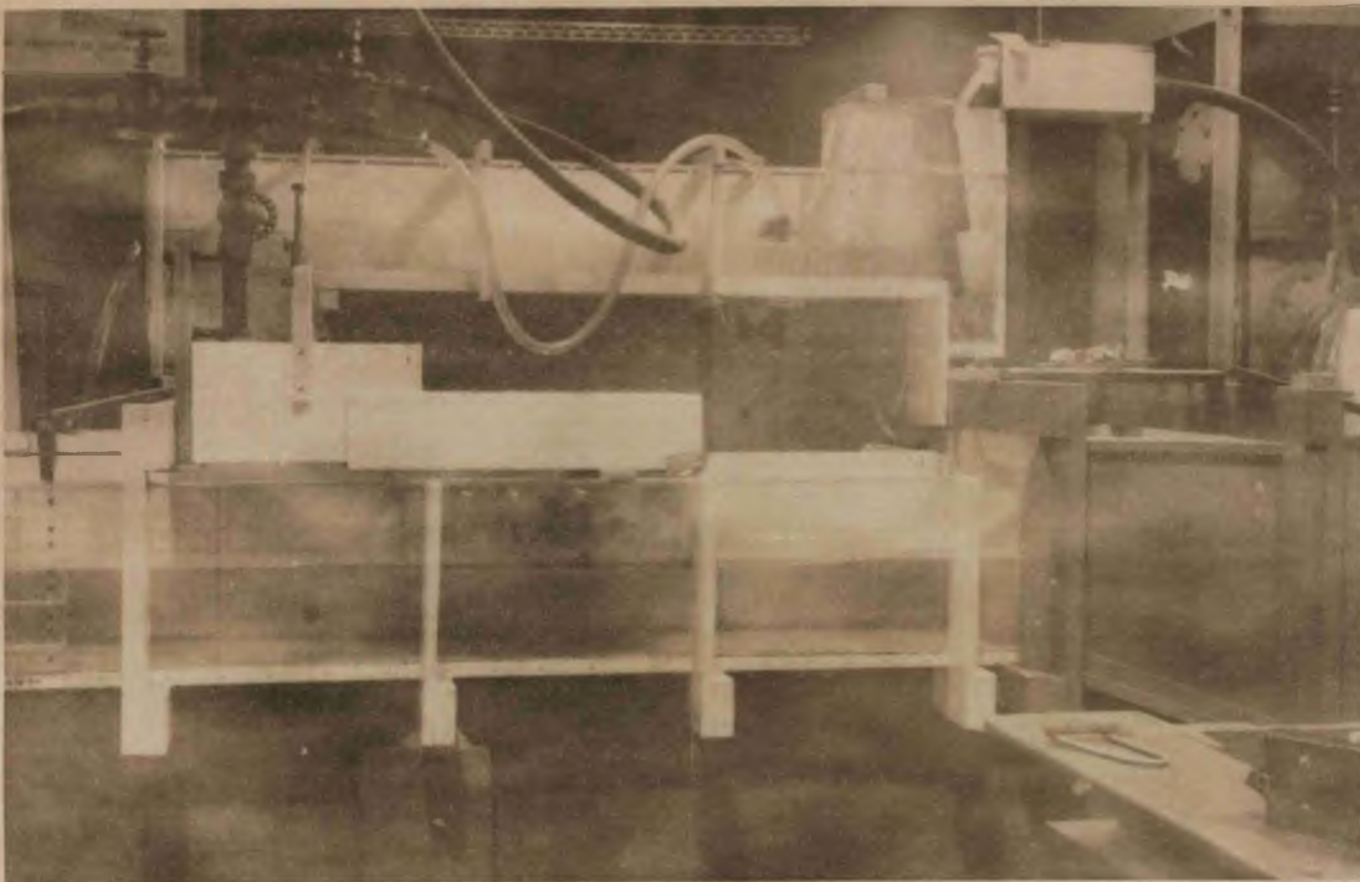


FIG 4.10 CALIBRATION OF SECONDARY FLOW V-NOTCH.

FIG. 4.11 SMALLER FLUME



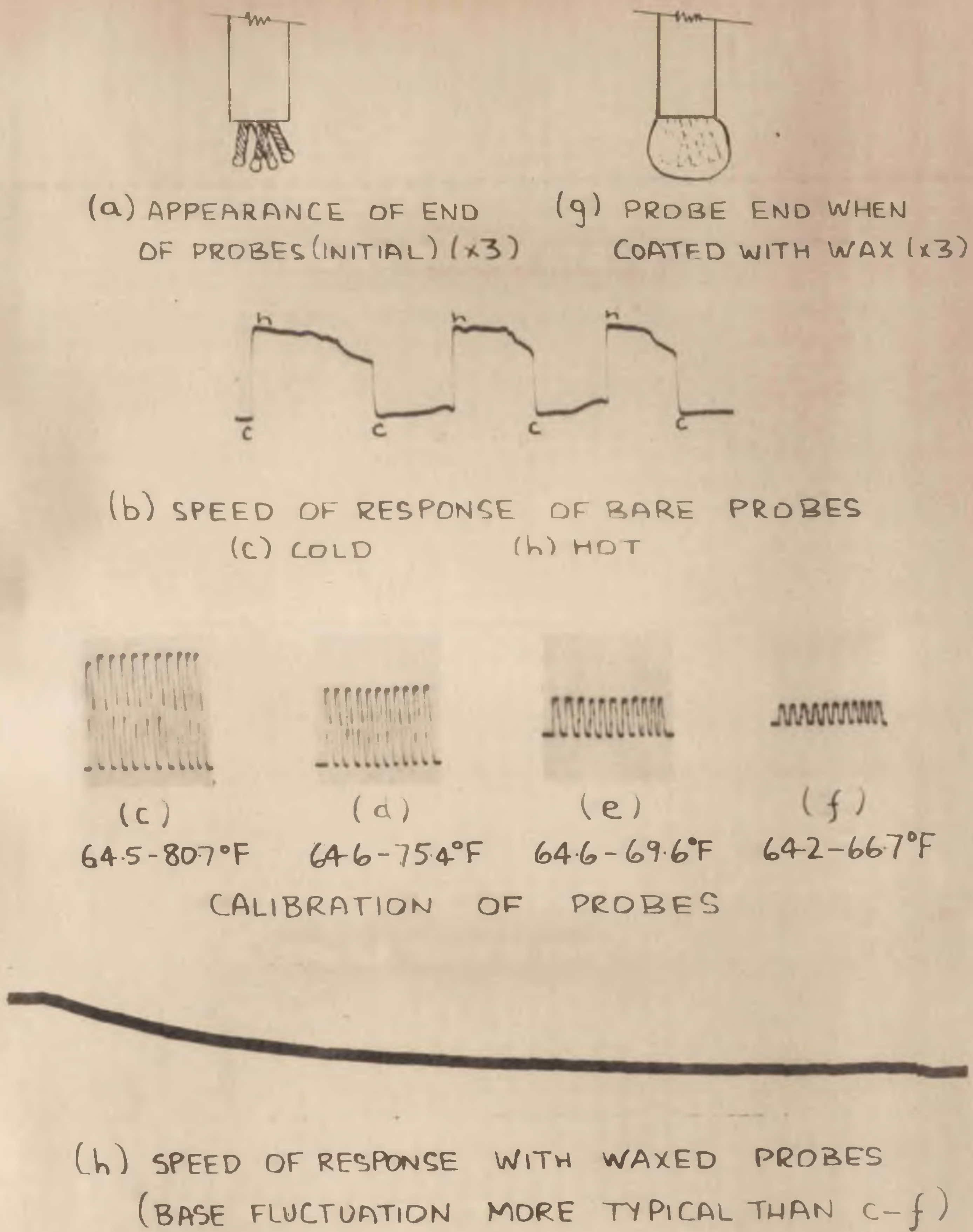
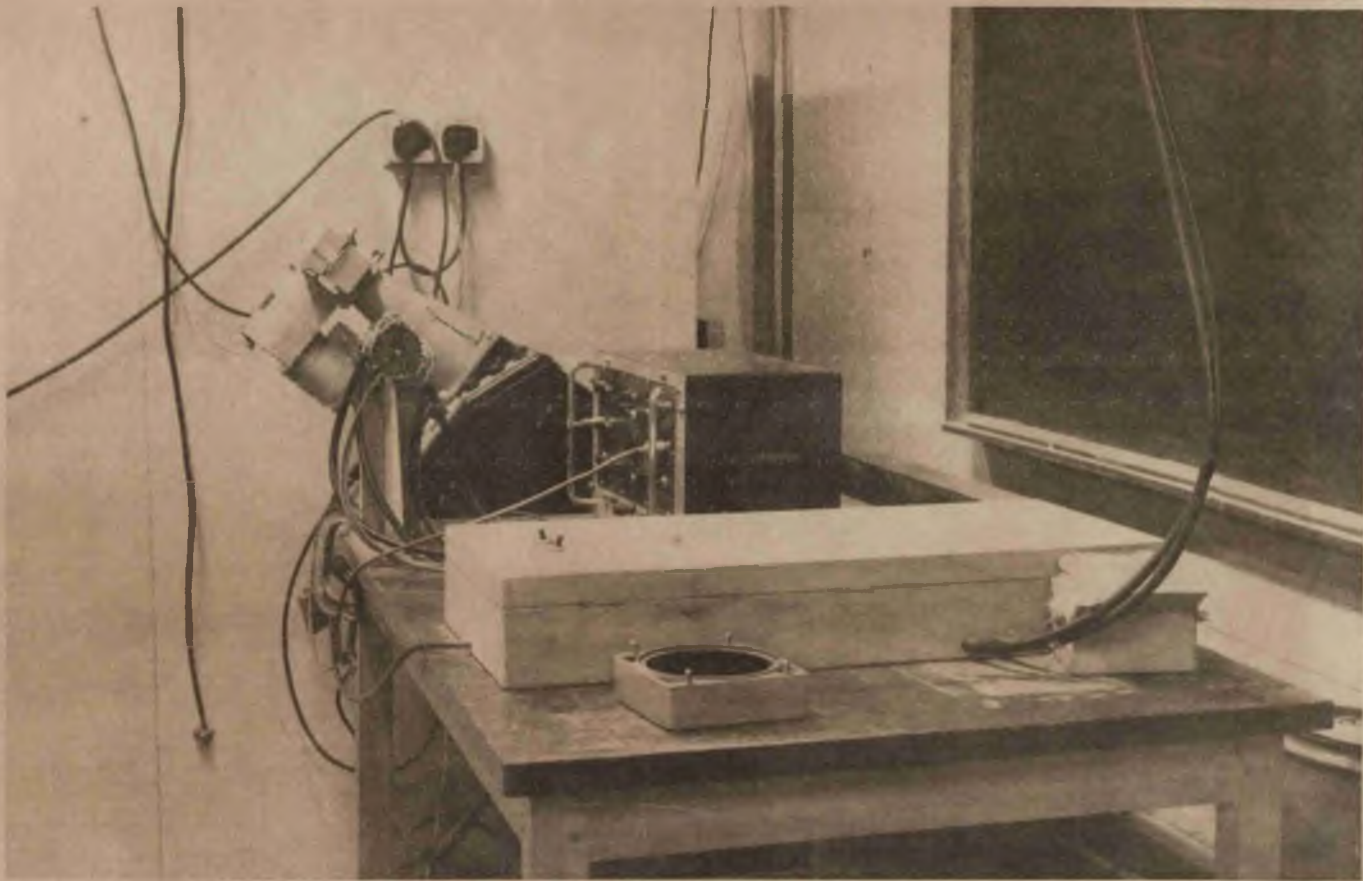
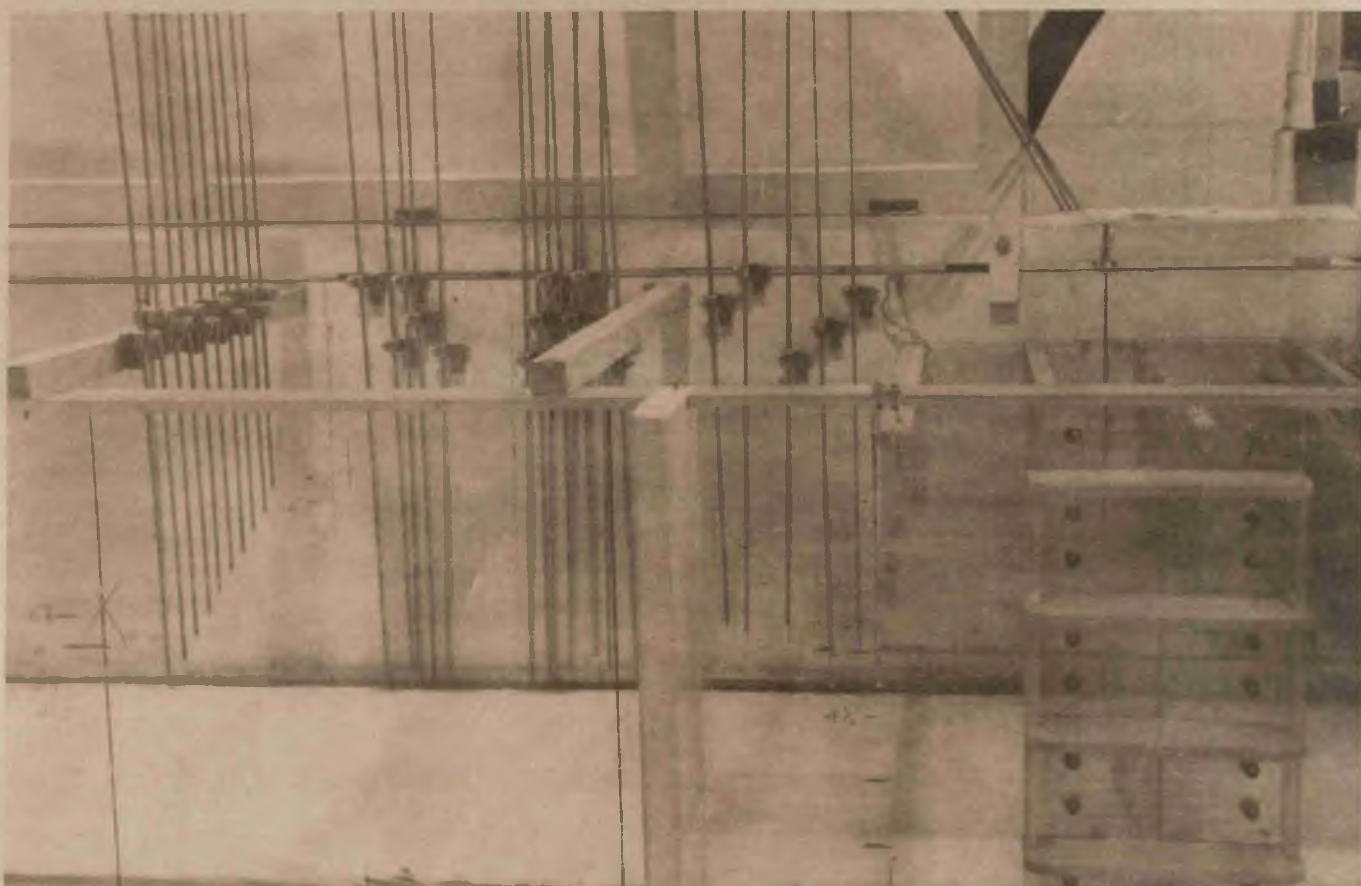


FIG. 5.1 CHARACTERISTICS OF RECORDING PROBES.

FIG. 5.2 RECORDING APPARATUS

FIG. 5.3 PROBES IN FLUME





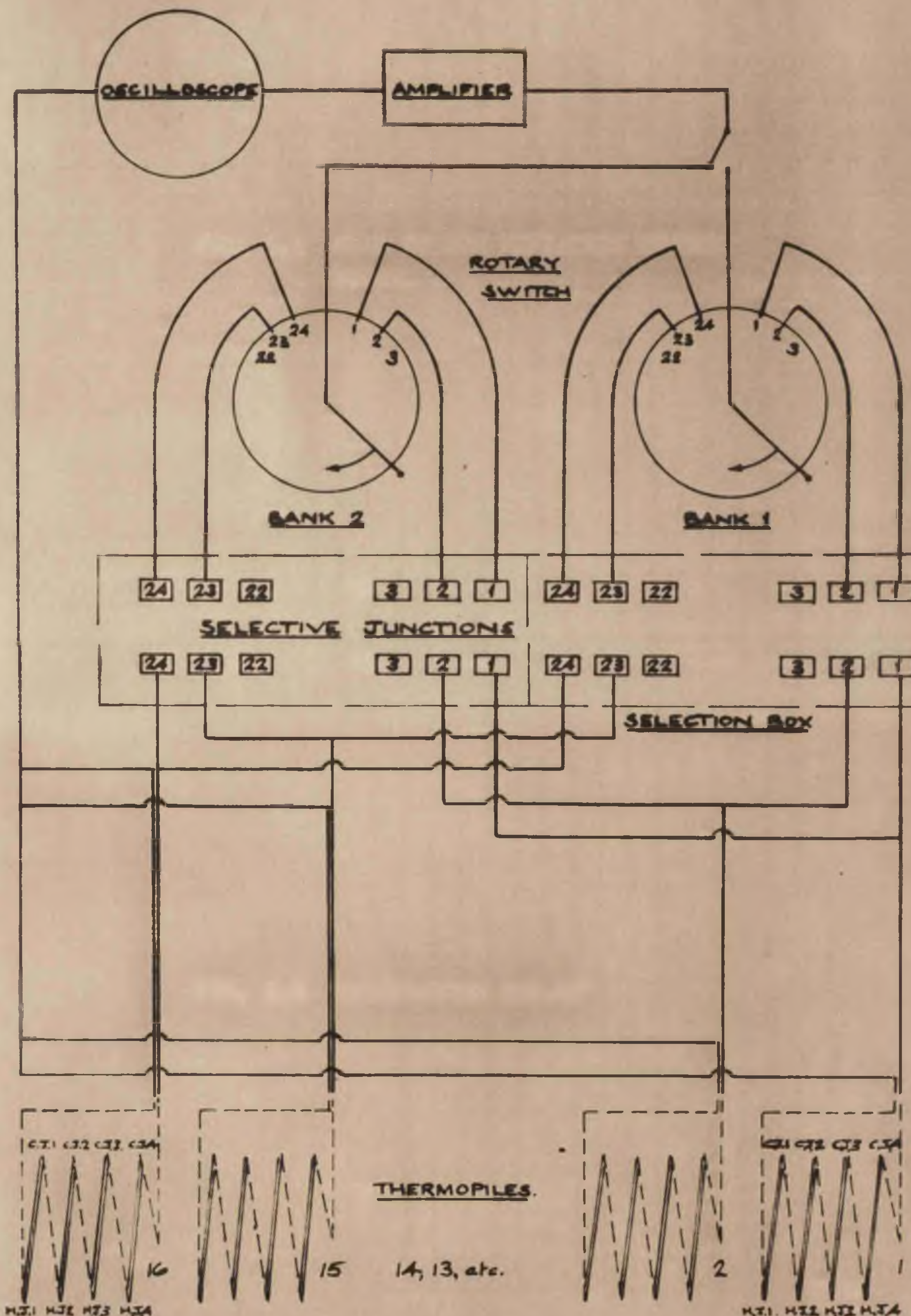


FIG. 5.4 CIRCUIT DIAGRAM.

FIG. 5.5 HEAD OF HRS MINIATURE CURRENT METER.

FIG. 5.6 CALIBRATION SET-UP

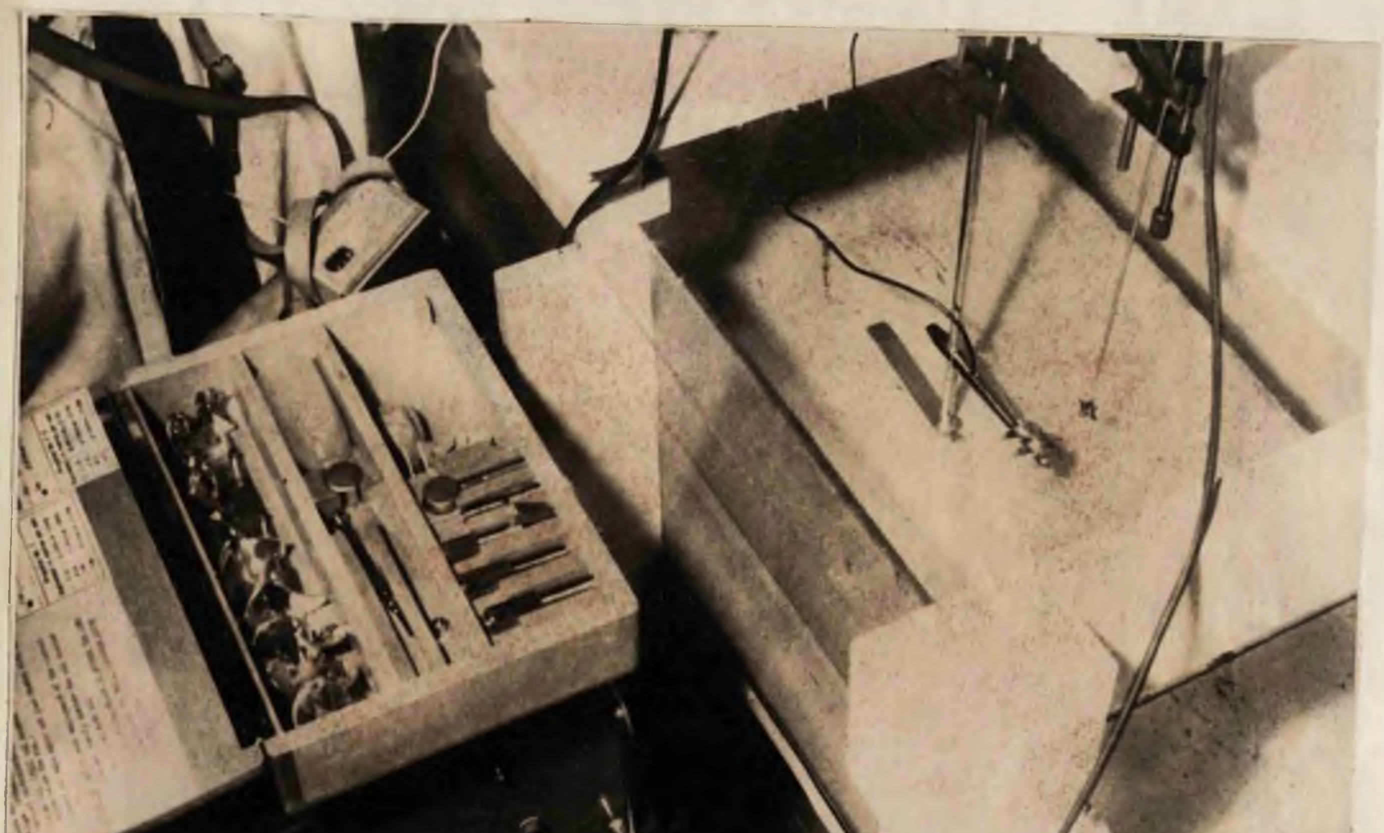
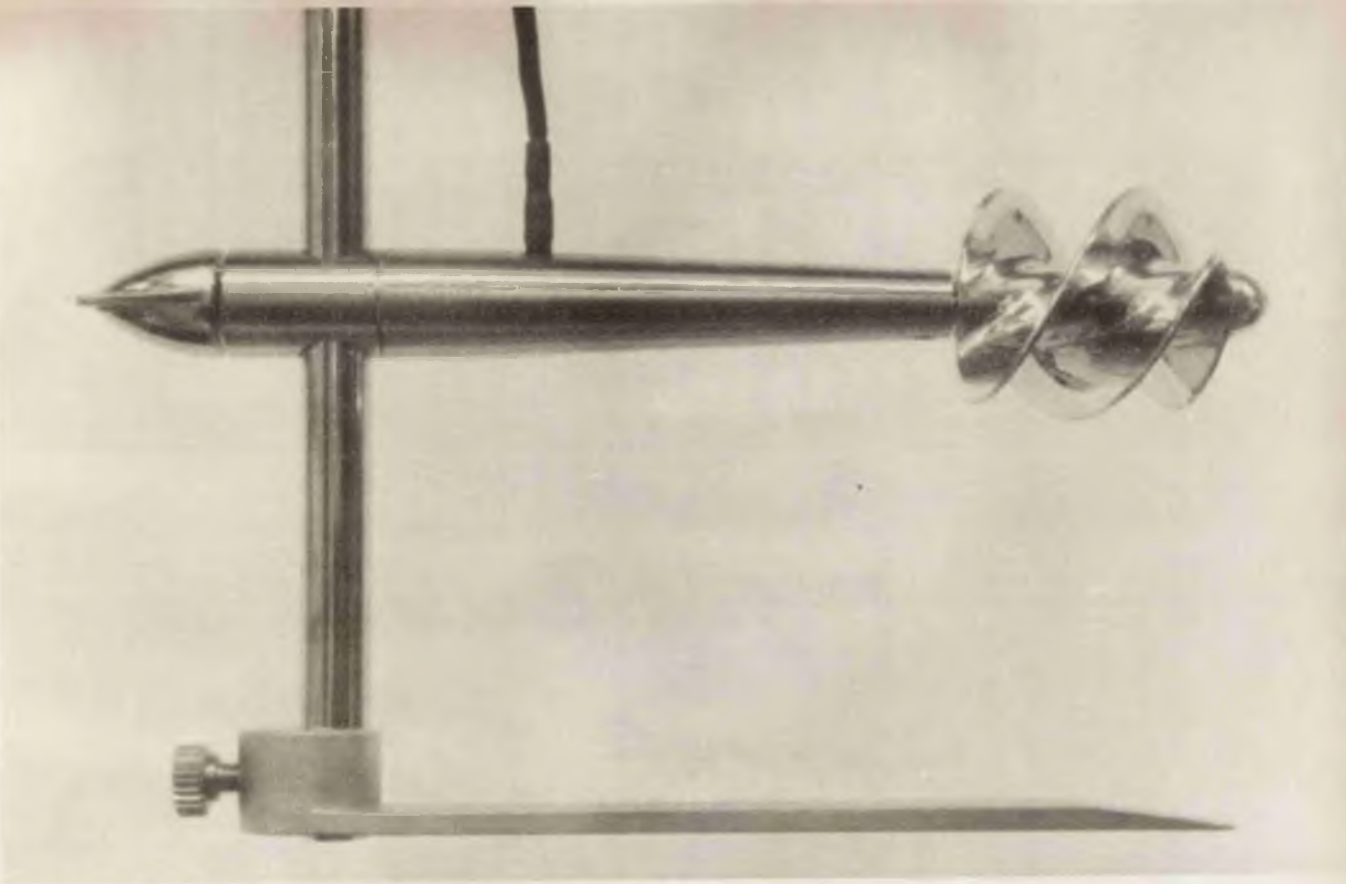


FIG. 5.7 OTT CURRENT METER



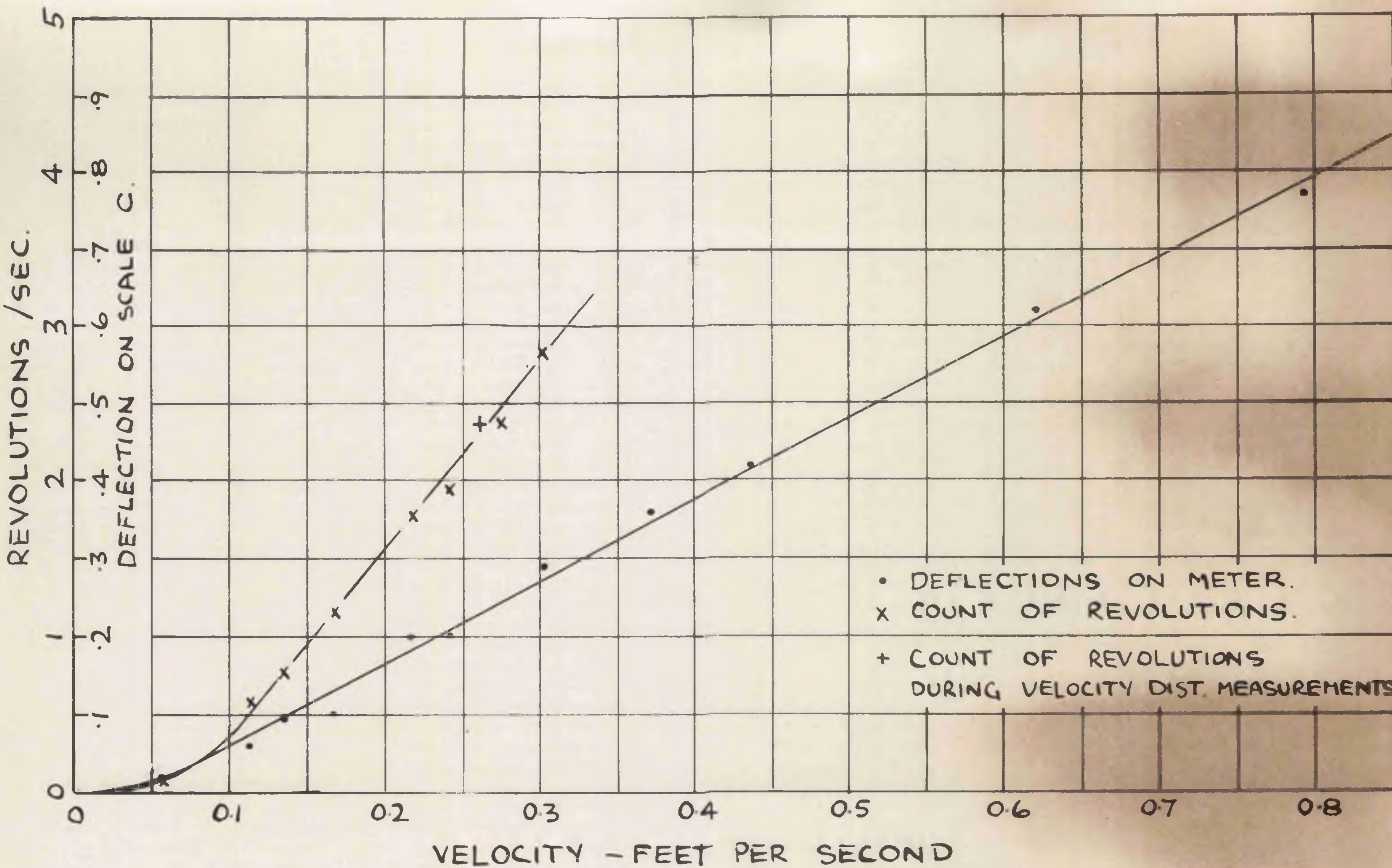


FIG. 5.8 MINATURE CURRENT METER CALIBRATION

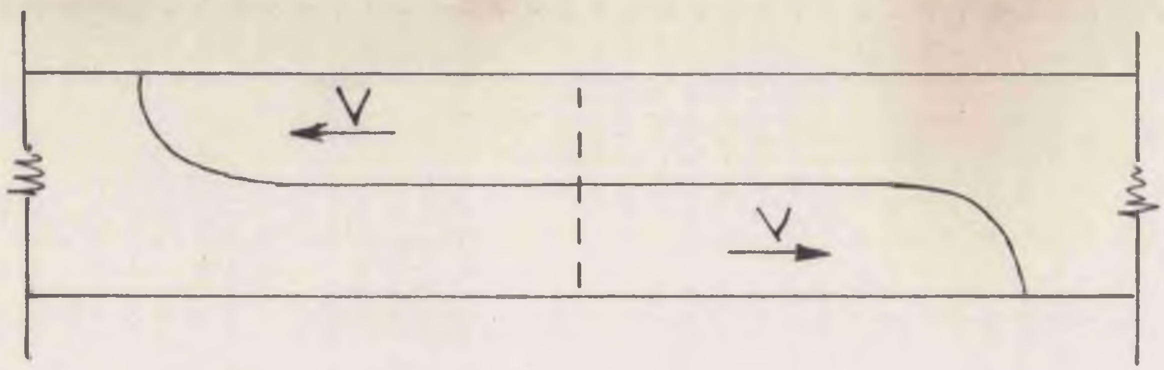


FIG. 7.1 COMPOSITE UNDERFLOW AND OVERFLOW FIGURE.

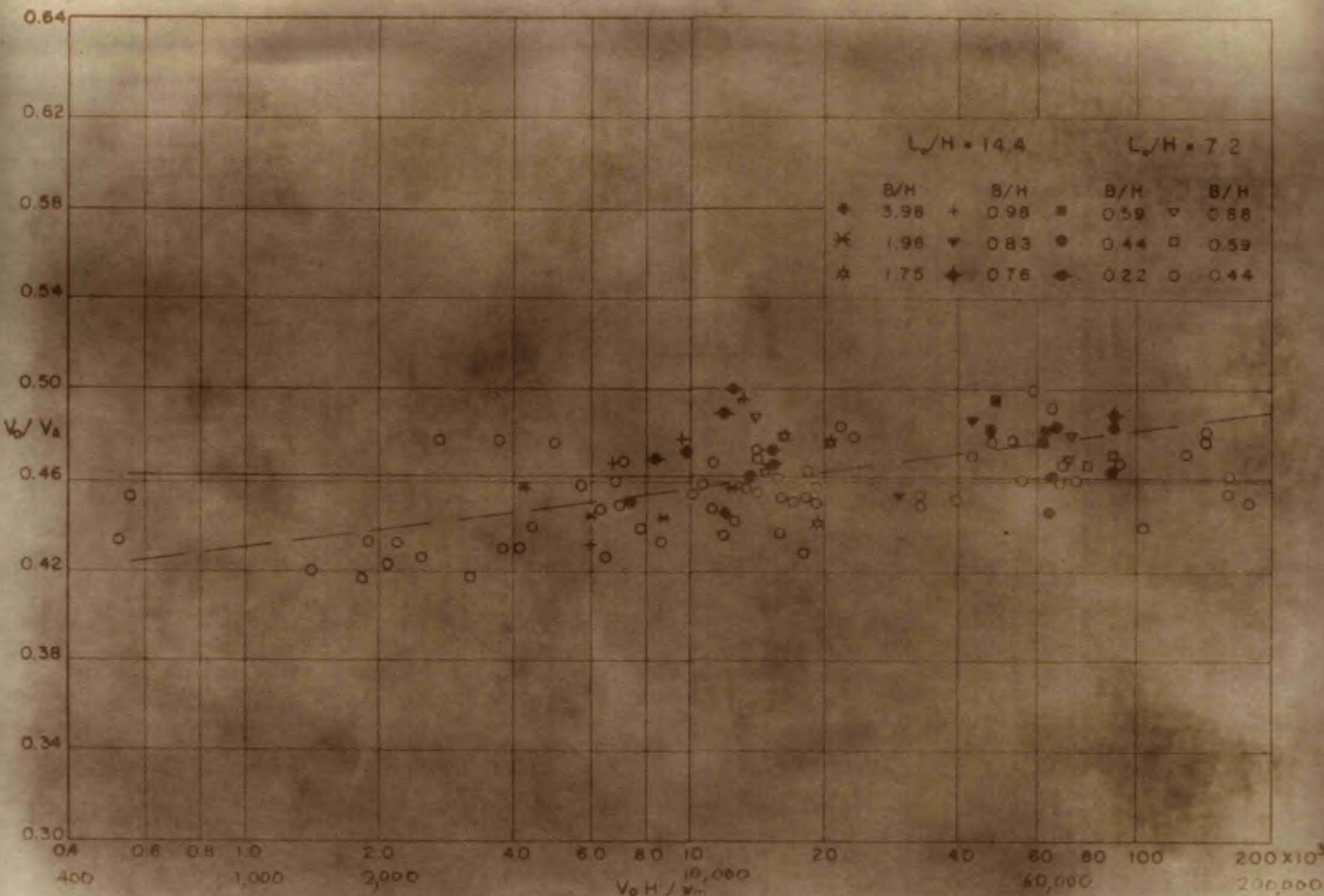


FIG 2 INITIAL FRONT VELOCITY OF SALINE WATERS EMERGING FROM LOCKS

FIG: 7.2 KEULEGAN'S EVALUATION OF UNDERFLOW INITIAL VELOCITY.

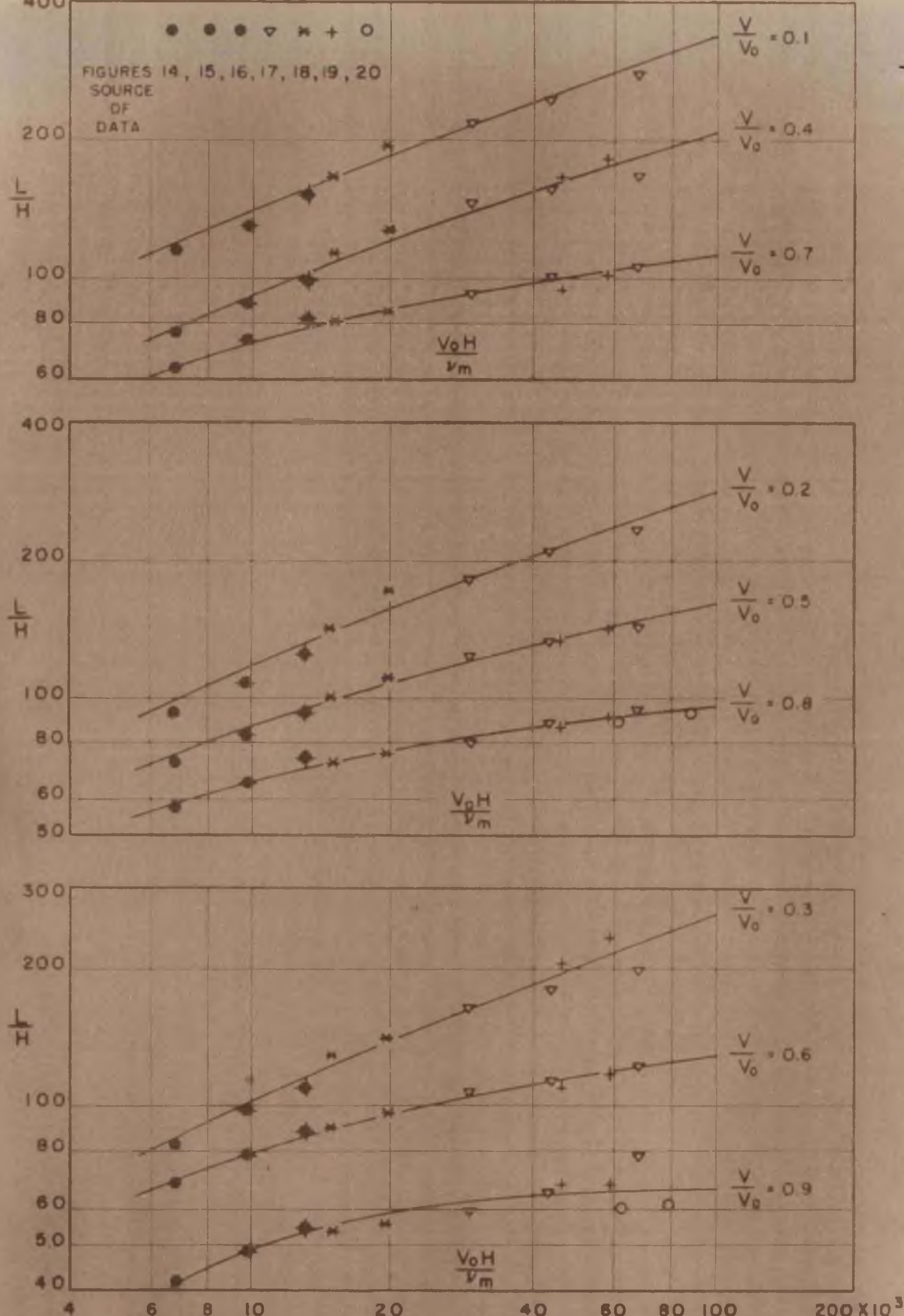


FIG. 22 CONGRUENCY OF DATA ON SALINE FRONT VELOCITIES TAKEN FROM VARIOUS CHANNELS. $L_o/H = 14.4$, $H/B = 2$.

FIG. 7.3 TYPICAL KEULEGAN CONGRUENCY DIAG. FOR DIMUNITION OF UNDERFLOW VELOCITY.

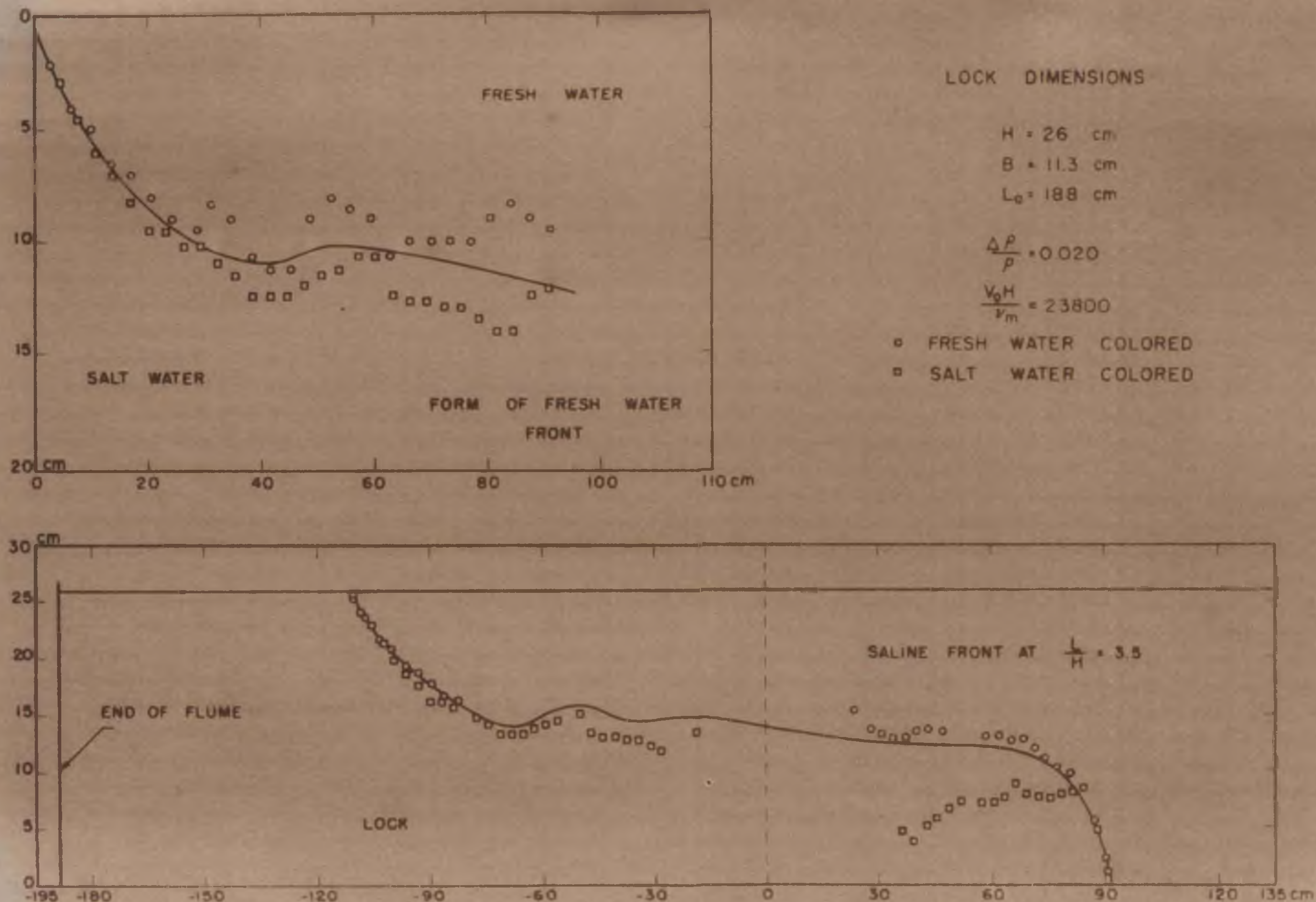


FIG. 52 DEPLOYMENT OF SALT WATER FOR SUCCESSIVE DISPLACEMENTS OF SALINE FRONT

FIG. 7.4 KEULEGAN'S OBSERVATIONS OF OVERFLOW AND UNDERFLOW SHAPE

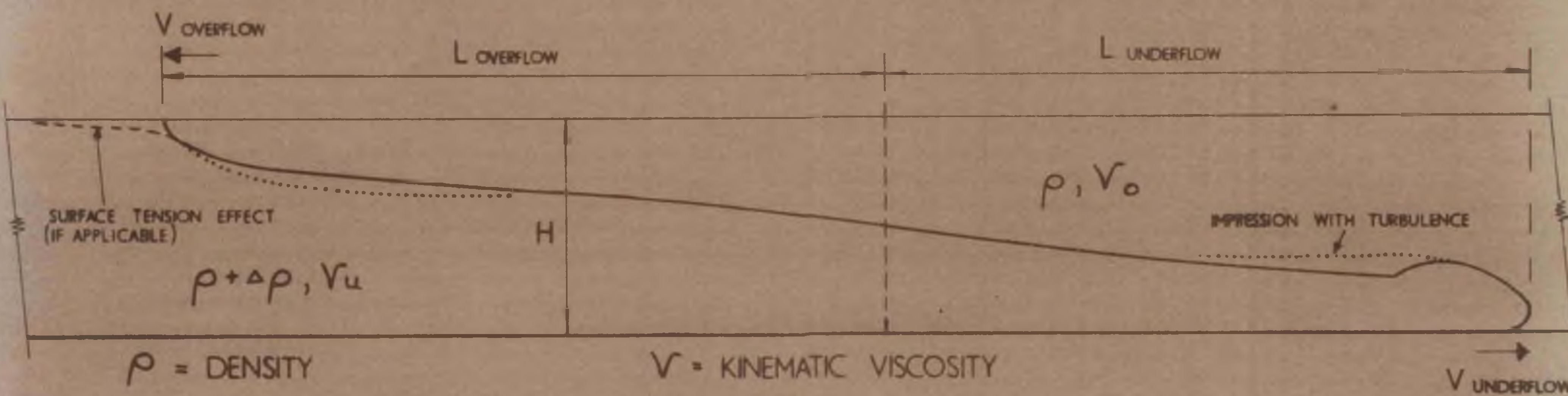


FIG. 7.5 — LOCK EXPERIMENTS - NOTATION.

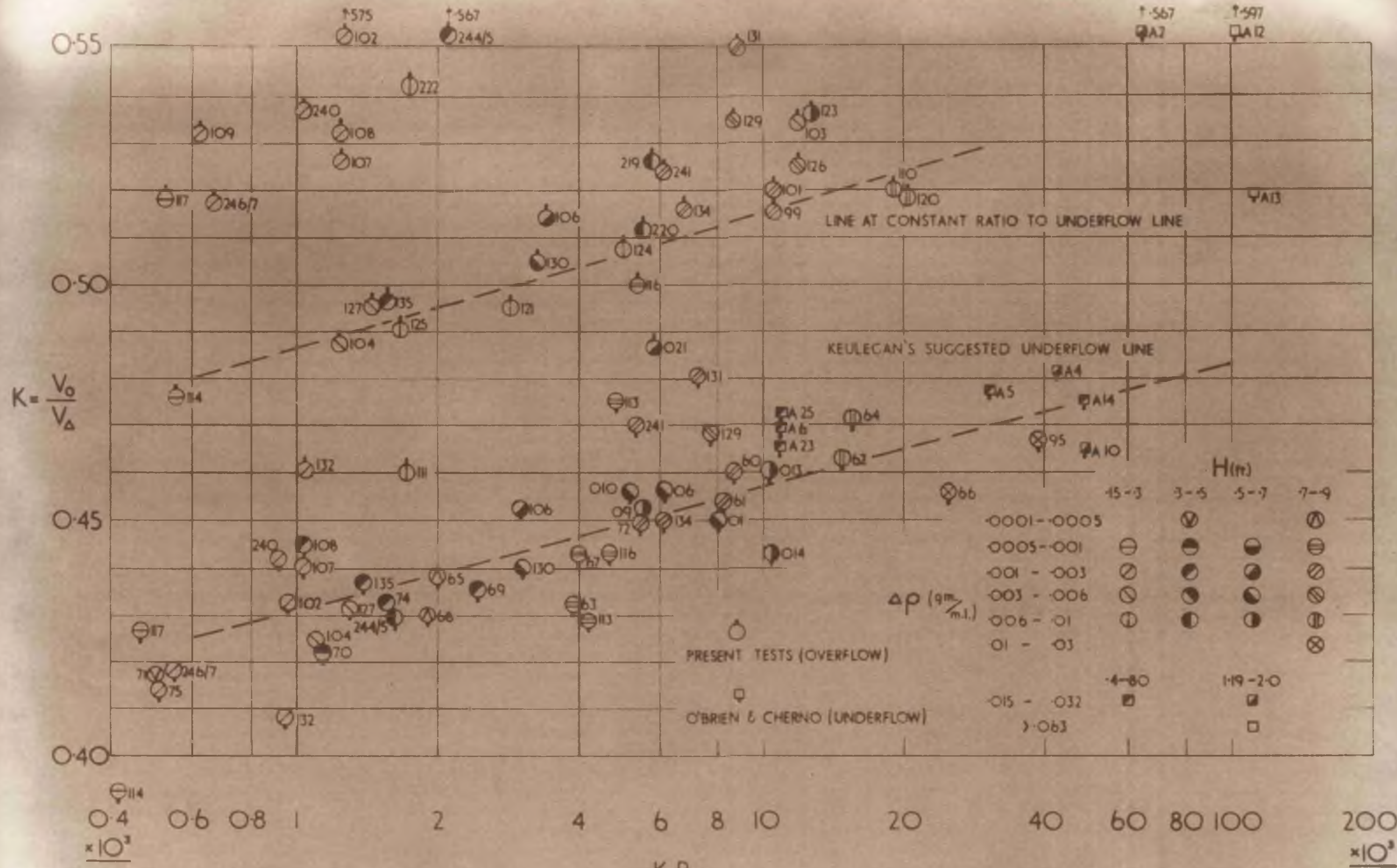


FIG. 7.6 - SALINE COEFFICIENTS OF PROPORTIONALITY.

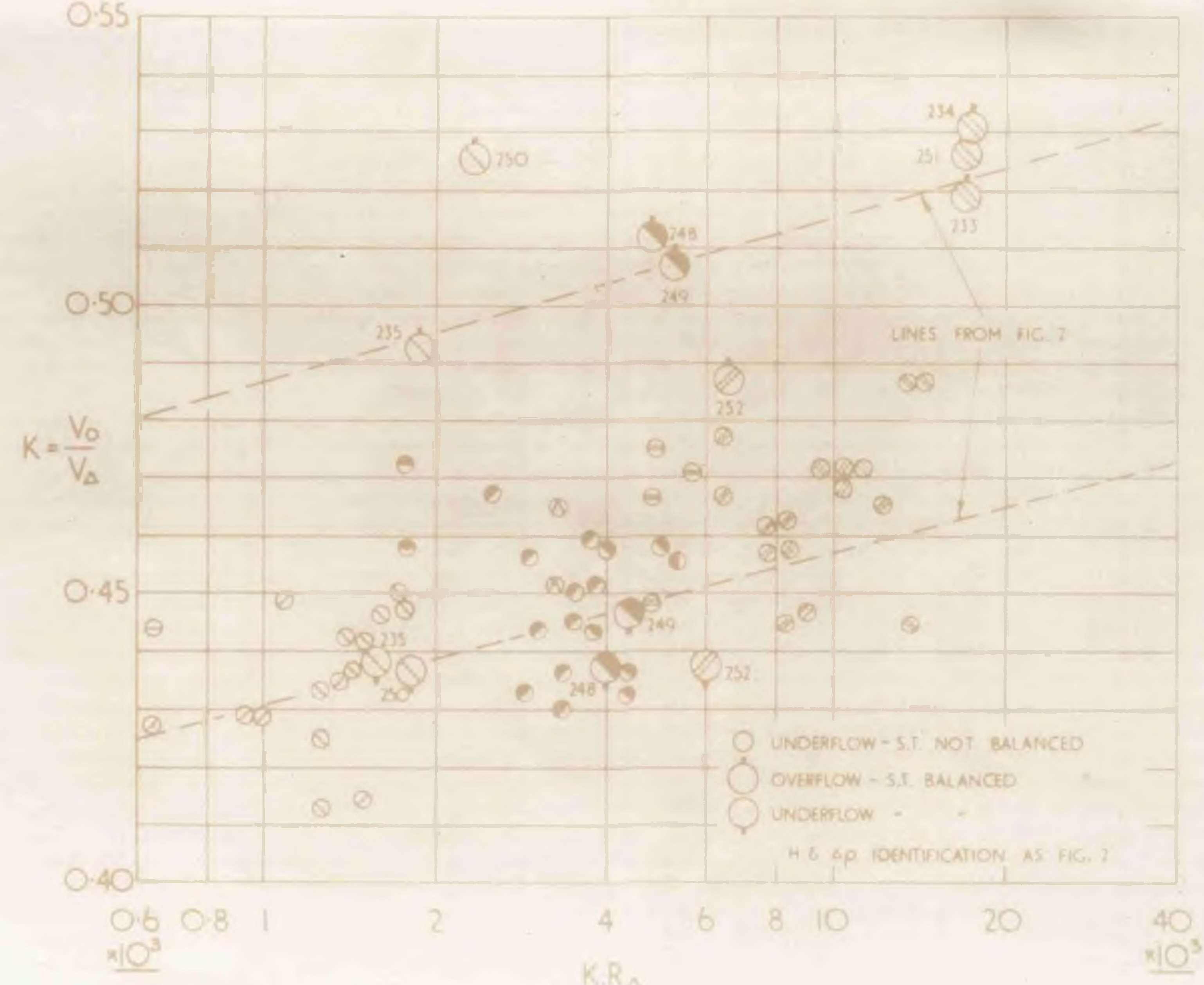


FIG. 7.7 - THERMAL COEFFICIENTS OF PROPORTIONALITY.

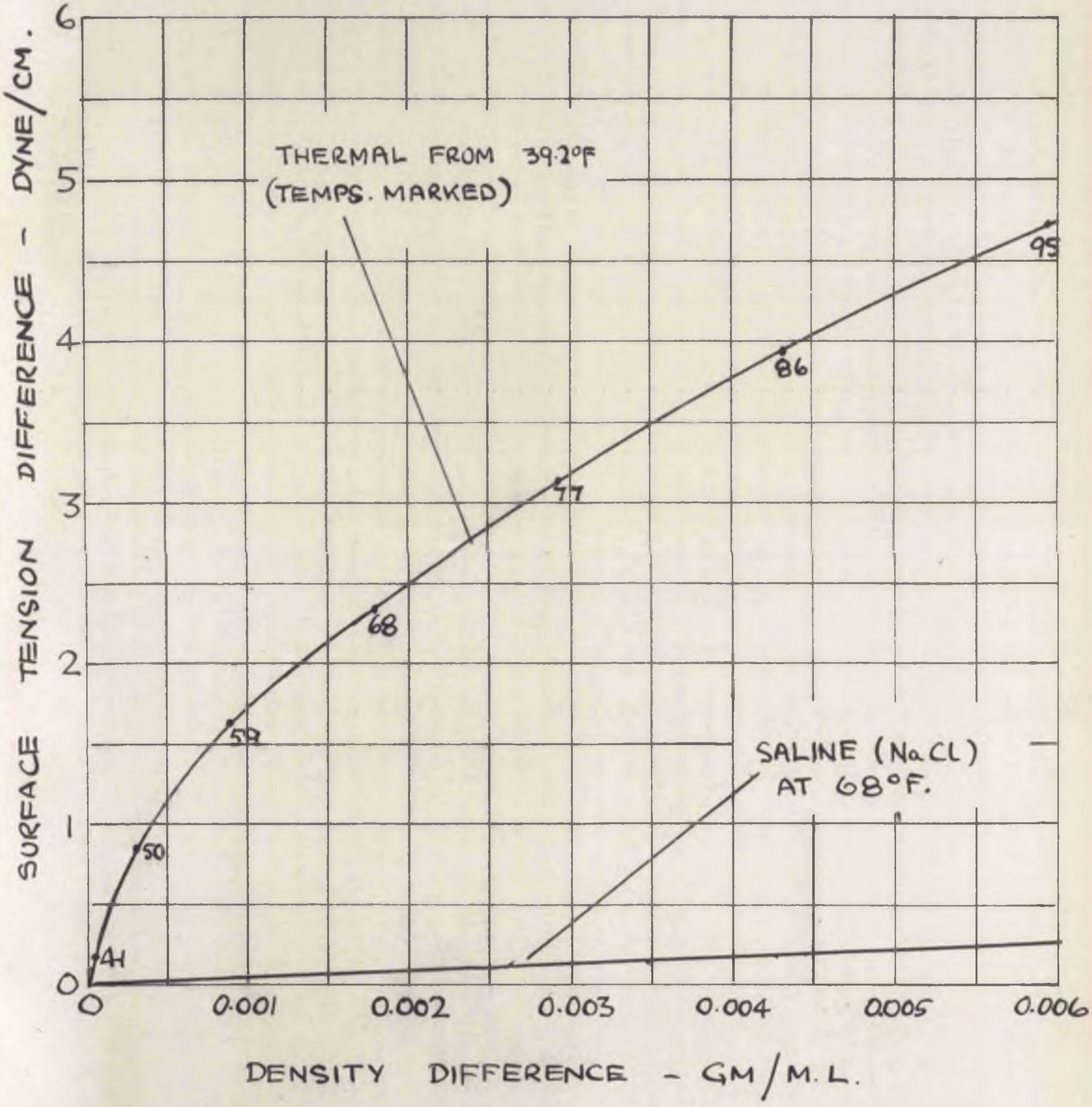
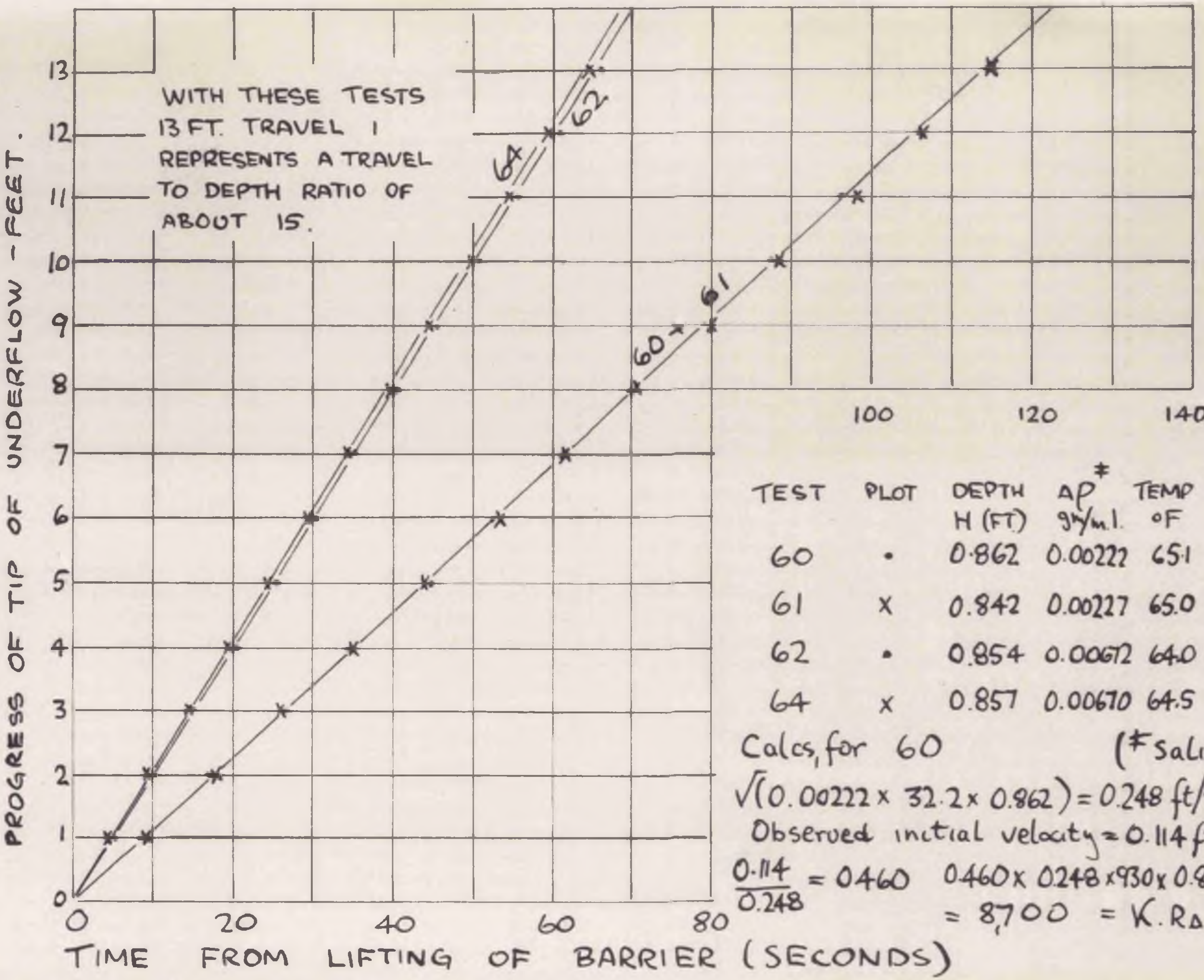


FIG. 7.8 SURFACE TENSION VARIATION FOR SALINE AND THERMAL DENSITY DIFFERENCES.



TEST	PLOT	DEPTH H (FT)	$\Delta\rho$ * gm/ml	TEMP °F	K.R_Δ
60	•	0.862	0.00222	65.1	8,700
61	x	0.842	0.00227	65.0	8,200
62	•	0.854	0.00672	64.0	14,700
64	x	0.857	0.00670	64.5	15,150

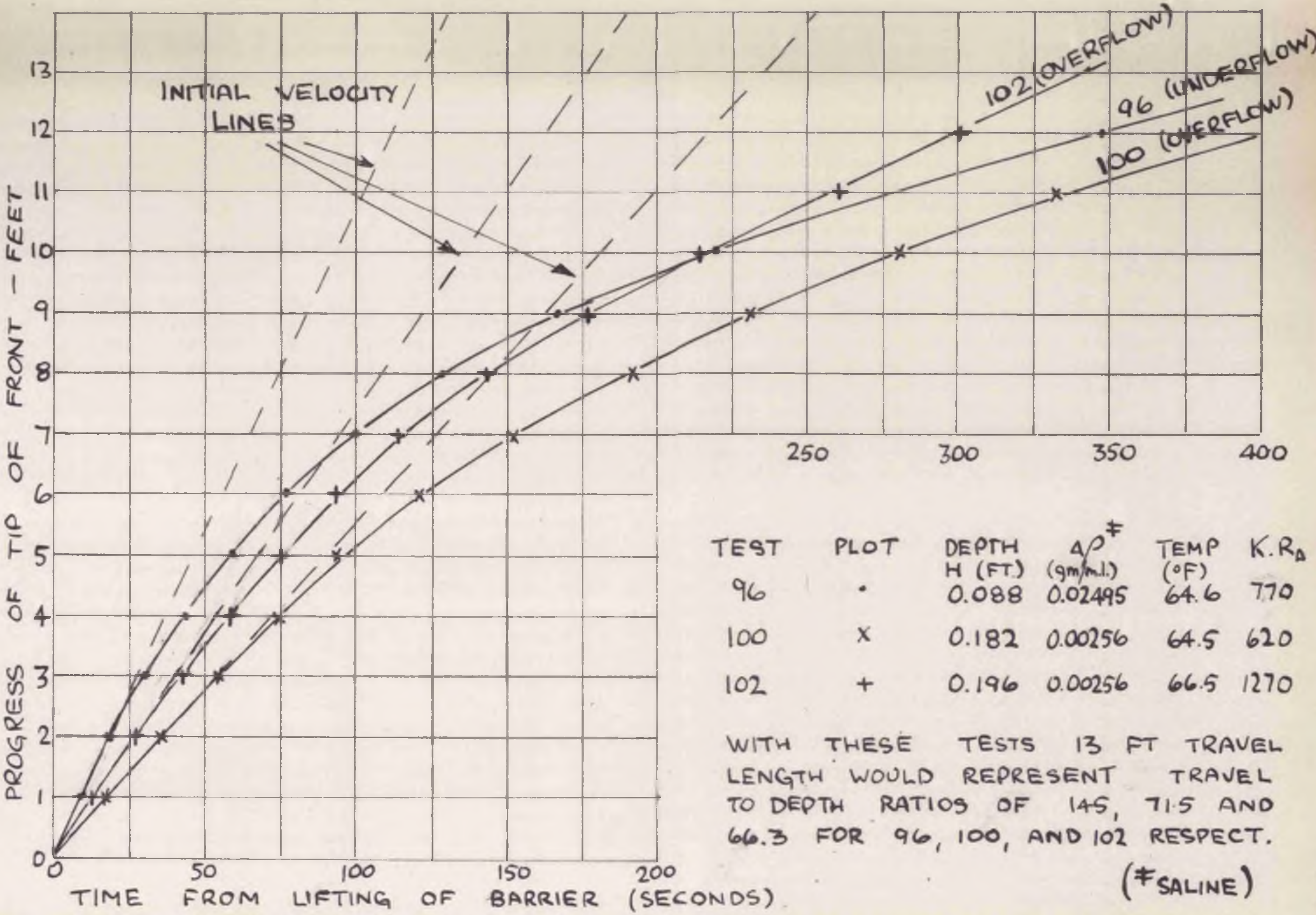
Calcs, for 60 (* saline)

$\sqrt{(0.00222 \times 32.2 \times 0.862)} = 0.248$ ft/sec.

Observed initial velocity = 0.114 ft/sec.

$\frac{0.114}{0.248} = 0.460$ $\quad 0.460 \times 0.248 \times 930 \times 0.862 = 8{,}700 = K.R_\Delta$

FIG. 7.9 TYPICAL PLOTS OF ADVANCE OF FRONT - FASTER RANGE.



TEST	PLOT	DEPTH H (FT.)	$\Delta\rho$ # (gm/ml.)	TEMP (°F)	K.R_{Δ}
96	•	0.088	0.02495	64.6	770
100	x	0.182	0.00256	64.5	620
102	+	0.196	0.00256	66.5	1270

WITH THESE TESTS 13 FT TRAVEL LENGTH WOULD REPRESENT TRAVEL TO DEPTH RATIOS OF 145, 71.5 AND 66.3 FOR 96, 100, AND 102 RESPECT.

(# SALINE)

FIG. 7.10 TYPICAL PLOTS OF ADVANCE OF FRONT – SLOWER RANGE.

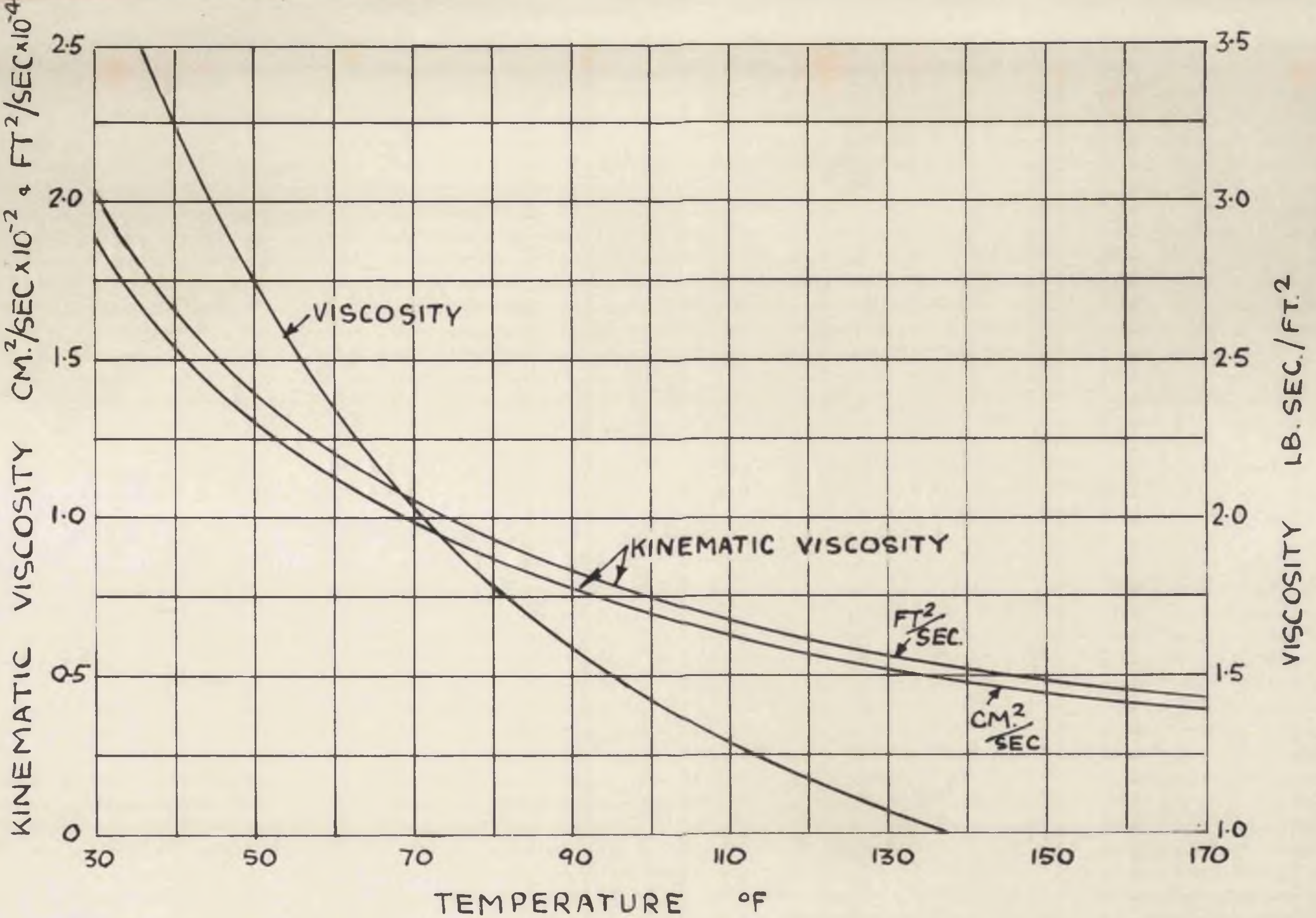


FIG. 7.11 VISCOSITY OF FRESH WATER.

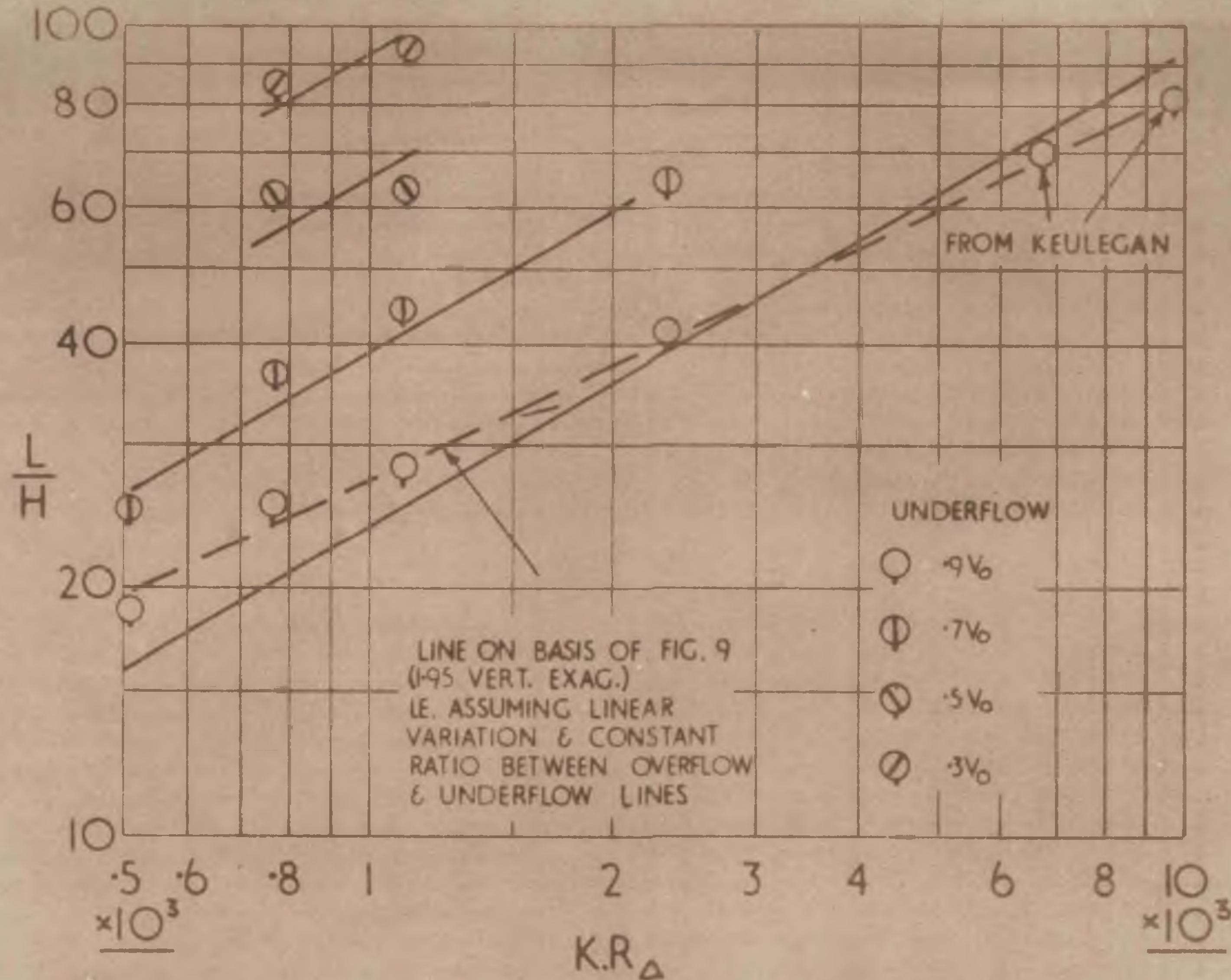


FIG. 7.12 – KEULEGAN TYPE CONGRUENCY DIAGRAM.

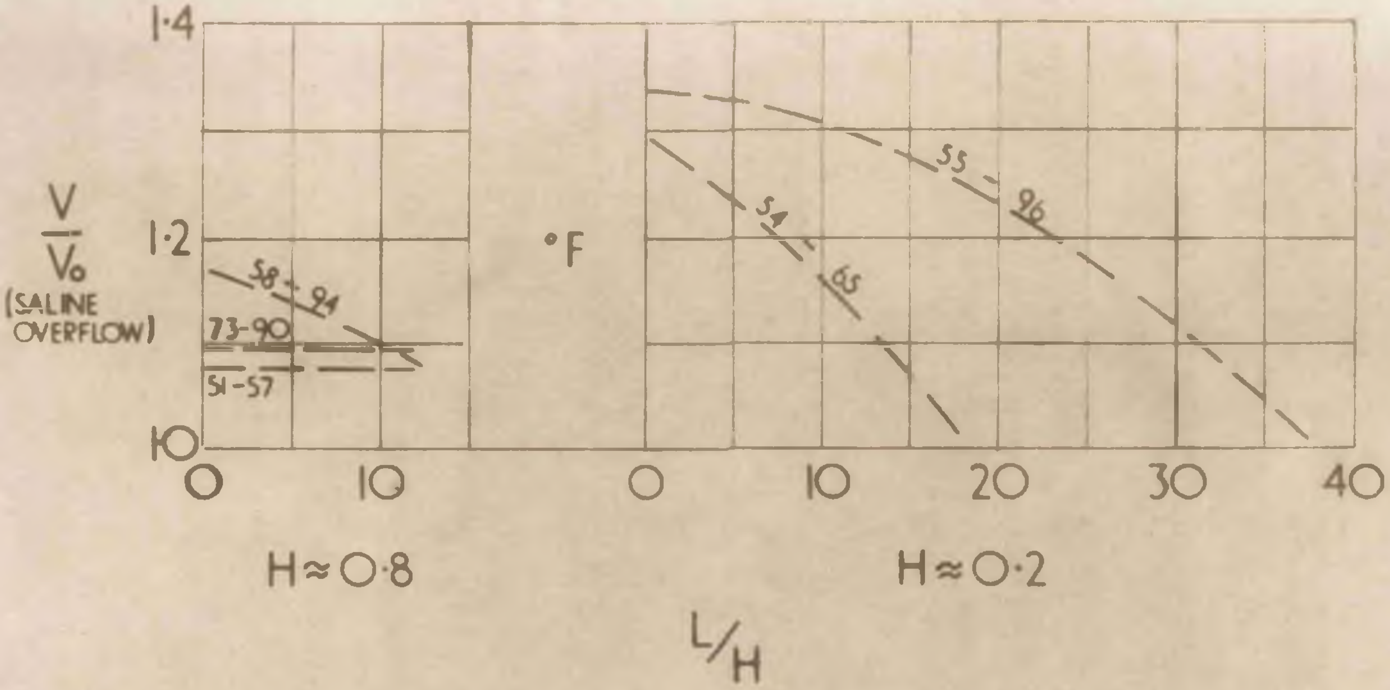


FIG. 7.13 – EFFECT OF SURFACE TENSION ON THERMAL OVERFLOW. – I.

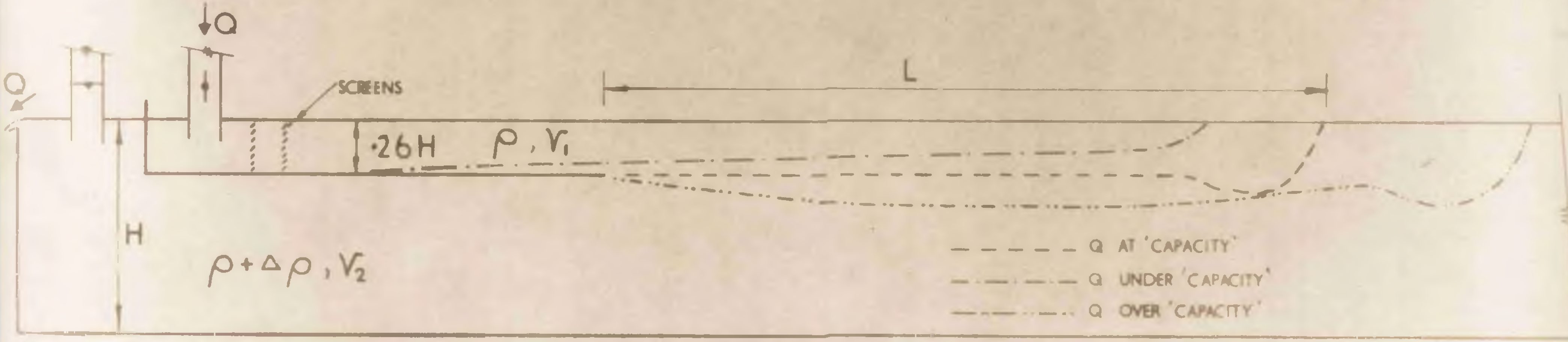


FIG. 7.15 – DIAGRAMATIC ILLUSTRATION OF FORCED SURFACE DENSITY CURRENTS.

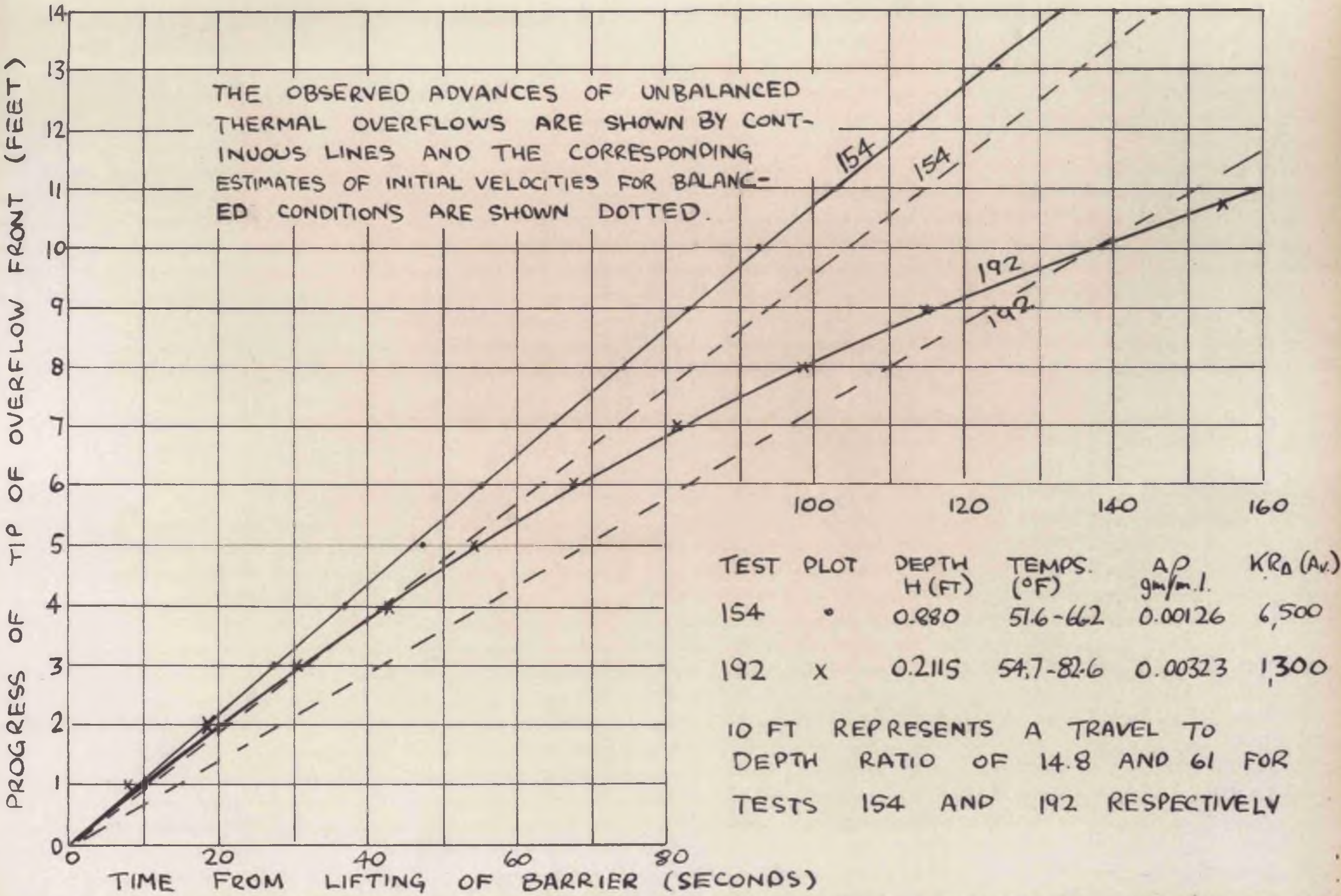
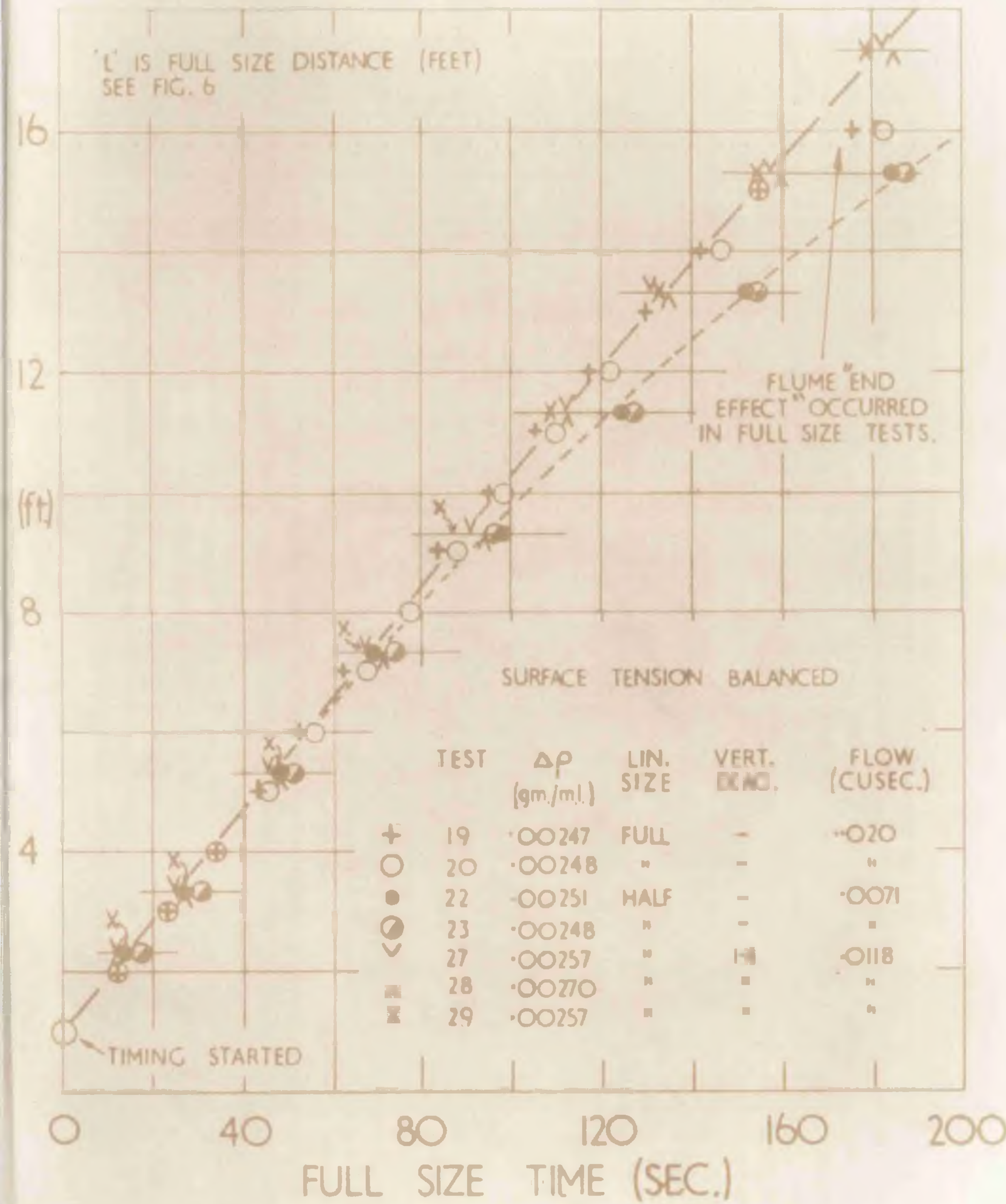


FIG. 7.14 EFFECT OF SURFACE TENSION ON THERMAL OVERFLOW-2.



IG. 7.17 – SIMILARITY IN FORCED SURFACE DENSITY CURRENTS.

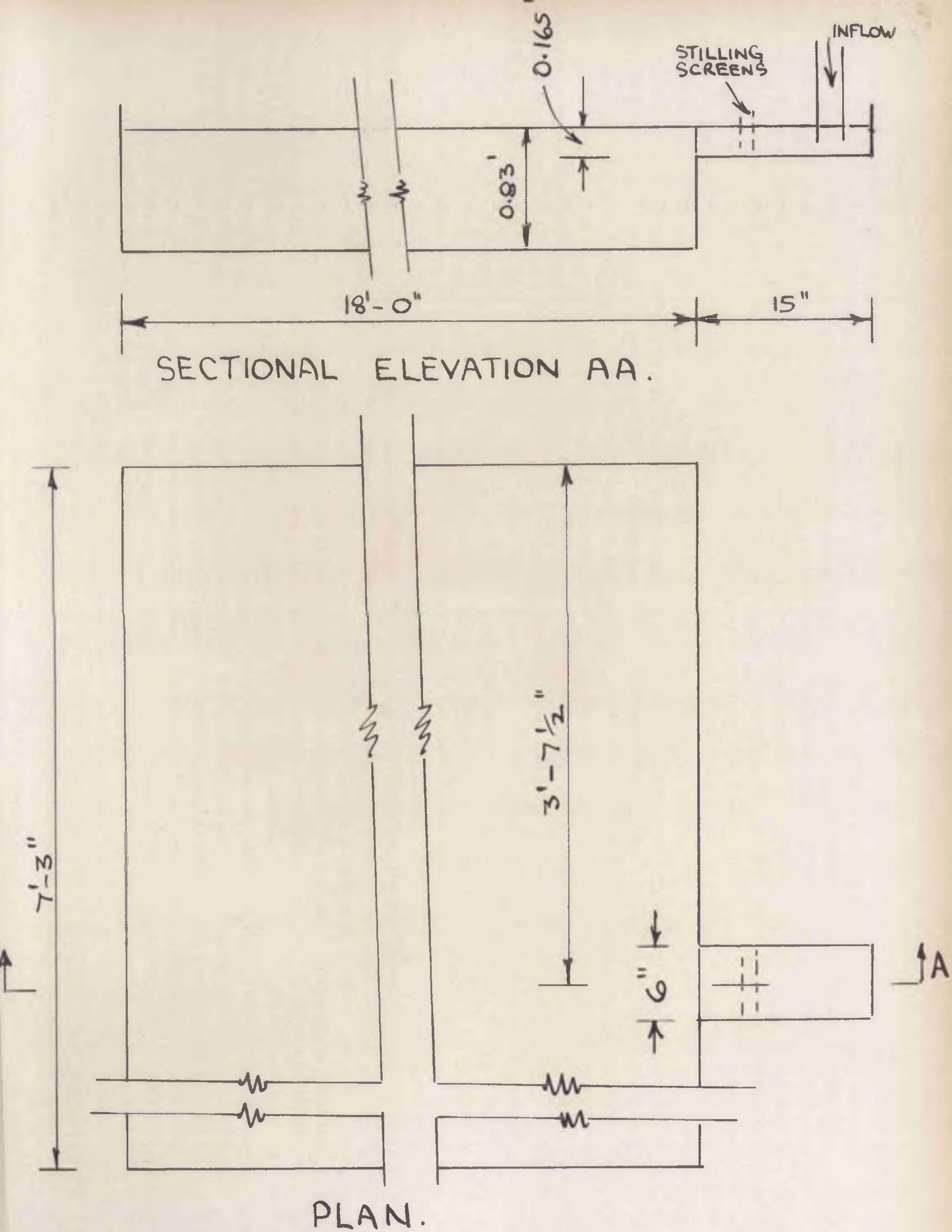


FIG. 7.18 SIMPLE OUTFALL EXPERIMENTS.
(TANK LAYOUT)

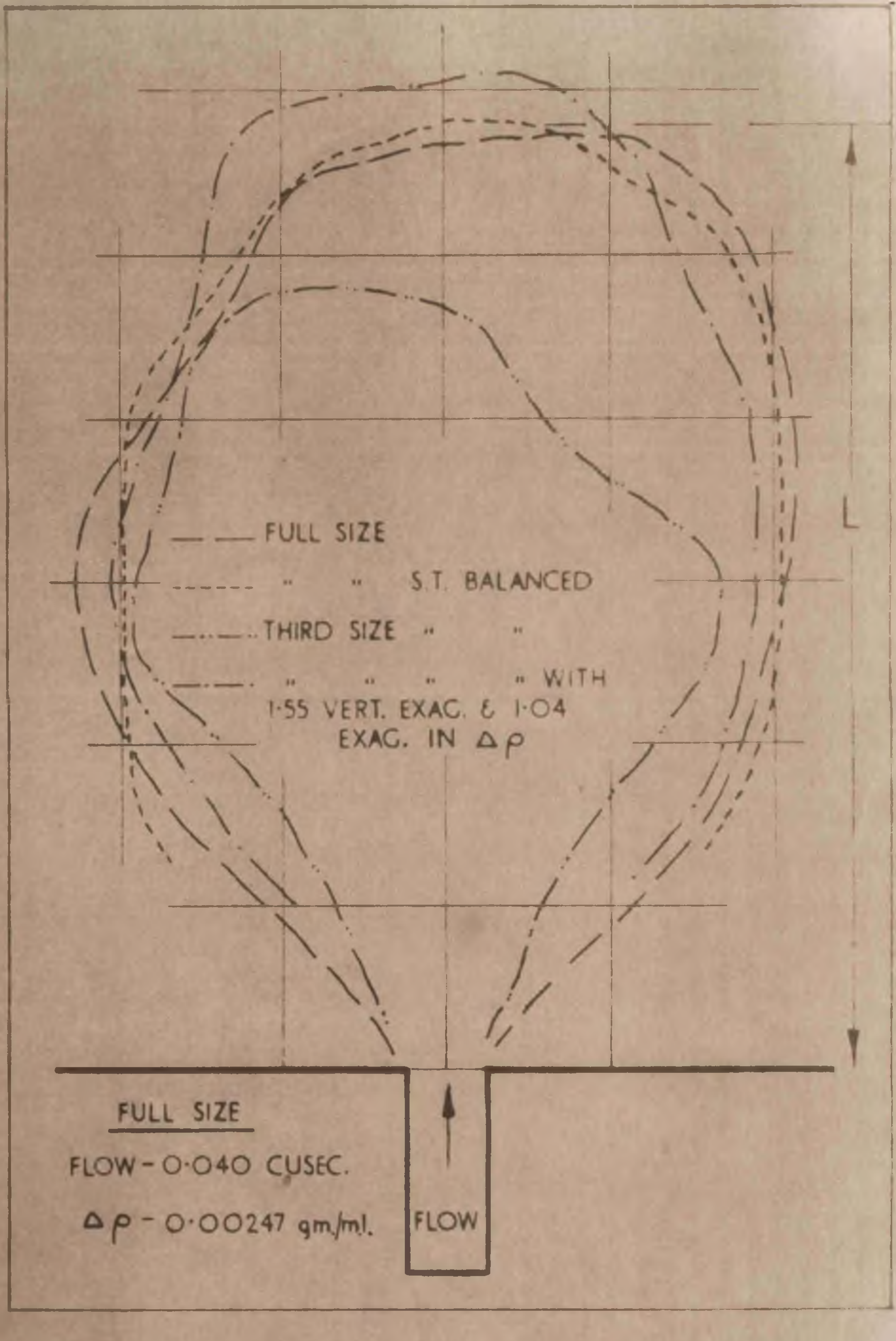


FIG. 7.19 – SPREAD OF HEATED WATER FROM SIMPLE OUTFALL.

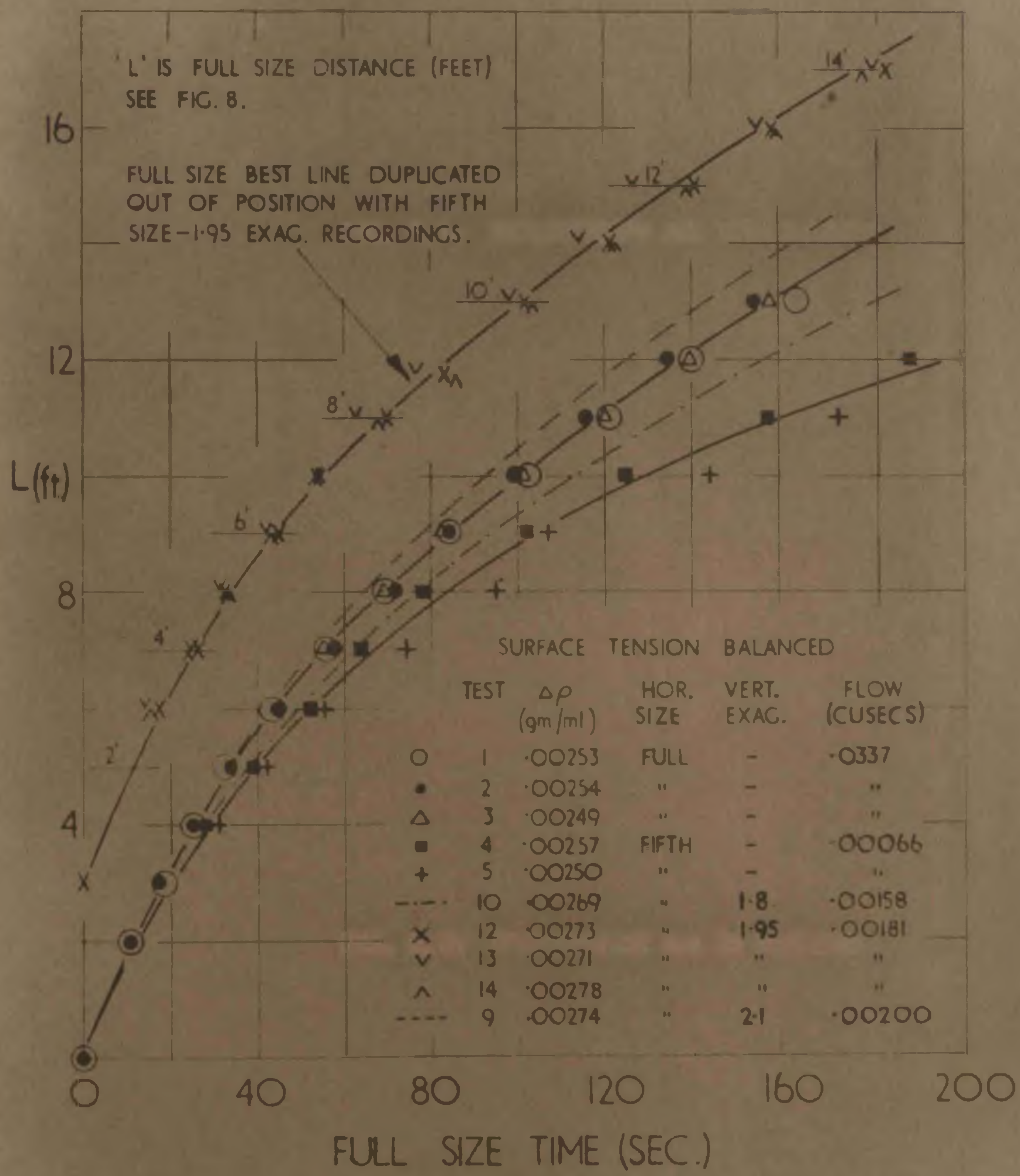


FIG. 7.20—SIMILARITY IN SIMPLE OUTFALL EXPERIMENTS.

FIG. 8.1a INTRODUCTION BOX WITH FAIRING

FIG. 8.1b INTRODUCTION BOX IN POSITION

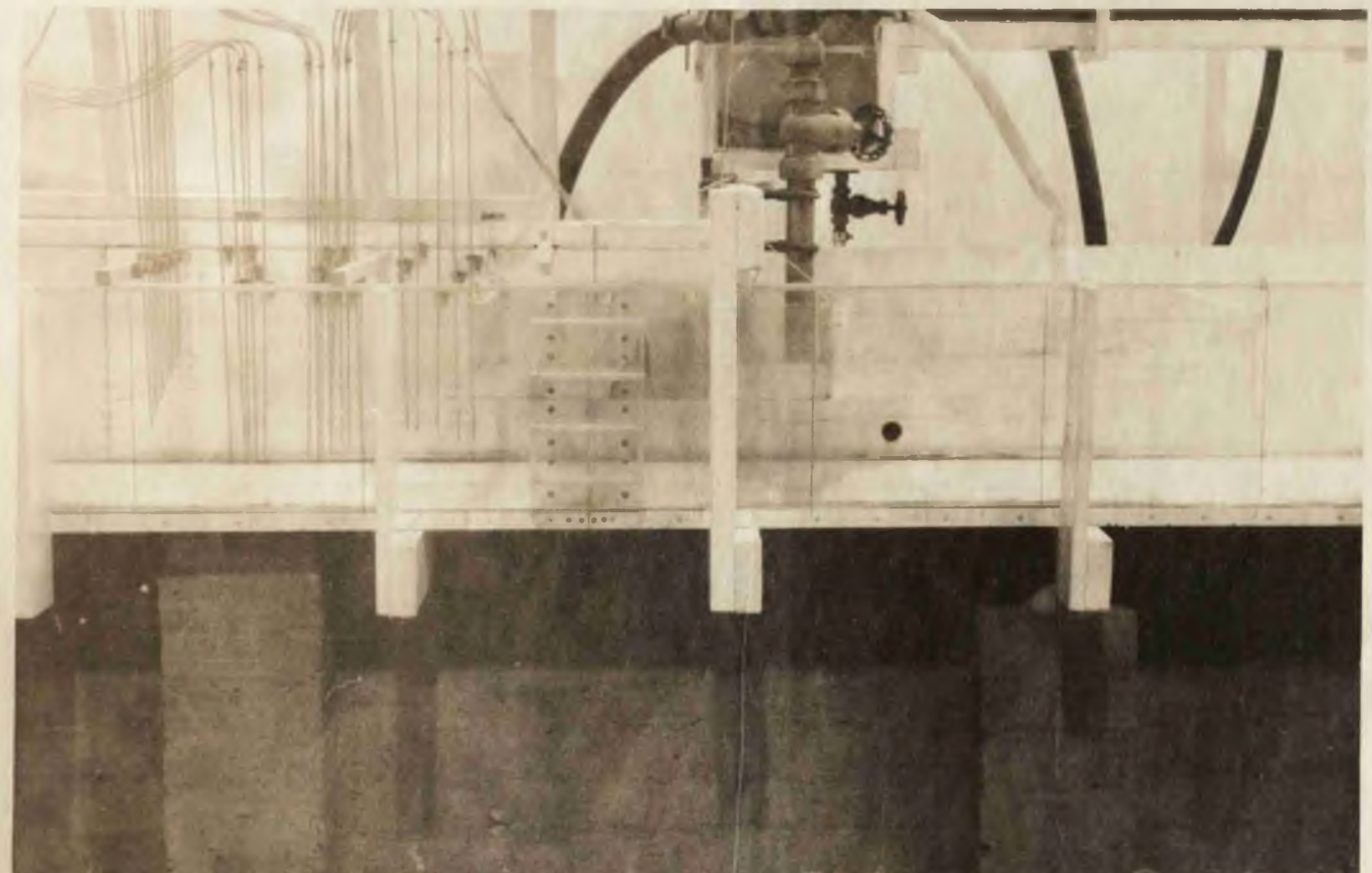
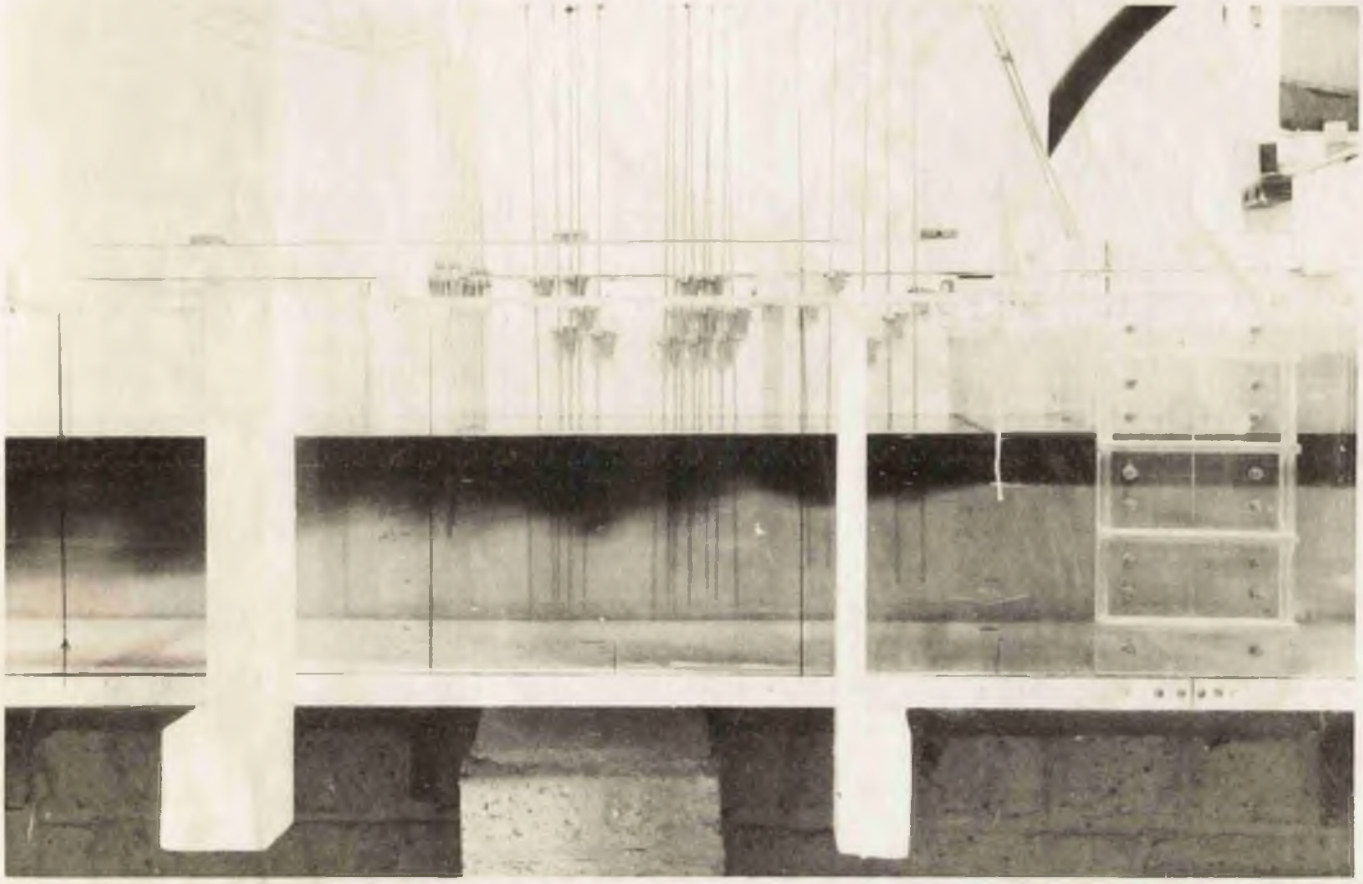
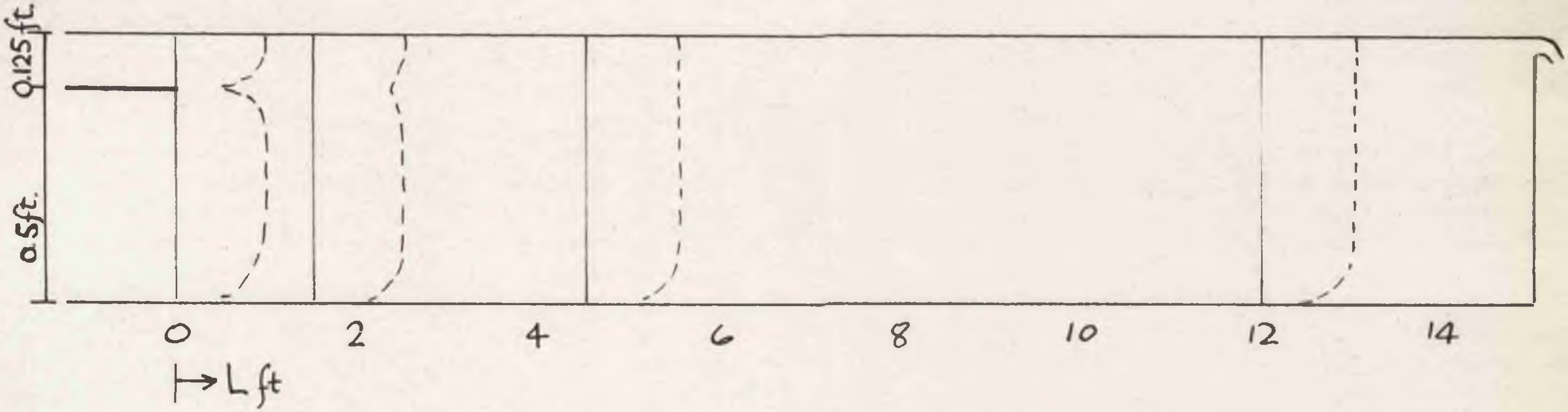


FIG. 8.2 TURBULENT MIXING IN STRATIFIED FLOW.





(VERTICAL EXAGGERATION x2)

FIG. 8.3 VELOCITY DISTRIBUTION IN CENTRE OF FLUME - FLOWS 2.

(CONFIGURATION A)

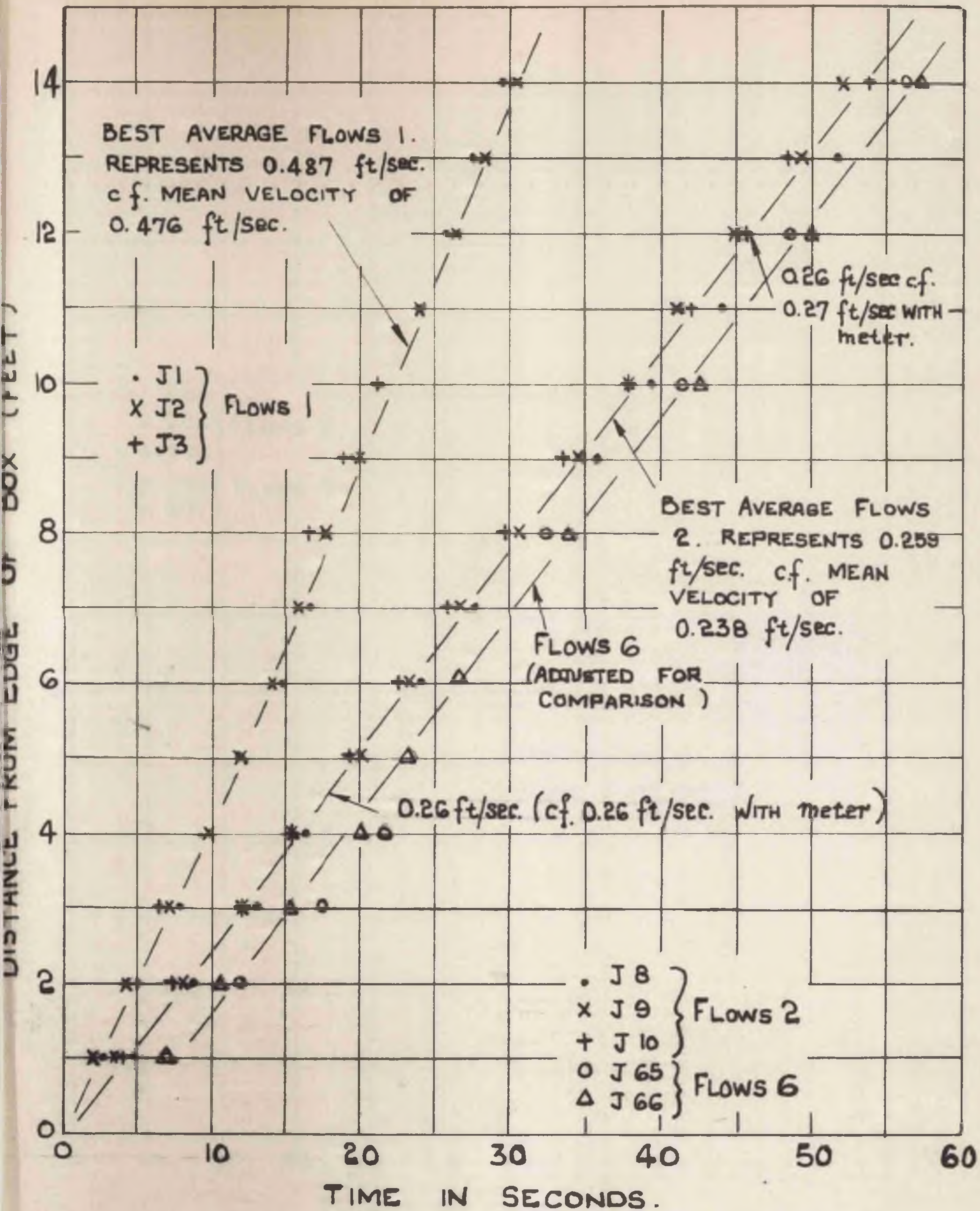


FIG. 8.4 SURFACE FLOAT PLOTS – FLOWS 1, 2 AND 6. (WITH NO DENSITY DIFFERENCE)

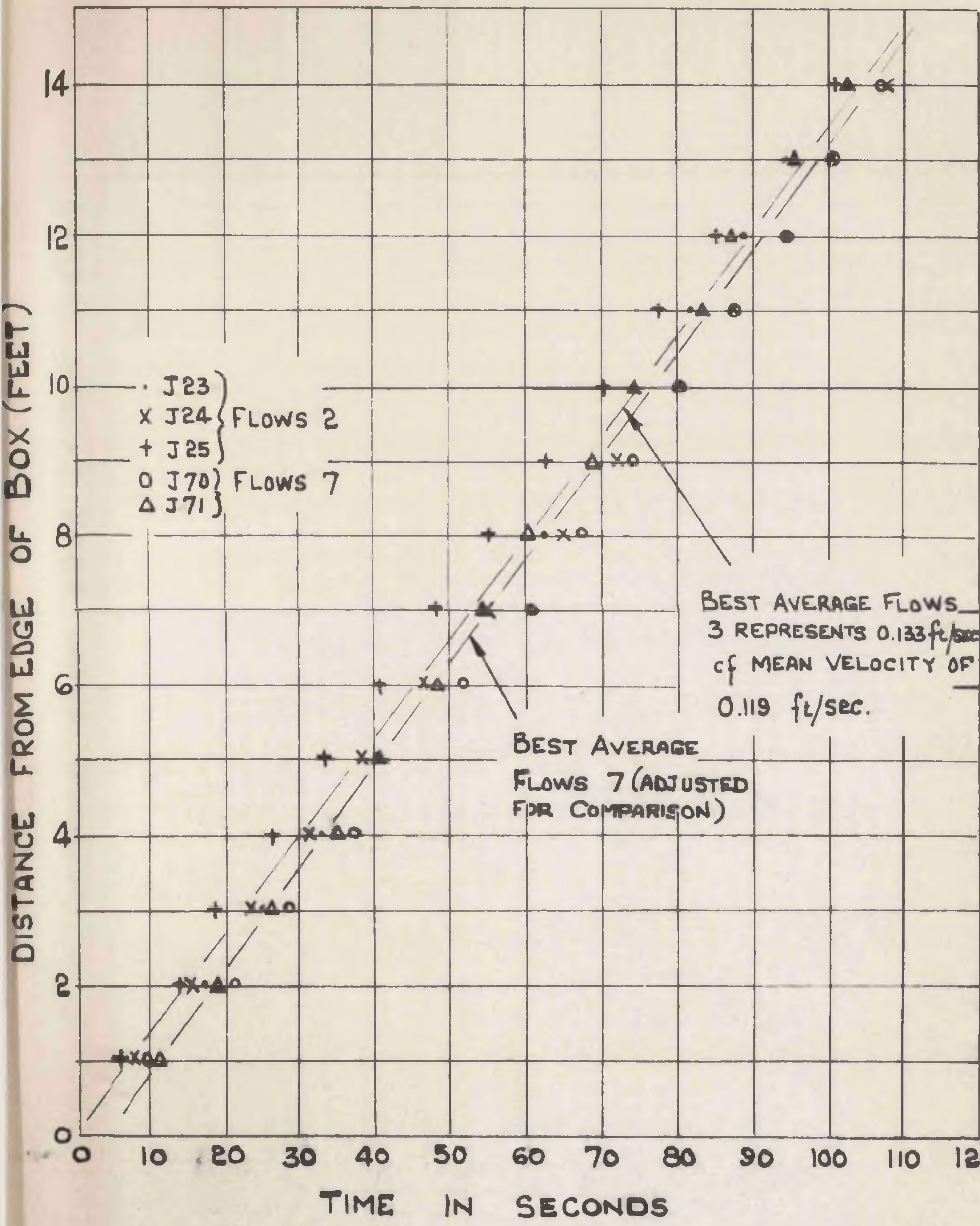


FIG. 8.5. SURFACE FLOAT PLOTS – FLOWS 3 AND 7 (WITH NO DENSITY DIFFERENCE).

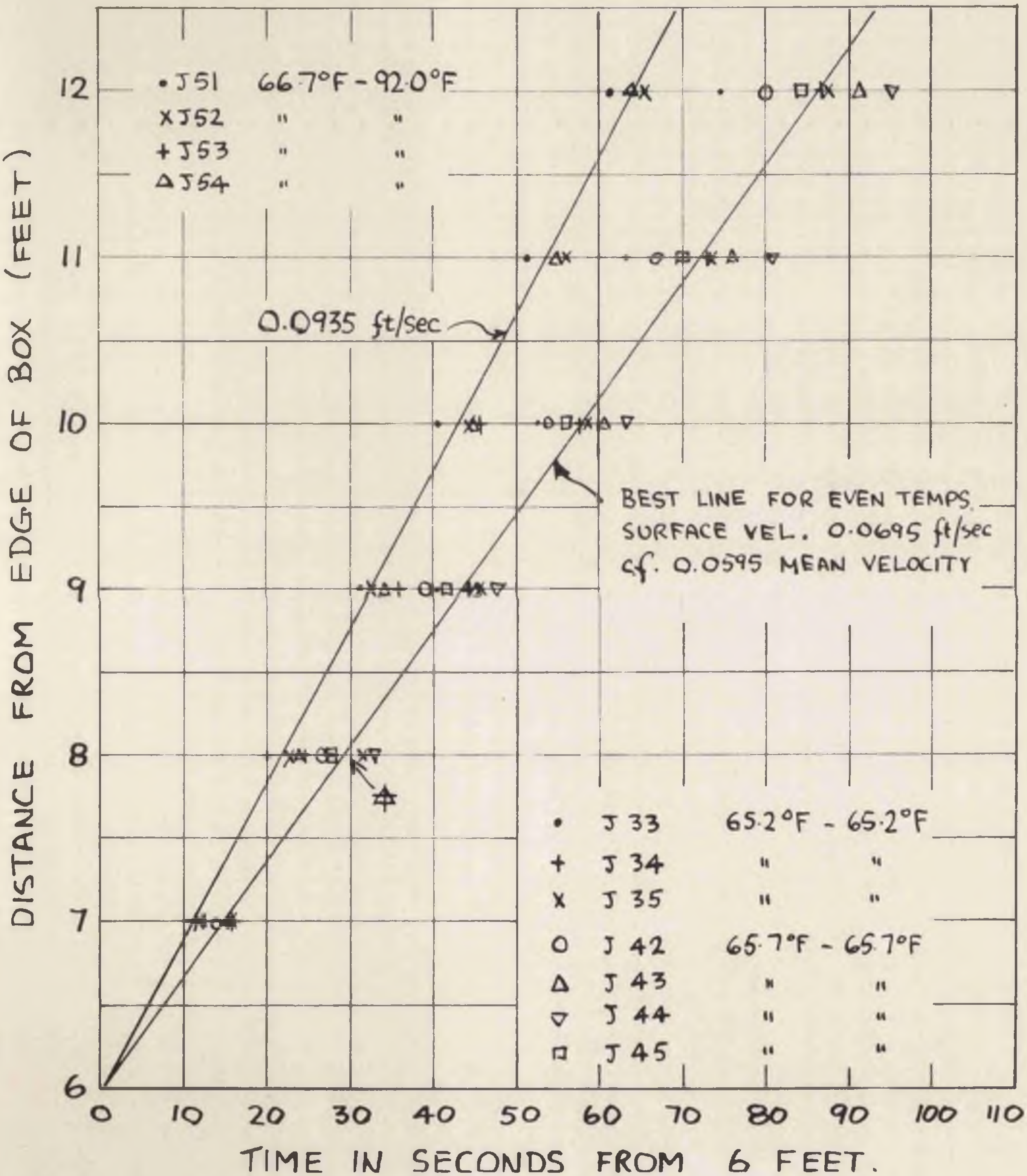
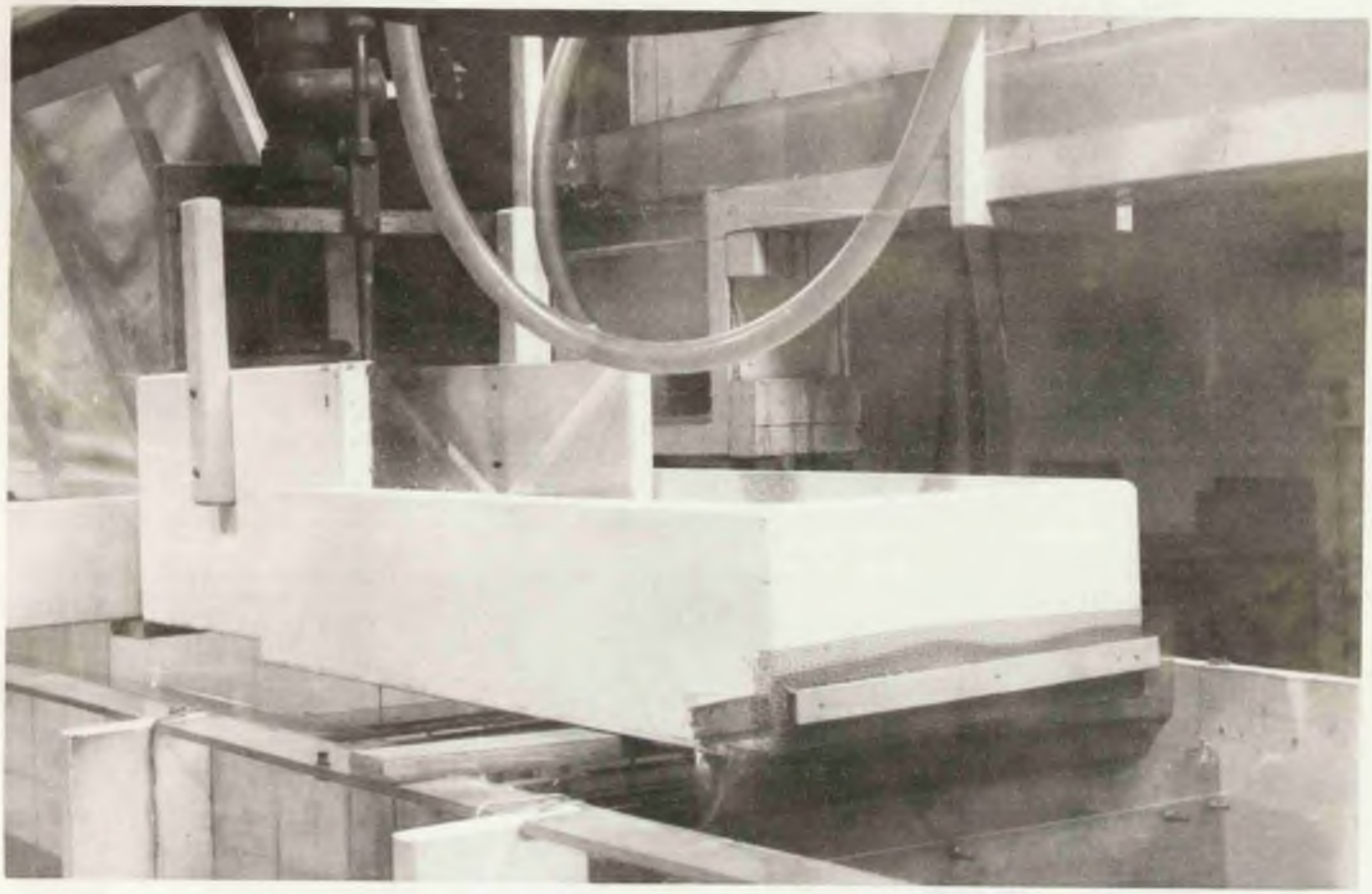


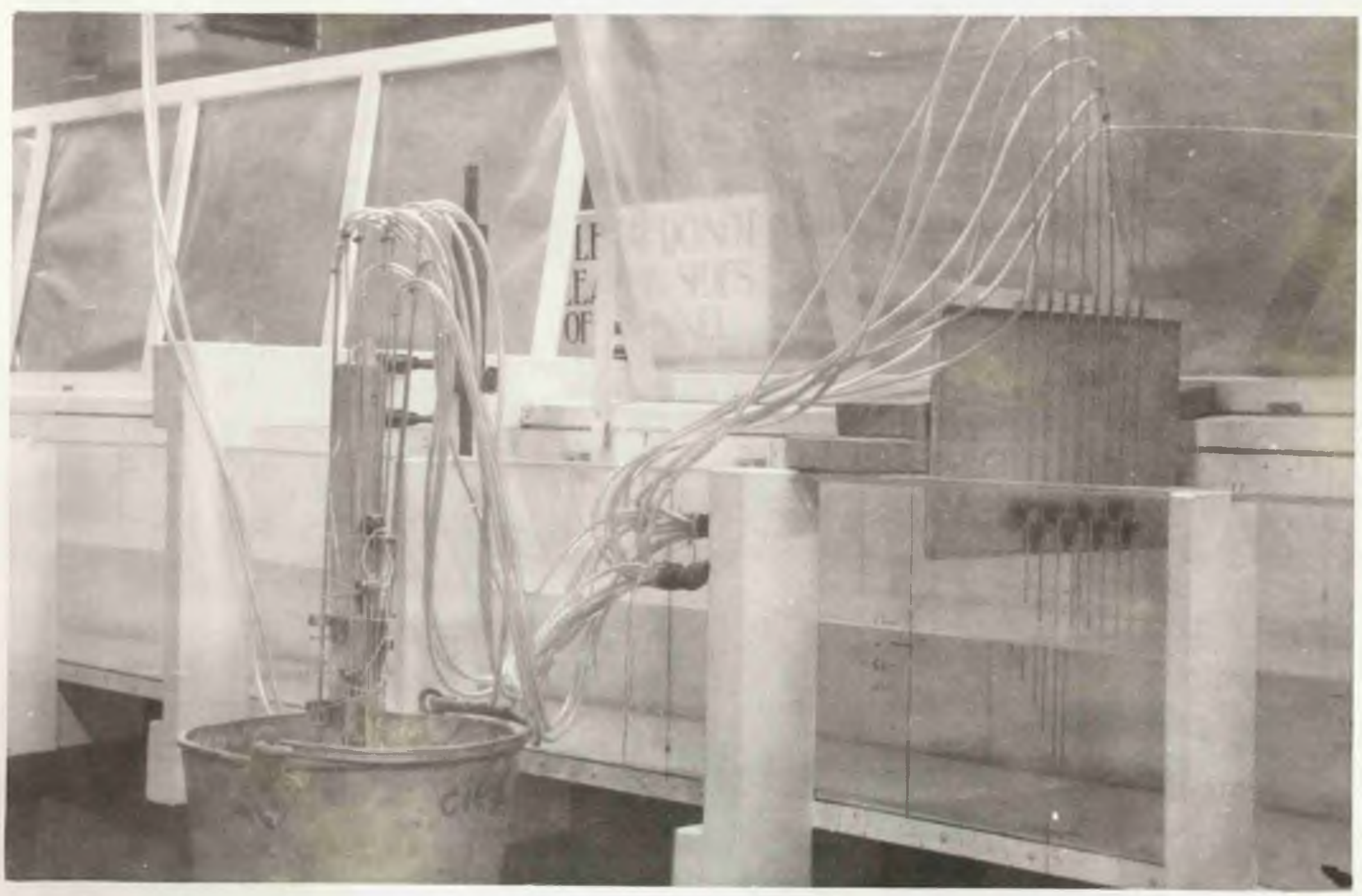
FIG. 8.6 SURFACE FLOAT PLOTS FROM 6 FEET - FLOWS 4.

(IN LARGER FLUME WITH CONFIGURATION A)

FIG. 8.7 UPPER FLOW V-NOTCH BOX

FIG. 8.8 PROBES WITH TRAVELLER AND BUCKET





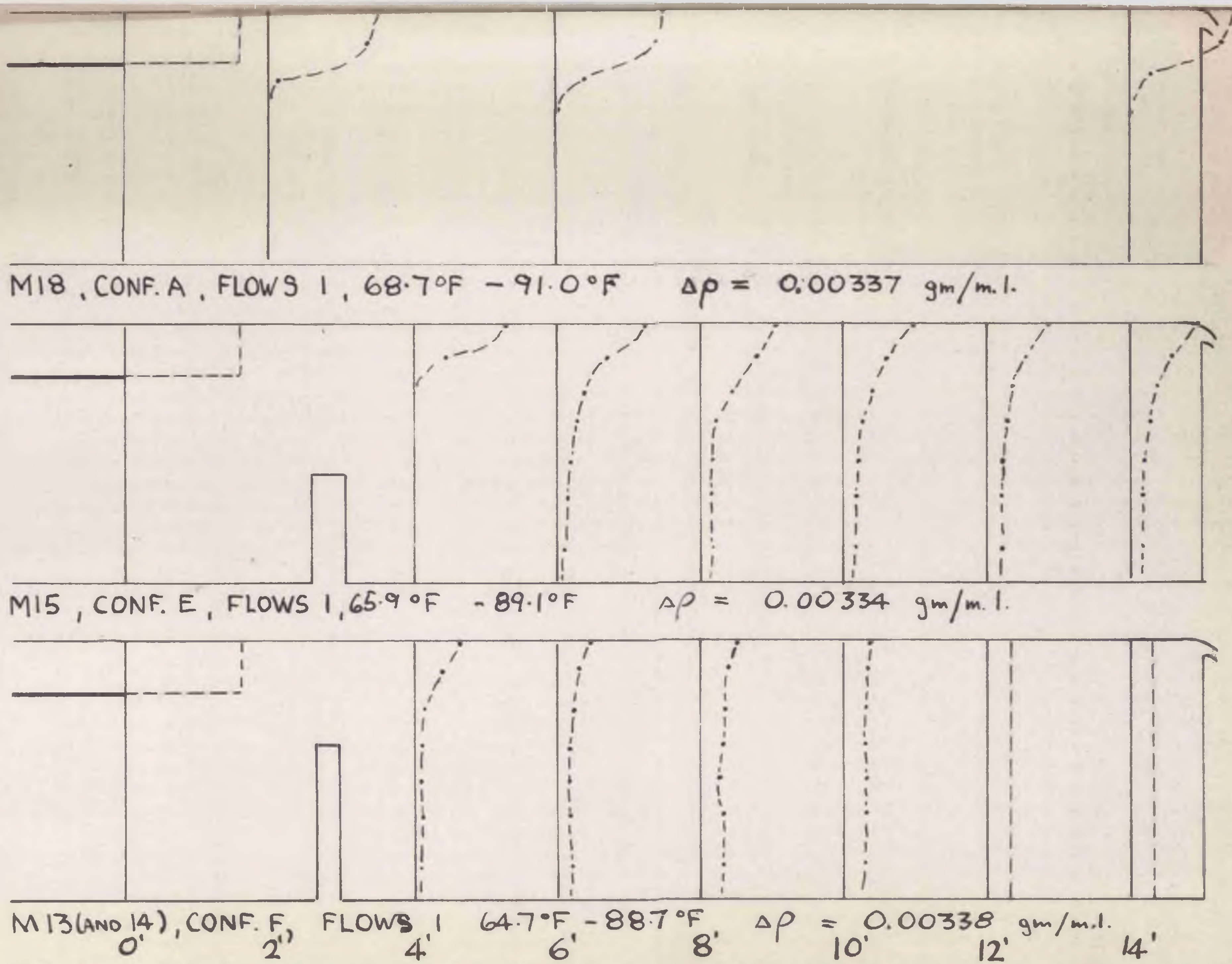
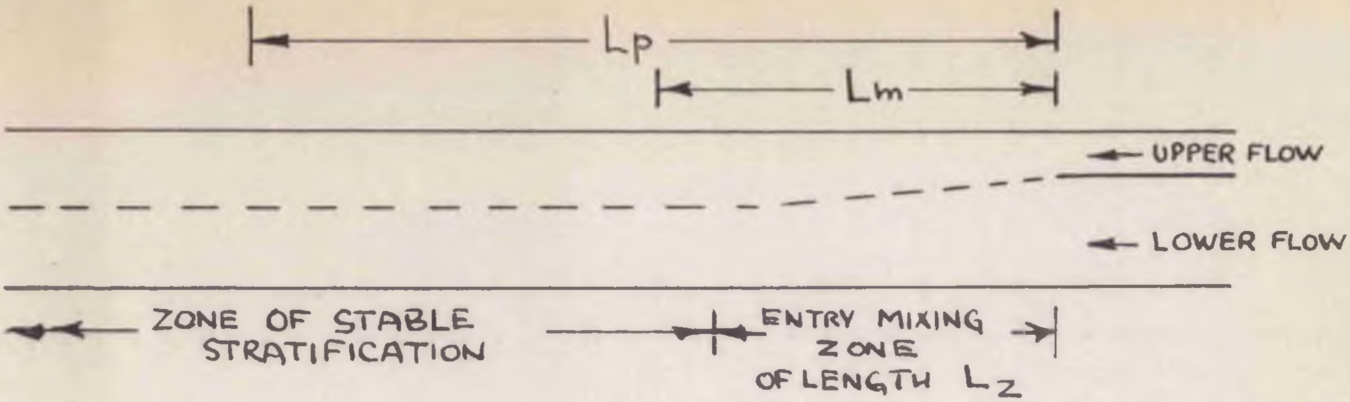
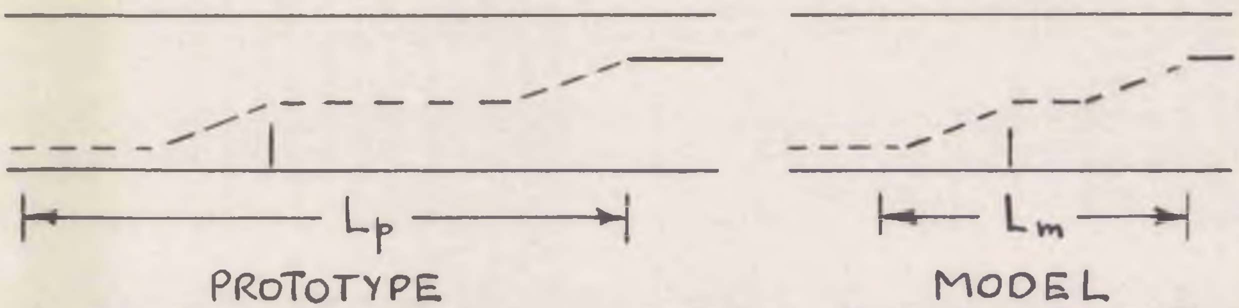


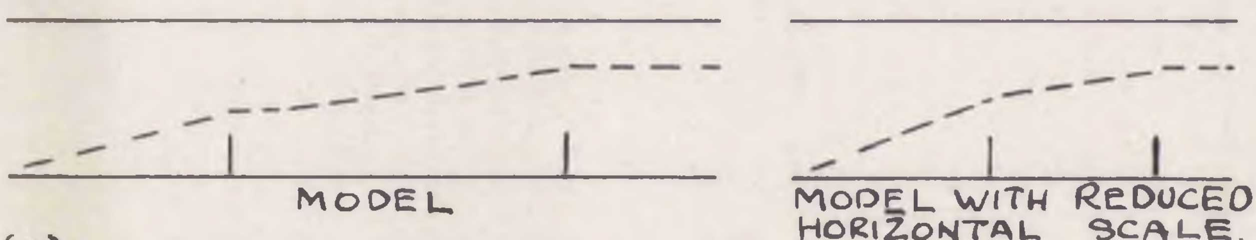
FIG. 8.9 MIXING IN LARGER FLUME WITH FLOWS 1 AND $\Delta\rho \doteq 0.00336$ GM./M.L.



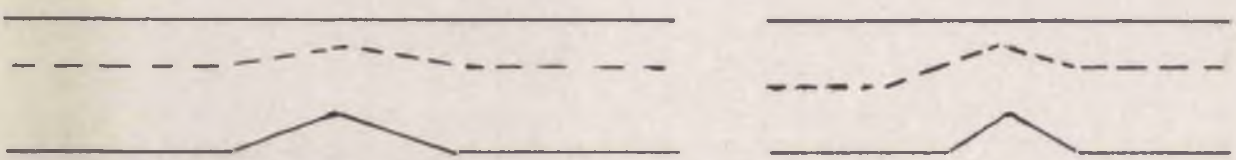
(a) FOR EXAGGERATION OF (SAY) 2 CONDITIONS AT L_m ($<L_z$) MAY SUFFICIENTLY REPRESENT CONDITIONS AT L_p



(b) CONDITIONS AT L_m MAY STILL SUFFICIENTLY REPRESENT THOSE AT L_p



(c) EFFECT OF MERGING OF MIXING ZONES WHERE OBSTACLES ARE DEFINITE MAY CAUSE VARIATIONS BETWEEN RESULTS FROM MODELS WITH DIFFERING HORIZONTAL SCALES.



(d) 'VENTURI' RECOVERY MAY BE ALTERED BY CHANGES OF SLOPE RESULTING FROM CHOICE OF HORIZONTAL SCALE.

G. 8.10 DIAGRAMATIC ILLUSTRATION OF EFFECT OF VERTICAL EXAGGERATION ON MIXING.

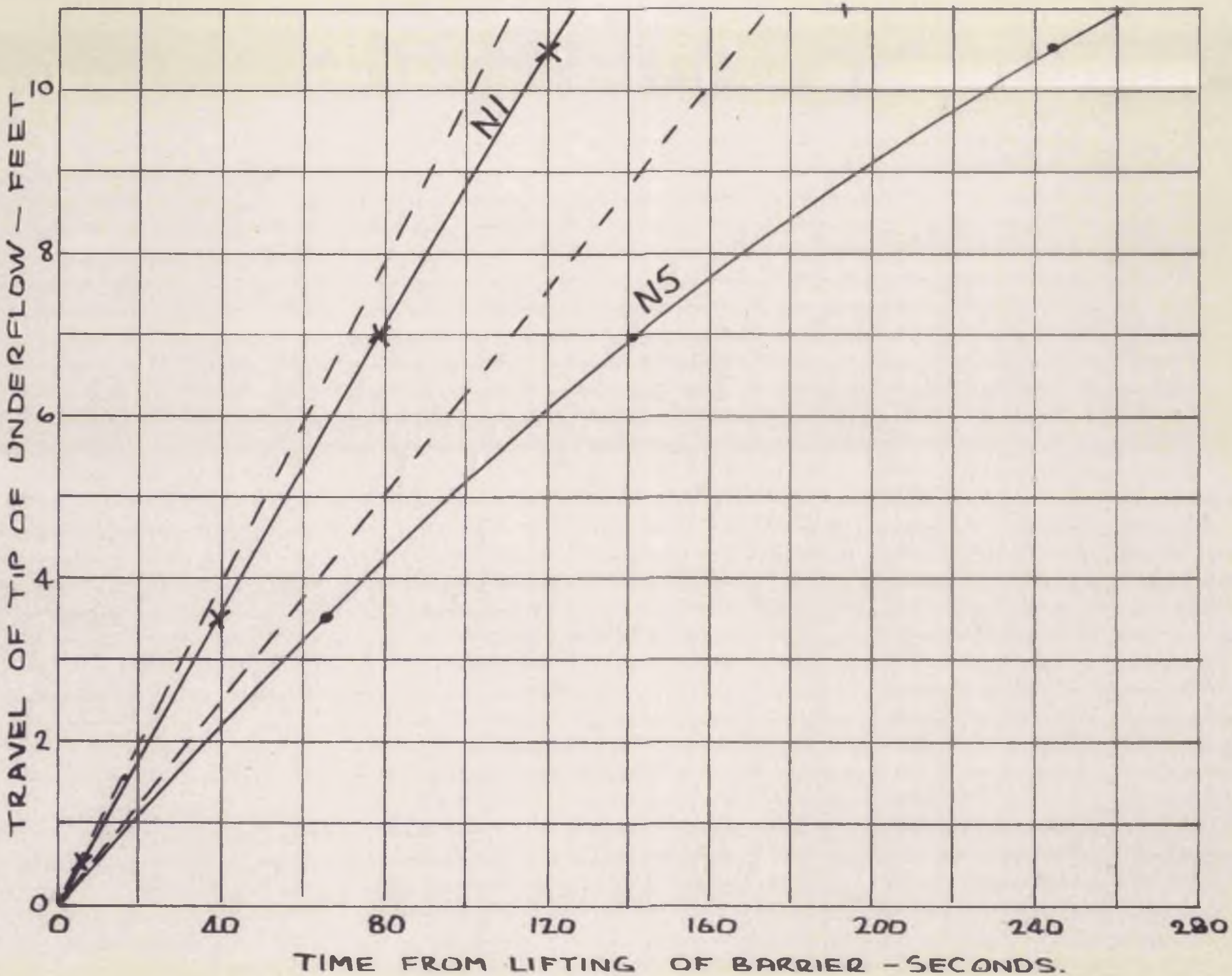


FIG. 9.1 PROGRESS OF UNDERFLOW FRONTS.

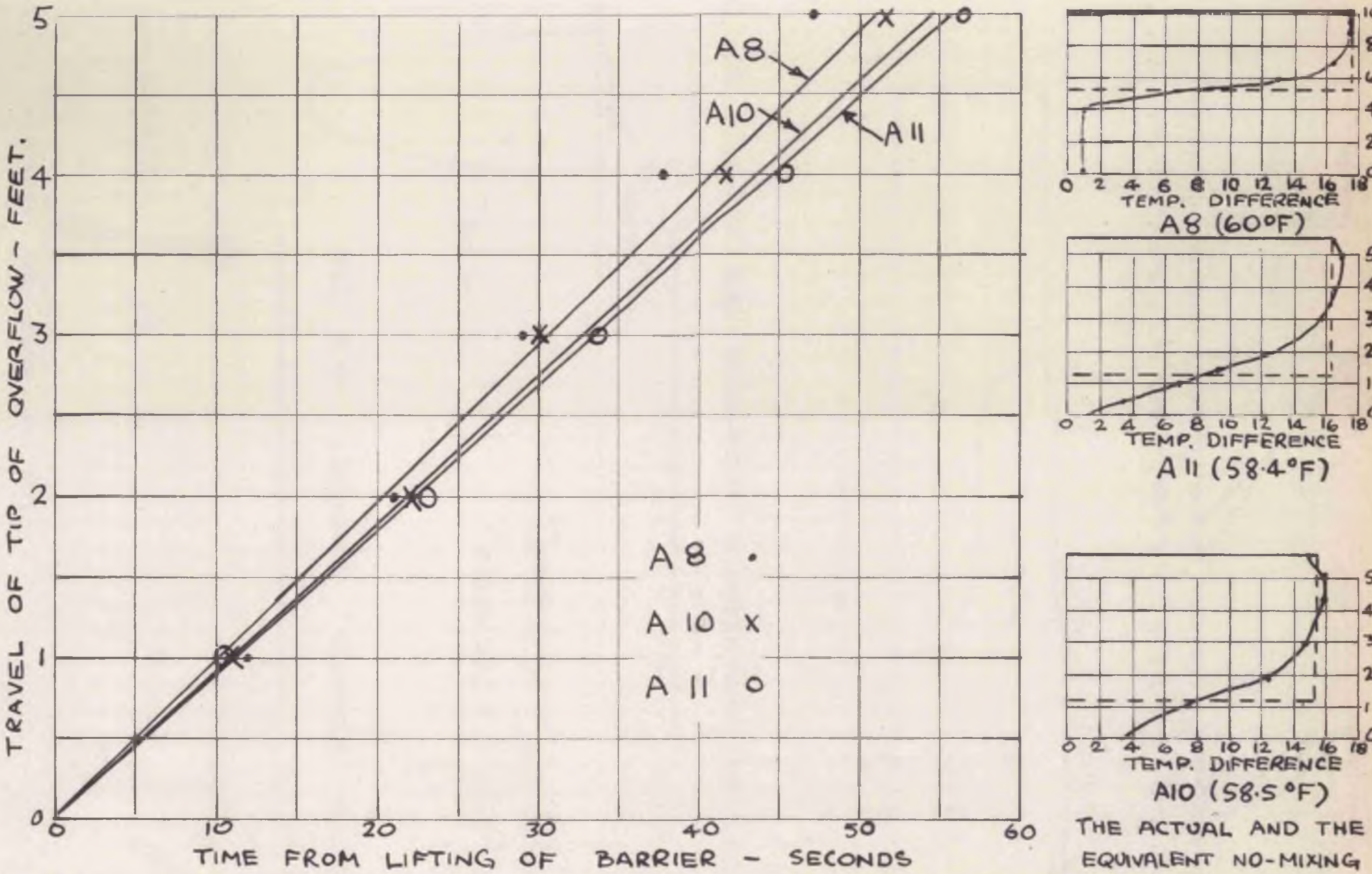


FIG. 9.2 VERTICALLY MODIFIED LOCK CASE - TEST RESULTS.

THE ACTUAL AND THE EQUIVALENT NO-MIXING PROFILES ARE SHOWN ABOVE, WITH THE BASIC TEMPERATURES GIVEN AFTER THE TEST Nos.

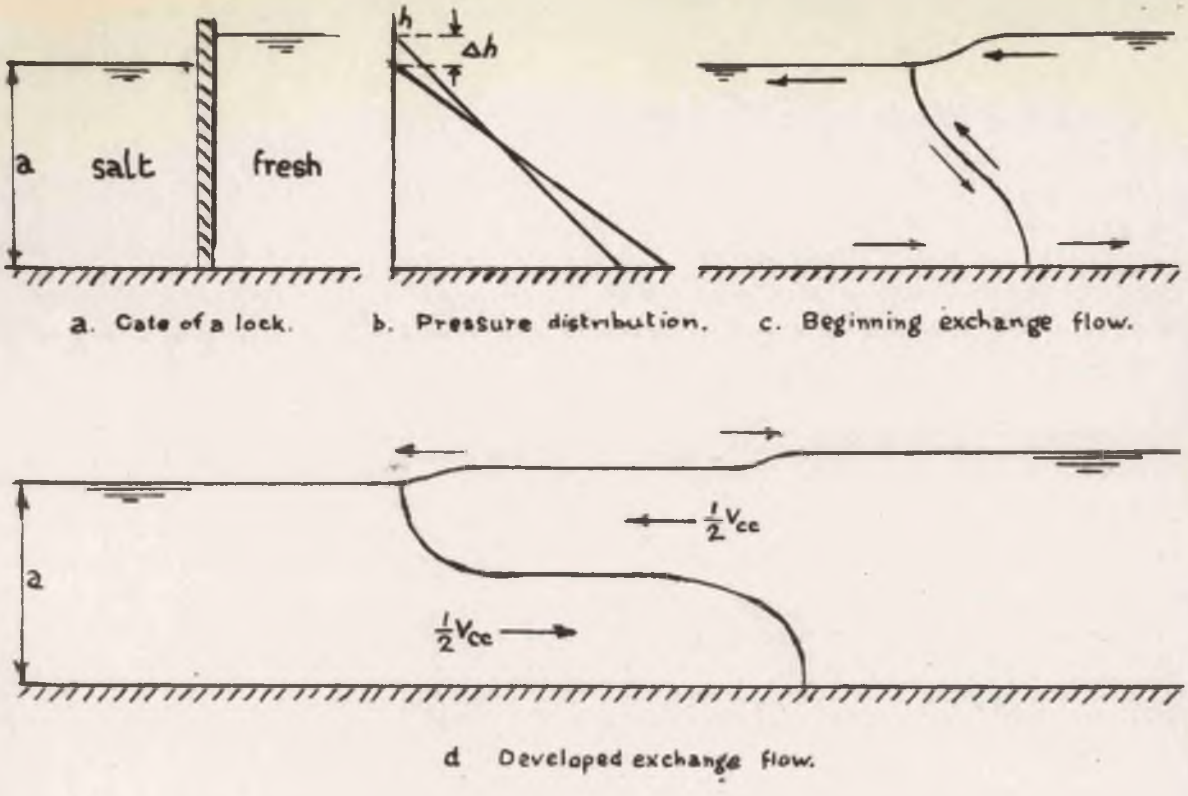
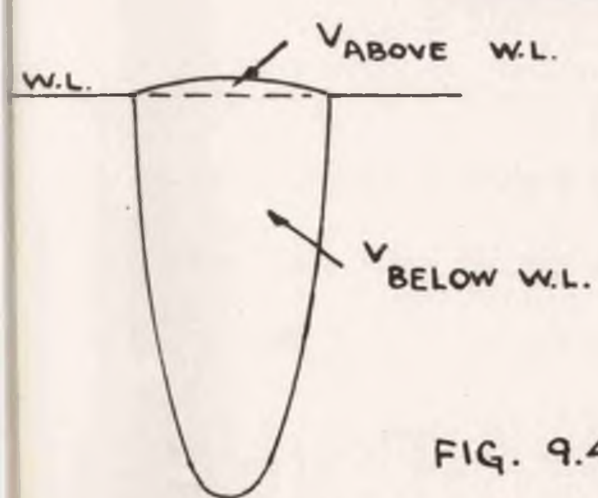
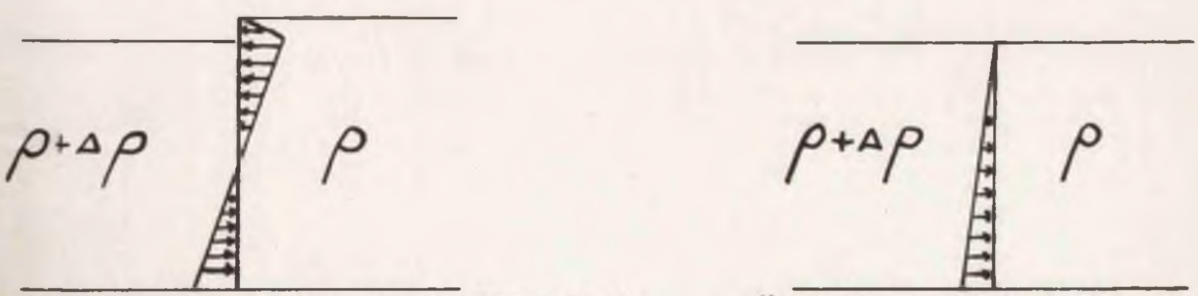


FIG. 9.3 SCHIJF AND SCHONFELD ILLUSTRATIONS OF LOCK CASE.



$$\frac{V_{ABOVE\ W.L}}{V_{BELOW\ W.L.}} = \frac{\Delta\rho}{\rho}$$

FIG. 9.4 LINDERS GLOBULE ILLUSTRATION

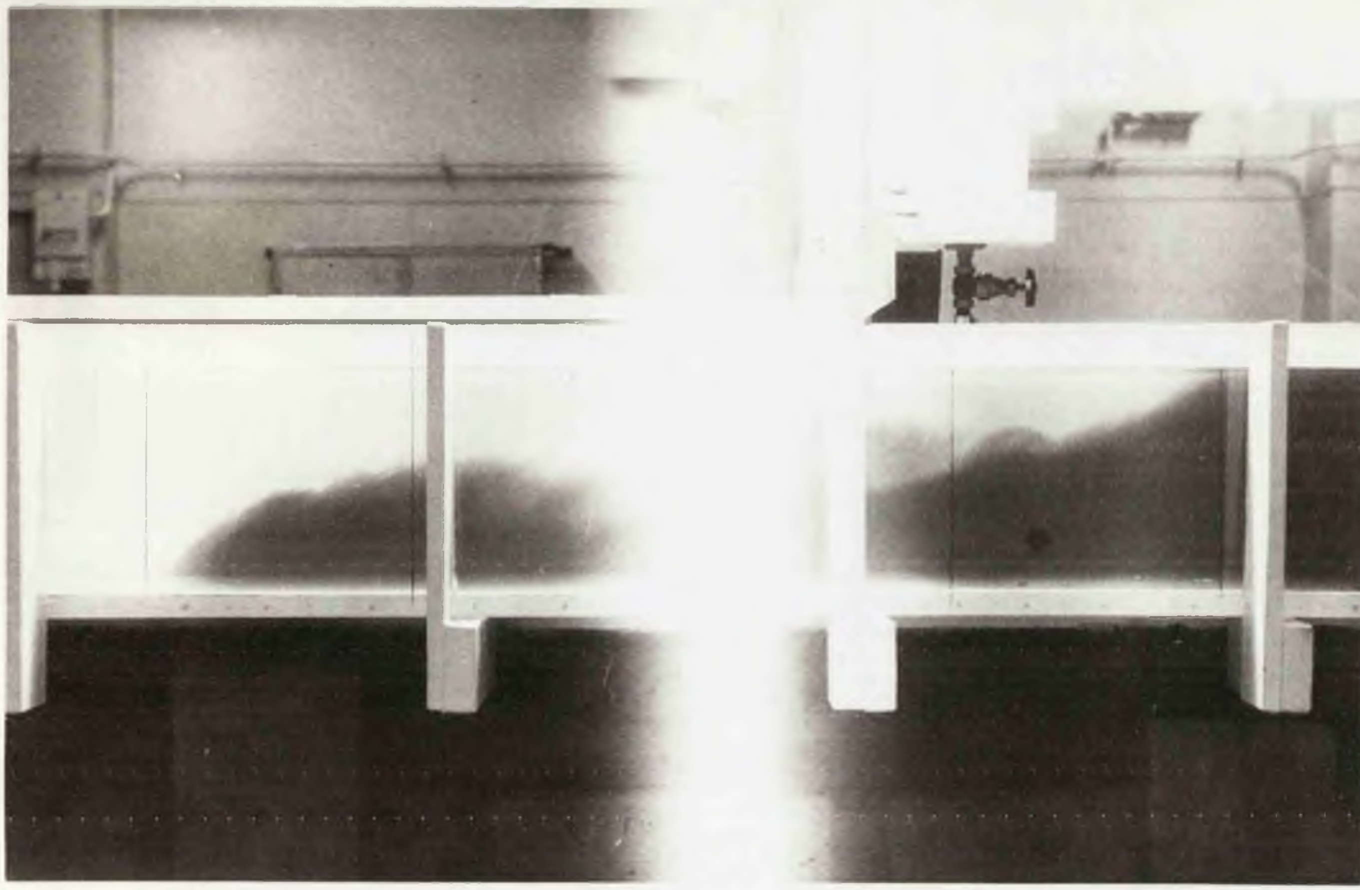


(a) NETT PRESSURE DIST. FROM FIG. 9.3b (b) NETT PRESSURE WITH LEVEL SURFACES.

FIG 9.5 PRESSURE DISTRIBUTION ON BARRIER PRIOR TO LOCK FLOWS.

FIG. 9.6 DEVELOPMENT OF LOCK FLOW - 1

FIG. 9.7 DEVELOPMENT OF LOCK FLOW - 2
(SAME TEST AS 1)



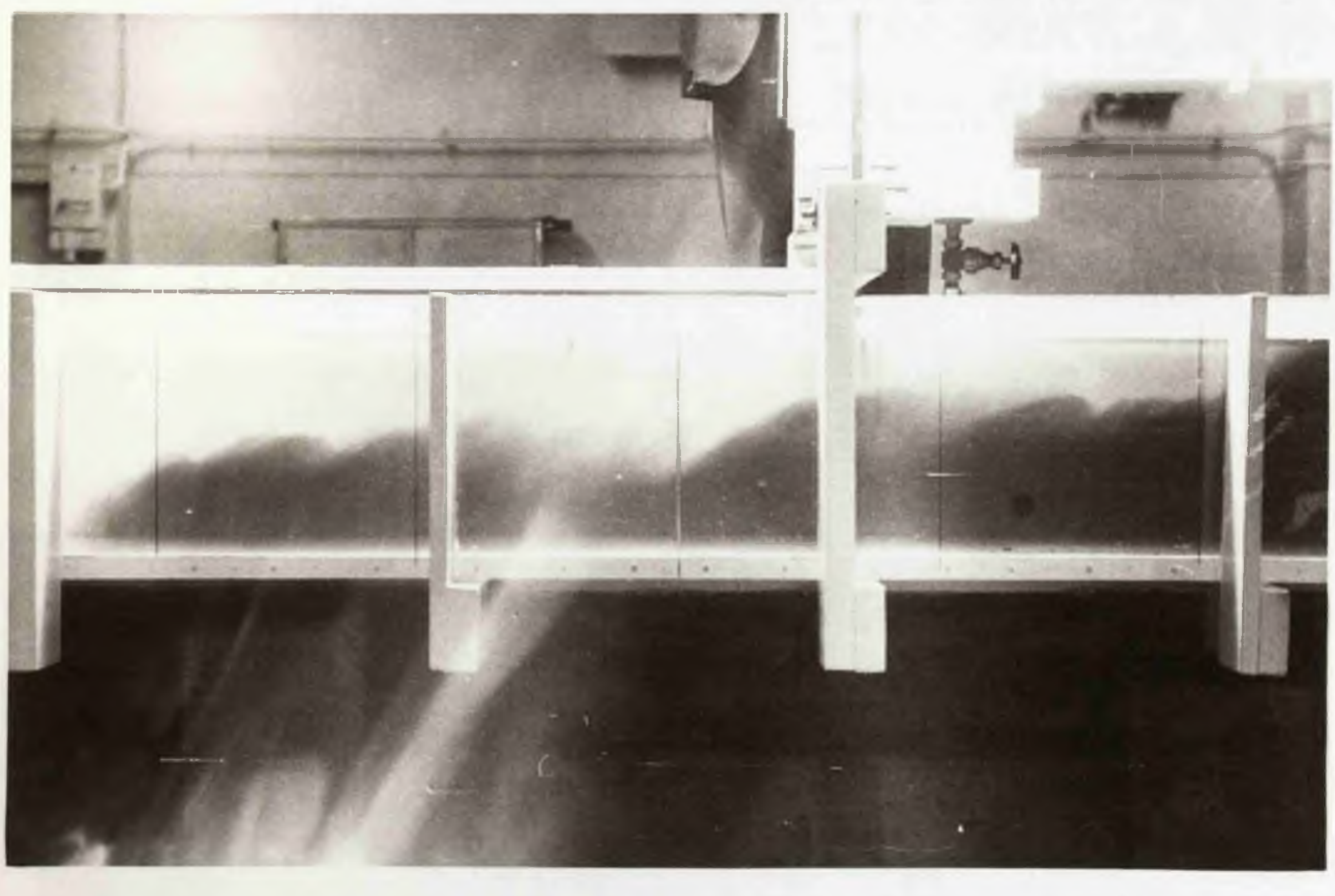
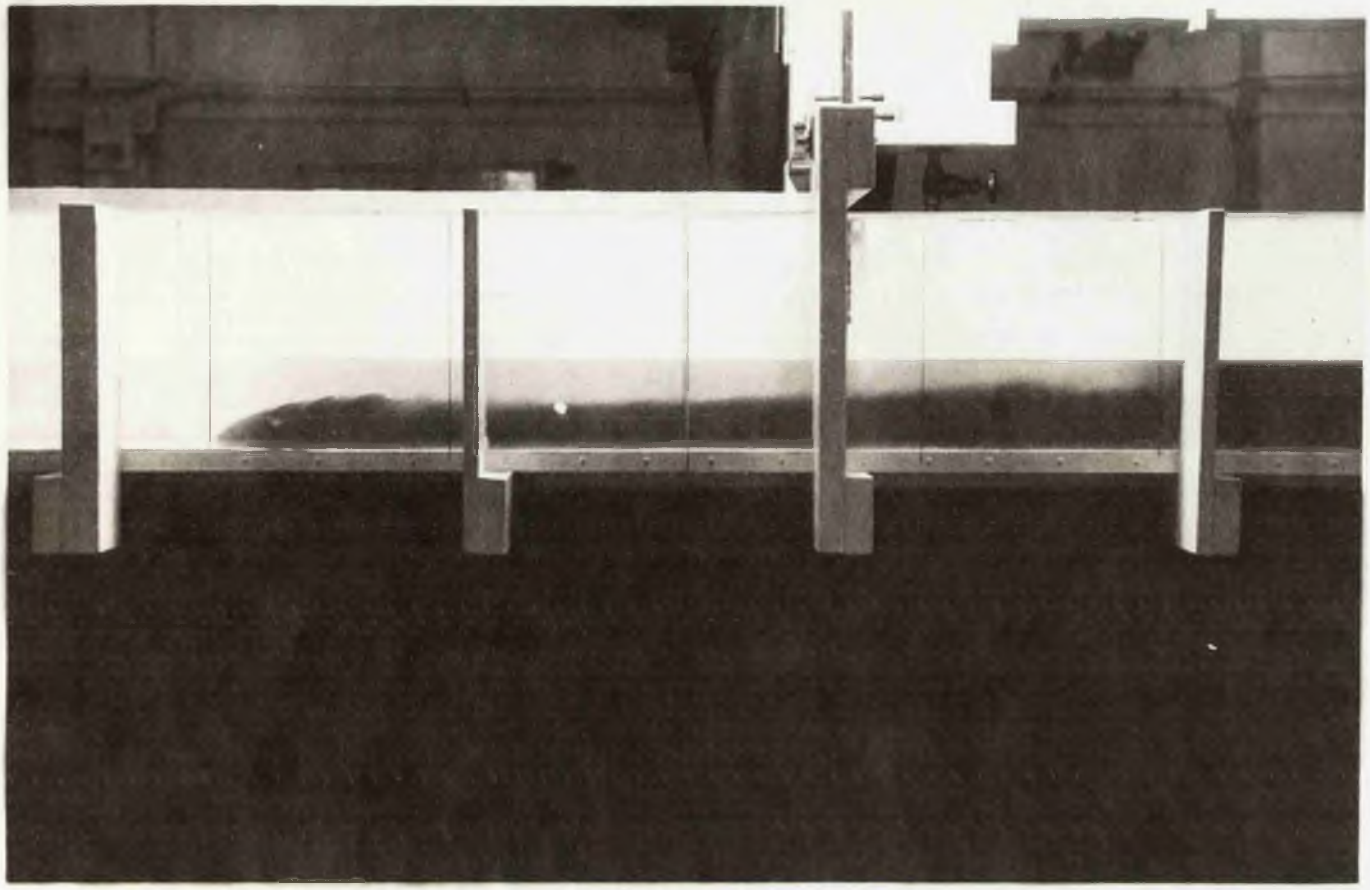


FIG. 9.8 DEVELOPMENT OF LOCK FLOW - 3



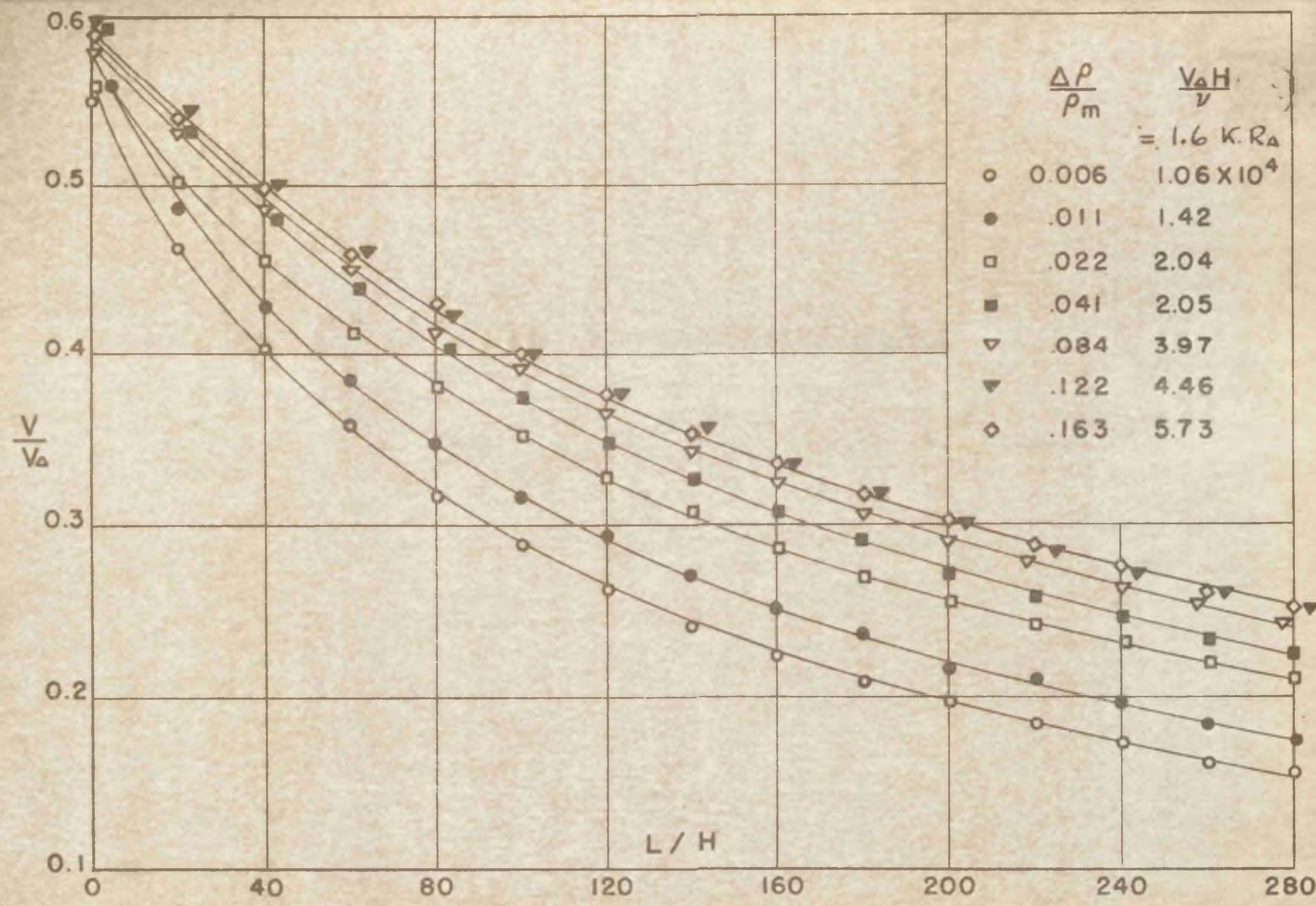
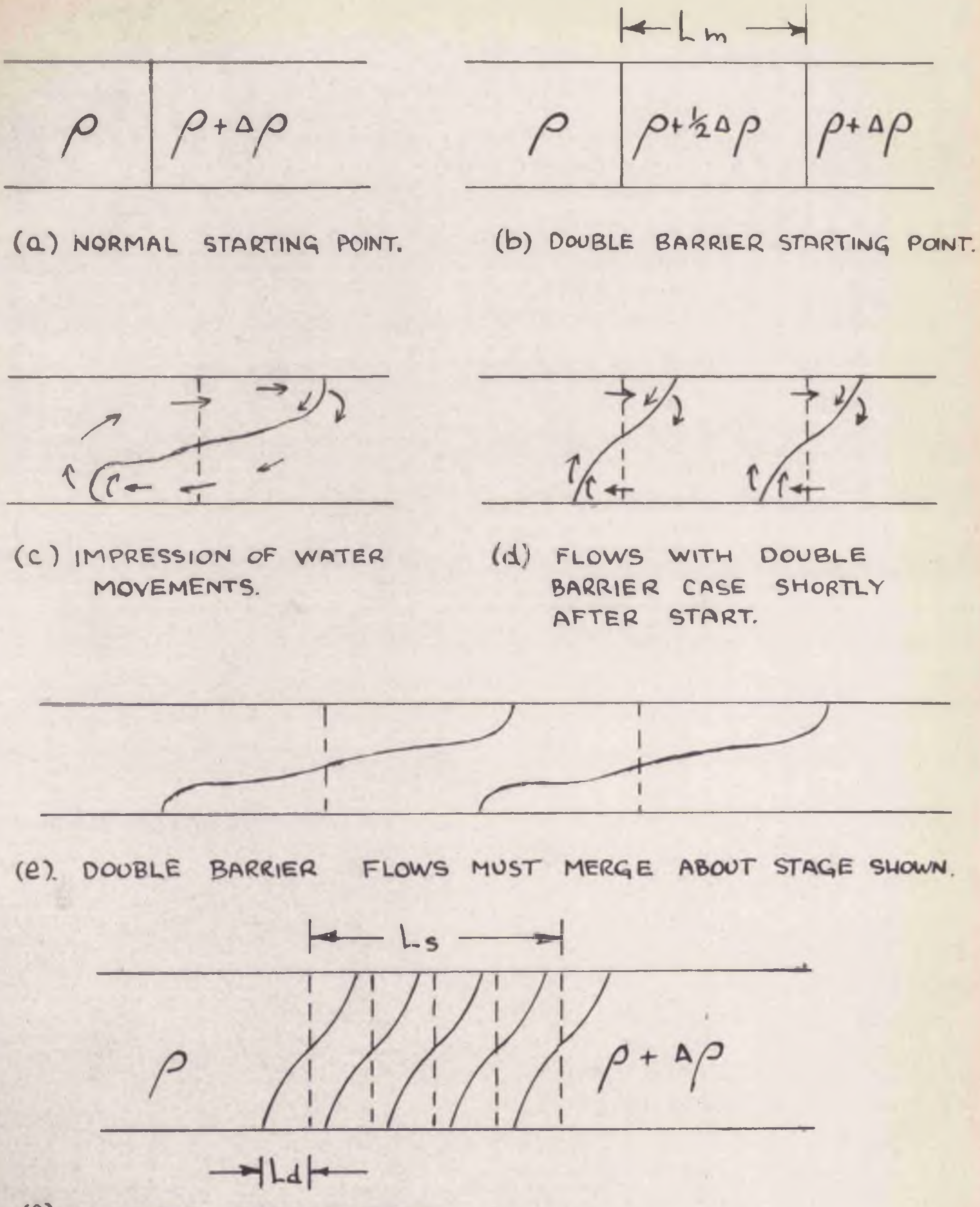


FIG. 24 VELOCITY OF SALINE FRONTS. SMOOTHED VALUES. CHANNEL H=11.2, B=11.3 cm

FIG 9.9 KEULEGAN'S RESULTS FOR CHANNEL AND SEA EXPTS.



(a) NORMAL STARTING POINT.

(b) DOUBLE BARRIER STARTING POINT.

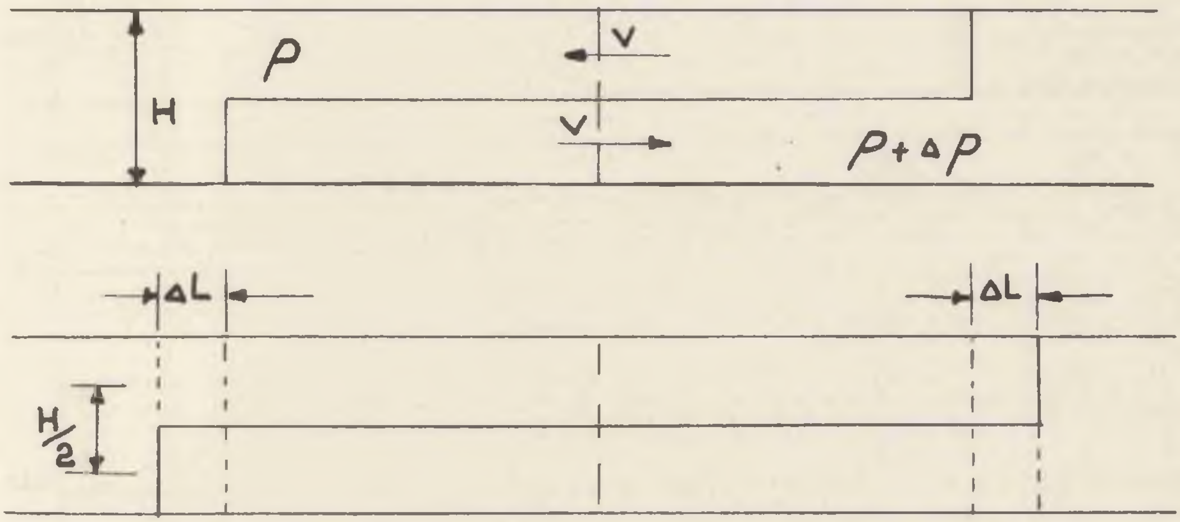
(c) IMPRESSION OF WATER MOVEMENTS.

(d) FLOWS WITH DOUBLE BARRIER CASE SHORTLY AFTER START.

(e). DOUBLE BARRIER FLOWS MUST MERGE ABOUT STAGE SHOWN.

(f) MULTIPLE BARRIER CASE.

FIG. 10.1 ILLUSTRATIONS OF HORIZONTALLY MODIFIED LOCK CASE.



$$\Delta L \times \frac{H}{2} \times \frac{H}{2} \times \Delta \rho = \Delta L \times H \times \rho \times V^2$$

$$V = .5 \sqrt{\left(\frac{\Delta \rho}{\rho} \cdot g \cdot H\right)}$$

FIG. 10.2 ILLUSTRATION OF INCREMENTAL ASSUMPTION FOR LOCK FLOWS.

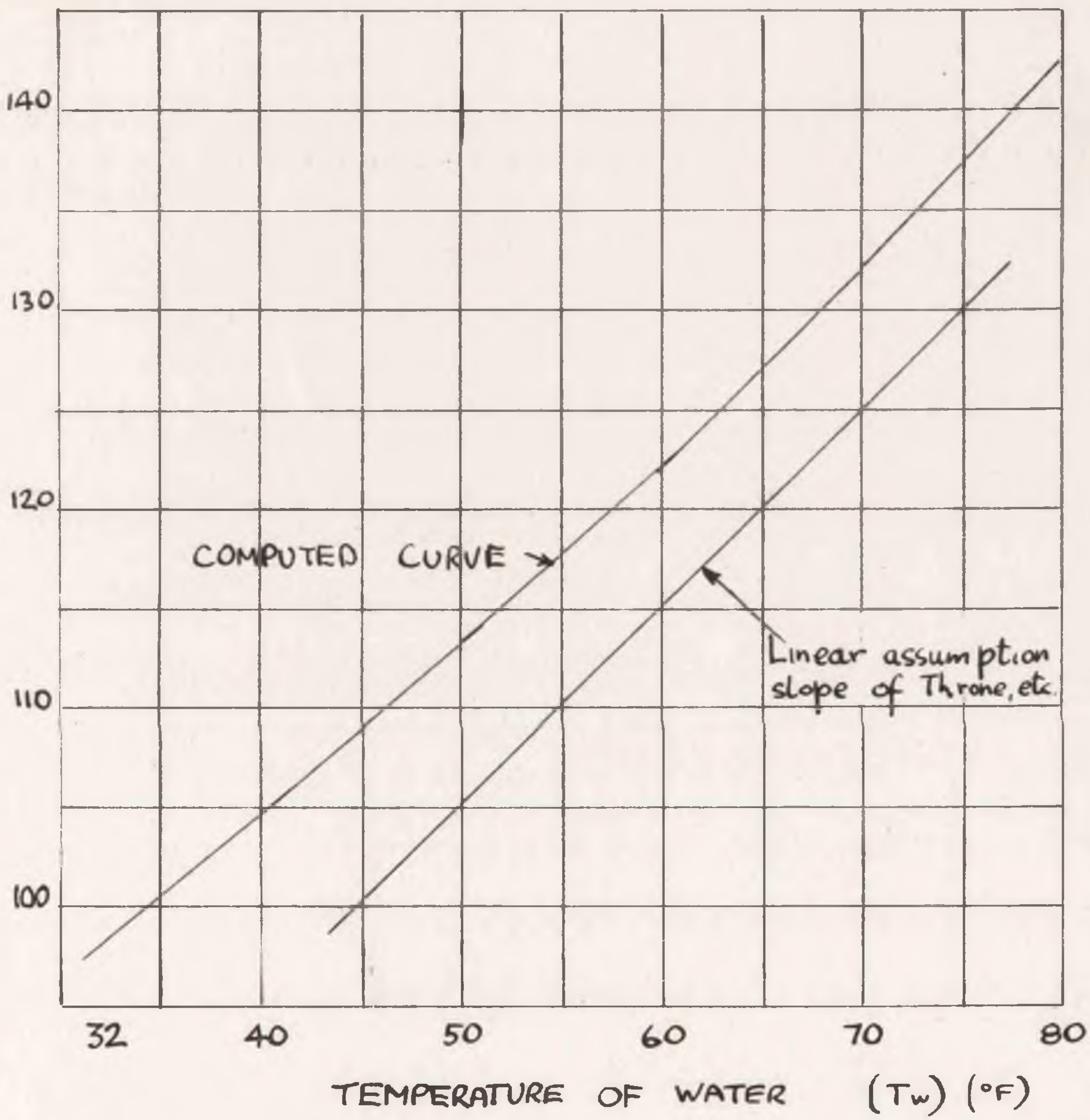
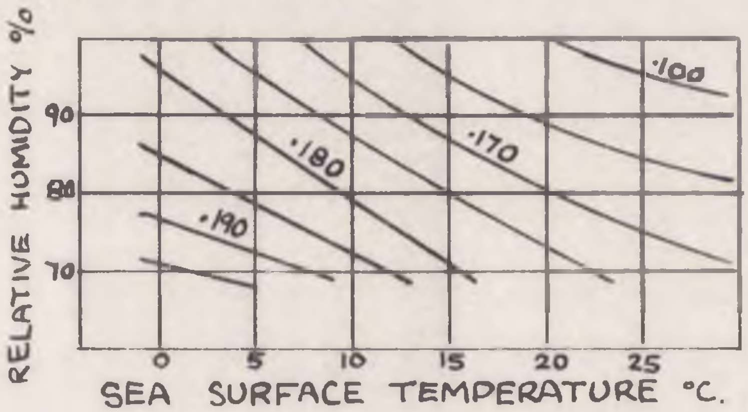


FIG 11.1 BLACK BODY RADIATION
COMPARISON OF VALUES



EFFECTIVE BACK RADIATION IN GM CAL/CM²/MIN. FROM THE SEA SURFACE TO A CLEAR SKY. REPRESENTED AS A FUNTION OF SEA-SURFACE TEMPERATURE AND RELATIVE HUMIDITY OF THE AIR AT A HEIGHT OF A FEW METERS.

FIG. 11.2 EFFECTIVE BACK RADIATION – AFTER SVERDRUP, MARTIN AND FLEMING.

Run No	Depth of Water Trapped In.	Basic. Temp. °F	Temp. Increase at 6.0 ft. O.D. °F	Period of Comparison: Start: Time Min.	Start: Temp of Trapped Water °F	Finish: Time Min.	Finish: Temp. of Trapped Water °F	Deduct for glass BTU/sq ft./hr.	Experimental Loss BTU/sq ft/hr.	Average Air Temp. Dry °F	Average Air Temp. Wet °F	Average Temp of Pools °F	Est. Wind Vel Ft/Sec	Assumed Natural Temp. °F	Thrones Formula Loss BTU/SqFt/Hr	New Formula Loss BTU/SqFt/Hr
128	5/8	–	15	18	57·7	24	56·3	1·0	44·5	47	41·5	–	1	41·5	47	44·5
130	7/16	46·3	15	18	53·55	22	52·5	1·0	35·0	445	39·5	400	1	400	385	365
136	1/2	51·3	30	20	65·1	26	61·7	3·5	90·0	49	42·5	42·0	1	42·0	67	71·5
137	13/24	–	15	12	45·9	18	45·3	1·5	15·0	44	39·5	38·6	1/3	39·5	15	
138	3/8	–	30	5	56·75	8	54·85	4·5	72·5	44·5	41	38·6	1/2	400	45	49·5
139	1/2	-	Max.	10	61·0	20	56·3	3·5	70·0	46	43	39·0	1/2	41·0	47	48·5
139	1/2	–	-	30	53·85	40	52·05	1·5	26·5	45	41·5	39·2	1/2	40·5	35	33·5
140	Thermos Jar		-	10·45 (Hr + Min)	93·2	11·05 (Hr + Min)	92·0	–	166	68·5	59	-	1/3	59·0	137	157

FIG. 11.3. DETAILS OF KINCARDINE MODEL HEAT LOSS EXPERIMENTS.

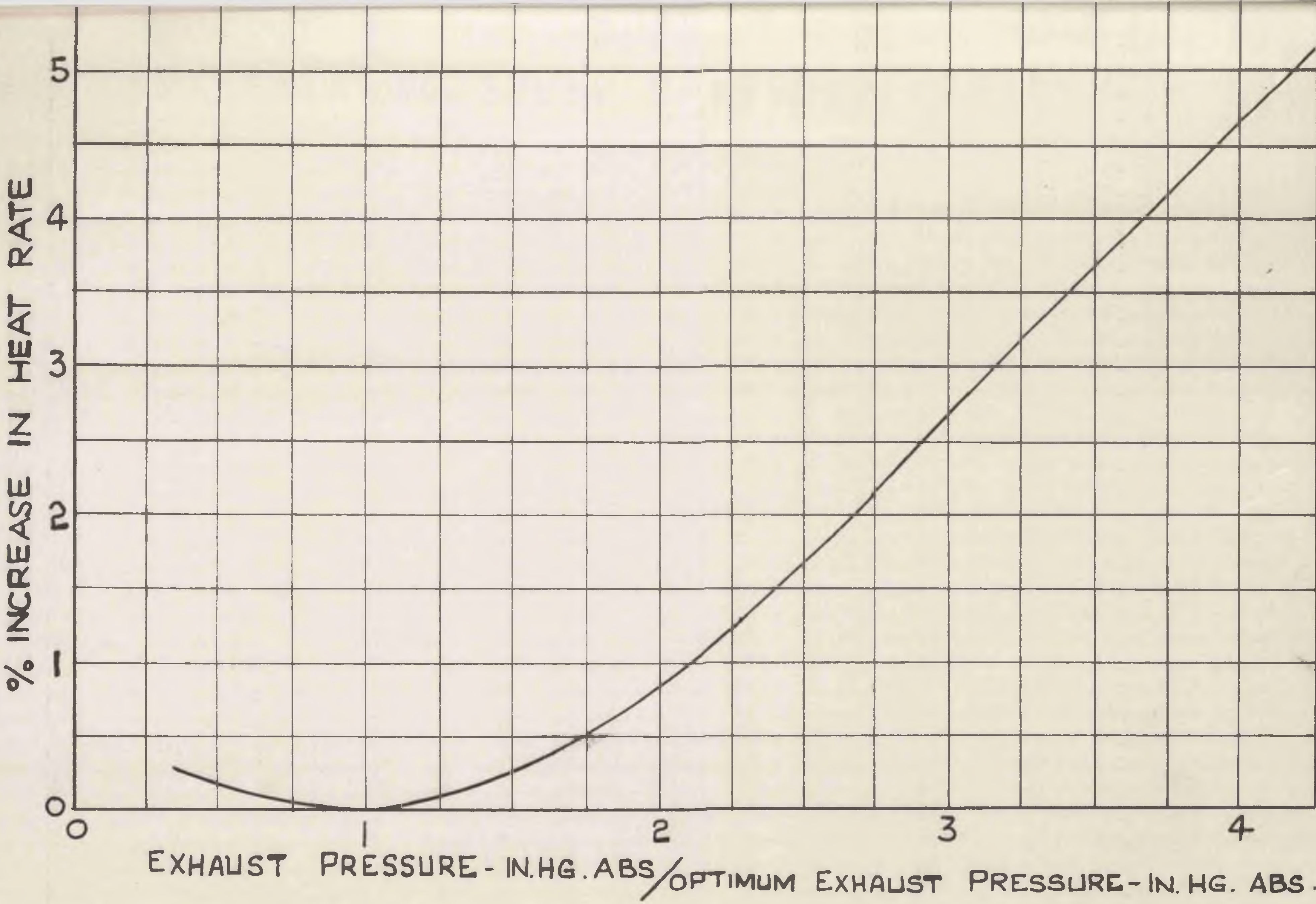


FIG. 121 PART OF KELLER AND DOWNS CURVE.

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TABLE 12·2 LAST STAGE DETAILS FOR BRITISH TURBINE DESIGNS.

NO	MAN-FAC.	RATED CAP. MW	STEAM CONDITIONS: INIT PRESS lb/□"	STEAM CONDITIONS: TEMP INIT. °F.	STEAM CONDITIONS: TEMP RE HEAT °F	BLADE LENGTH ON BASE DIAM IN.	BLADE QUOTIENT	LAST STAGE ANNULUS SQ FT.	NO. OF FLOWS	TOTAL LAST STAGE AREA SQ. FT.	AREA. M.W. SQ. FT.	REL. AREA TO 70' fo 60MW.	RATED EX. PRESS IN Hg	K+D OPTM. EX Pr IN Hg abs	EXHAUST HEAT LOADING BTU/sec/ft²
1	M.V.	30	600	850	–								29·0		
2		30	900	900	–		App 1·2						29·0		
3		60	900	900	–	B			3				28·9		
4		60	900	900	–		App 1·2	35·2	2	70·4	1·17	1	28·9	0·66	1600
5		100	1500	1050	–	B			2				28·9		
6		120	1500	1000	1000	B		50 Equiv.	2	100	0·833	·93	28·9	0·72	1725
7		200	2350	1050	1000	B			3				28·9		
10	GEC.	30	600	850	–	20/275	1.38	32·7	1	32·7	1·09		28·7	0·77	
11		60	900	900	–	20/275	1.38	32·7	2	65·4	1·09		28·7	0·71	1720
12		120	1500	1000	1000	27/275	′	48·3	2	96·6	0·803		28·9	0·75	1790
13		200	2365	1050	1000	30/30	′	59·0	3	177·0	0·885	1·07	28·7	0·62	1500
14		200	2350	1050	1000	27/275	′	48·3	4	193·3.	0·968	1·17		0·57	1375
15		60	900	950	–										
17	R-W	60	1350	950	–	15·75/23·7	1·5	21·7	4	86·8	1·445		29·1		
19	EE.	30													
20		60	900	900	–			29·8	2	59·6	0·992			0·78	1890
21		60	1500	1050	–				2	[59·6]	0·992		28·75	0·68	1655
22		120													
23		200	2350	1050	1000	27/26	·97	44·3	3	133	0·665	0·80	28·7	0·83	2000
24		275	2300	1050	1050	36/32	·89	78·5	4	314	1·14	1·41	29·0	0·47	1150
25		100	1500	1050	–				2						
26		350								[314]	0·818				
27	PARSONS	60	900	900	–		1·25	35·0	2	70	1·165	1	28·9	0·67	1610
28		100	1500	1050	–				3				28·9		
29		120	1500	1000	1000				3	105	0·875	·97	28·9	0·69	
30		125	1425	1000	1000		1·2		4						
31		200					1·1		3						
32		100	1500	975	955										
34	BTH.	60	900	900					2	71·7	1·19	1	29·0	0·65	1570
		120	1500	1000	1000				3	115·1	0·96		29·0	0·62	1500
		200	2350	1050	1000		1·25		3	153·9	0·77		29·0	0·72	1730

NB 'B' IN BLADE LENGTH COLUMN INDICATES BAUMAN MULTIPLE EXHAUST. FIGURES IN FRAMES ARE INFERRED RATHER THAN BASED ON PUBLISHED DETAILS OR FROM OTHER RELIABLE SOURCE.

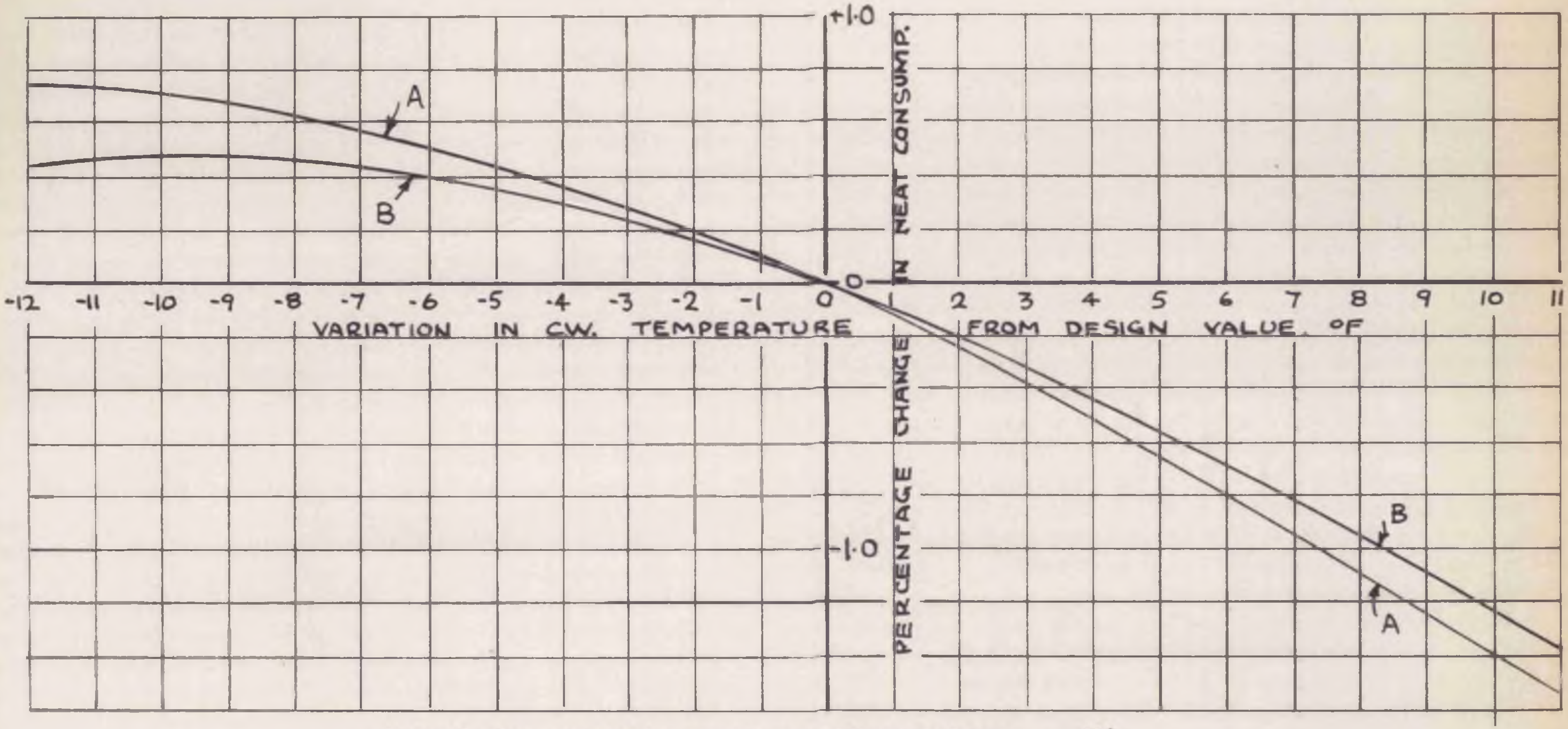
TABLE 12.3 - CENTRAL ELECTRICITY GENERATING BOARD STANDARD STEAM CYCLES [12, 13-14]

1	STOP VALVE PRESSURE (lb/sq. in gauge)	A	B	C	D	E	F	G	
		600	900	1500	1500	2350	2300	2300	
2	STOP VALVE TEMP. °F	850	900	1050	1000	1050	1050	1050	
3	REHEAT TEMP °F	–	–	–	1000	1000	1050	1050	
4	VACUUM in. Hg	28.9	28.9	28·9	28·9	28·9	28·9	28·9	
5	FINAL FEEDWATER TEMPERATURE °F	330	385	400	435	460	486	486	
6	No. OF FEED HEATING STAGES	4	5	6	6	7	7	7	
7	RELATIVE AVAILABLE HEAT DROP.	100	102·9	117·5	126·3	131·4	129·8	129·8	
8	RELATIVE STEAM TO STOP VALVE PER MW.	100	96·6	85·9	77·3	75·1	74·8	74·1	
9	STEAM TO STOP VALVE lb/KWH	8·64	8·35	7·42	6·68	6·48	6·45	6·40	
10	STEAM TO CONDENSER REL. TO STEAM TO STOP VALVE	78·0	73·7	72·7	70·7	67·4	66·5	66·5	
11	RELATIVE STEAM TO CONDENSER.	100	91·2	79·7	70·7	64·8	63·7	63·1	
12	STEAM TO CONDENSER lb/KWH	6·65	6·15	5·39	4·73	4·36	4·28	4·25	
13	HEAT TO CONDENSER BTU/SEC / MW ASSUMING DRY STEAM	2030	1870	1640	1440	1330	1310	1300	
14	RELATIVE SPECIFIC VOL. AT 28·9 IN. HG. -	100	98·7	99·3	105·8	104·6	104·0	104·0	
15	RELATIVE OUTPUT FOR CONSTANT ANNULUS AND CONSTANT LEAVING VEL.	100	111	126	135	148	151	153	
16	RELATIVE OUTPUT FOR CONSTANT ANNULUS AND CONSTANT % LEAVING LOSS	100	116	141	160	183	187	189	
17	APPROX. THERMAL EFFIC. ALLOWING FOR TURBINE AUXS.	34·1	36·5	39·3	40·6	42·9			

THE TABLE IS APPROXIMATE. FIGURES WILL VARY SLIGHTLY WITH LAST STAGE ANNULUS AREA OF THE PARTICULAR TURBINE, WITH THE FINAL FEED WATER TEMPERATURE AND THE REHEAT PRESSURE.

EFFECT OF VARIATION IN COOLING WATER TEMPERATURE ON

HEAT CONSUMPTION OF MODERN STEAM TURBO-GENERATORS



CURVE A:- LEAVING LOSS AT DESIGN POINT ≈ 1%

CURVE B " " " " " ≈ 1½%

FIG. 12.4A PARSONS HEAT RATE - EXHAUST TEMP. CURVES.

COPIED FROM MESSRS. C.A. PARSON'S DRG. Nº M.54·42 (13 FEB. 1959) WHICH WAS STATED THEN TO COVER MOST OF THE LARGE TURBINES DESIGNED BY THE FIRM FOR THE C.E.G.B. OR THE S.S.E.B.

CURVE SHOWN	....	— — —	———
INITIAL PRESS + TEMP. (PSIG + °F)	900 900	1,500 1,000	2,350 1,050
REHEAT TEMP °F	–	1000	1,000
FEED HEATING. °F + No OF HEATERS	385 5	435 6	460 6
RATED VAC. @ TOTAL L.S. ANNULUS (INS.HG + SQFT)	29·0 71·7	29·0 115.1	29.0 153.9
N° OF FLOWS AT LAST STAGE.	2	3	3

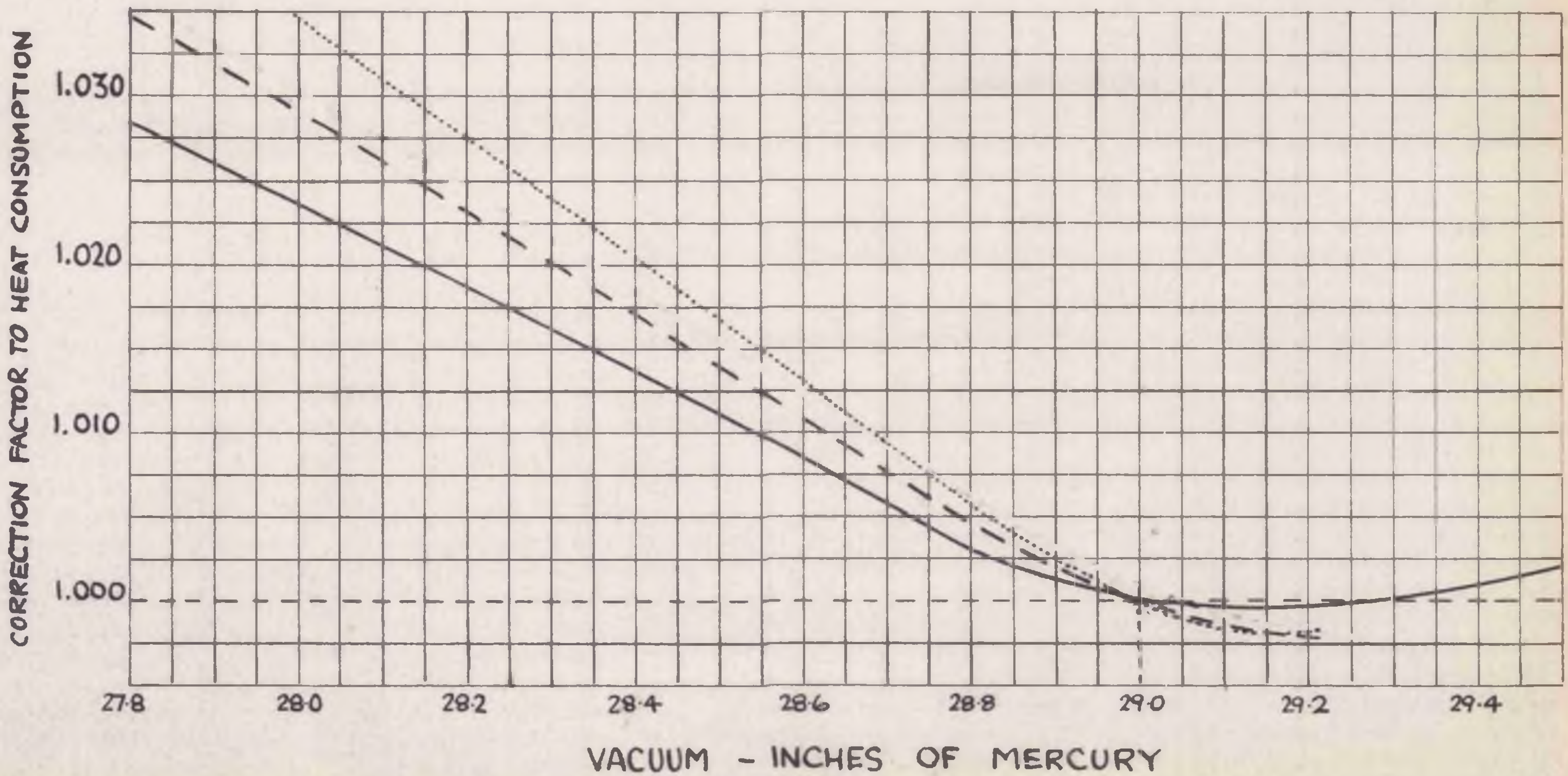


FIG. 12.4B B.T.H. HEAT RATE - EXHAUST TEMPERATURE CURVES.
(FROM B.T.H. DRGS. T.E.C. 5262, 5263, 5264-A.)

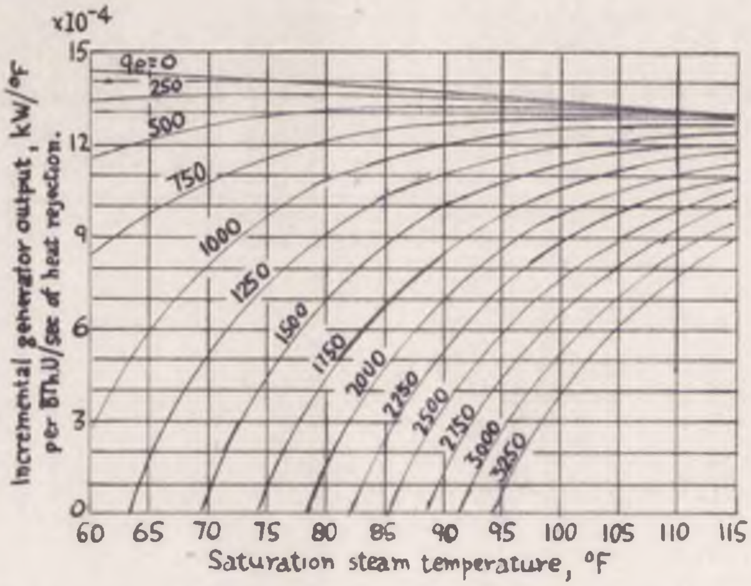


Fig. 3.—Incremental generator output per degree Fahrenheit in condenser steam temperature (based on $\eta_c = 0.7$)

Table 1

TYPICAL EXHAUST HEAT LOADINGS FOR TWIN-FLOW TURBINES

Turbine rating	Exhaust heat loading (q_e)
MW	B.Th.U./sec-ft^2
30	1,100
60	1,500
100	1,900

FIG. 12.5 KENNEDY AND MARGEN HEAT RATE - EXHAUST TEMPERATURE CURVES.

TABLE 12.7 CONDENSER DETAILS AND FULL LOAD DESIGN INCREMENTS FROM PRESENT BRITISH PRACTICE (OBTAINED FROM PUBLISHED DETAILS)

STATION	CLASSIFICATION	RATING OF TURBINES (MW) AND MANUF.	No OF SETS	FULL LOAD C.W. FLOW PER SET (CUSEC.)	INCREMENT °F	CONDENSER AREA/SET (SQ. FT.) AND NO OF PASSES	RATED EXHAUST TEMP AT INTAKE W. TEMP (°F at °F)	P (°F)	$\frac{H}{S \times C^2 \sqrt{\frac{Vt}{S}}}$
CONNAHS QUAY		30 PAR.	6	56	22·5		97·5 at 65	32·5	18
CARMARTHEN BAY	S?	52·5 MV 60 MV	2 4	117·5			79 at 58	21	
HAMS HALL 'C'	T	60 GEC	6	93·7	18·1 17·6	52,000 52,000	97·5 at 74·5 87·3 at 63·5	23 23·8	11
SOUTH DENES	R	60 MV		110·0		50,000 2	82 at 60	22	
FERRYBRIDGE 'B'	C	100 PAR		171·0		75,000	82 at 60	22	
WILLINGTON 'A'	C	100 EE		171·0	15·0 ?	76,000	82 at 60	22	11·5
BLYTH 'A'	S	120 MV		152·0	16·5	70,000	82 at 53	29	18
KINCARDINE	E	120 PAR.	3	160·0	15·8	70,000 2	82 at 55	27	17
HIGH MARNHAM	T	200 EE				2	87·2 at 60	27·2	
BLYTH 'B'	S	275 EE	2	294	17·5	165,000	79 at 52	27	14·5
THORPE MARSH	T	550 PAR				330,000			

THE GENERAL CLASSIFICATION OF THE COOLING WATER SYSTEM IS INDICATED THUS. (R) RIVER, (T) TOWER (C) COMBINED, (S) SEA (E) ESTUARY (L) LAKE

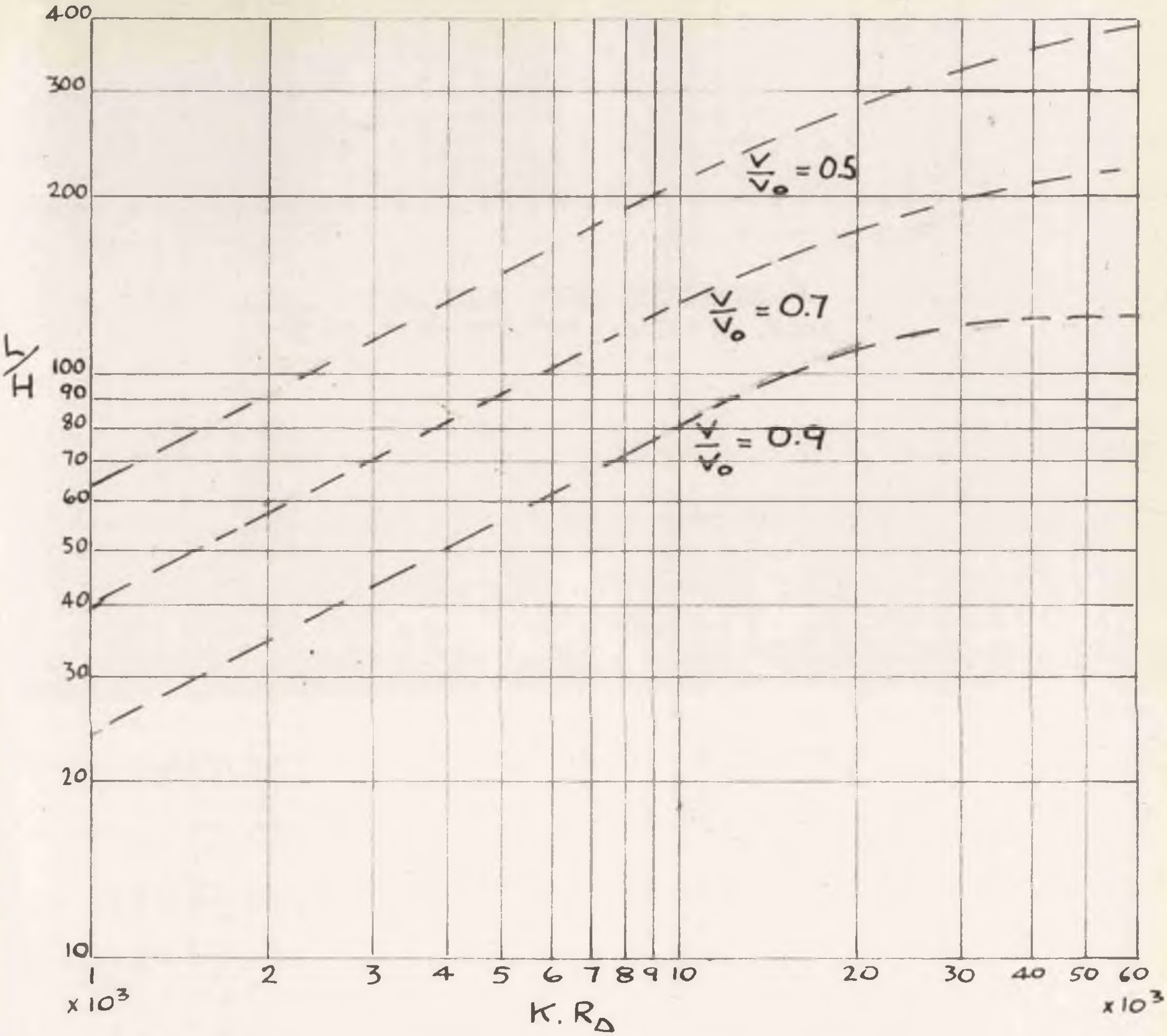


FIG. 13.1 PREDICTION OF EXTENDED CONGRUENCY DIAGRAM.

FIG. 16.1 FLUME ROUGHENING
$\frac{3}{4}$ in. mesh and down pebbles as shown

16. TEST RECORDINGS

16.1. Recordings for test series A and B

The recordings are in the form of tables and notes. The following abbreviations have been used in the tables. D refers to date (1958 missed). C to code showing thermal (T) or saline (S) density difference, with subscript O or U for overflow and underflow. (B) means surface tension balanced. Thus To(B) means thermal overflow with surface tension balanced. The second D refers to depth in feet (e.g. 0.75) or inches (e.g. $7\frac{1}{4}$). T_1 and T_2 are the temperatures. As the one compartment of the larger flume was 4 ft. long and the other 13 ft., it is obvious, from the further travel lengths, in which compartment the less dense water was at the start. The times (in seconds) for the tips of the fronts to travel to distances (1, 2, 3 ..... feet) are then given. Where additional times are entered they refer to (unless otherwise marked) 0.5, 1.5, 2.5 and 3.5 feet, as is indicated by their position.

Thermal density differences for the subsequent computations were obtained from a large scale plot of the International Critical Table data (as shown to small scale on Fig. 2.1); saline density differences were obtained from the information given in the notes, (i.e. a weight of salt in a volume of water) which follow the tables, and using Fig. 2.2. The notes also contain the observations made at the time of the tests.

The saline cases only were used from the series B tests; sufficient duplication of the thermal cases being available in series A.

For tests A8 - 11, where depth is marked N, further details are given at the end of the notes.

Nº	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
D	5/5	6/5	6/5	7/5	7/5	13/6	13/6	16/6	14/6	16/6	17/6	17/6
C	To	To	To	To	To	To	To	To	To	To	To	To
D	10⅛	10⅛	4½	4½	2¼	10⅛	10⅛	N	N	N	N	4½
T_1	56.7	56.0	55.6	61.0	55.8	57.6	55.3	60.0	68.5	58.5	58.4	58.5
T_2	67.5	66.8	66.4	78.0	66.8	68.5	66.2	77.3	76.5	74.5	76.2	76.0
1	16.0	16.5	24.5	13.0	18.0	15.0	17.0	12.0	13.0	11.0	10.5	14.0
2	26.5	26.0	43.0	25.5	46.5	27.5	28.5	20.0	22.0	22.0?	23.0	22.0
3	38.0	37.5	73.5	36.0	72.0	31.5	38.0	29.0	30.0	30.0	33.5	33.5
4	48.0	48.5	81.5	48.0	104.0	43.5	48.0	38.0	38.5	41.5	45.5	45.0
5	59.5	60.5	103.5	60.0	148.0	54.5	60.0	47.0	47.2	51.5	56.5	56.0
6	73.0	73.5	121.5	73.5	194.0	66.0	71.5	55.5	56.0	62.0	68.5	66.0
7	85.5	86.5	141.5	89.0	253.0	76.5	84.5	65.0	66.5	75.0	80.5	79.0
8	99.0	98.5	161.5	101.5	349.0	88.5	97.0	76.0	75.0	87.5	92.0	95.0
9	111.5	110.0	180.5	115.5	471.0	101.5	109.5	87.0	85.0	100.5	105.0	110.0
10	126.0	124.0	206.5	131.5	586.0	114.5	124.0	99.5	94.0	116.0	110.0	126.5
11	138.5	137.5	228.5	149.0	-	126.0	139.0	109.5	106.0	130.0	136.0	141.0
12	153.5	-	258.5	167.0	1150.0	139.0	154.5	120.0	117.5	142.0	151.0	150.0
13	163.5	165.0	291.5	184.0	-	151.5	169.0	135.5	133.0	162.0	167.0	178.5

Nº	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24
D	18/6	18/6	19/6	19/6	19/6	20/6	20/6	20/6	21/6	23/6	23/6	23/6
C	To	To	To	To	To	To	To	To	To	To	To	To
D	10⅛	10⅛	10⅛	·378	·856	·841	·375	·8455	·196	·849	·848	·849
T_1	55.3	55.2	56.5	56.2	56.5	57.2	56.0	56.3	62.8	58.3	57.8	57.6
T_2	67.5	64.2	68.2	70.0	72.2	86.9	85.8	88.2	71.2	94.0	103.0	59.4
1	9.0	12.0	11.5	12.0	10.0	6.2	7.5	6.0	17.8	3.8	2.6	30.0
2	20.0	25.0	21.0	26.5	17.5	12.3	14.2	11.3	40.5	-	-	60.2
3	31.0	37.5	30.0	41.5	25.5	17.2	22.5	16.0	64.6	13.0	9.9	84.0
4	43.0	51.0	40.5	55.0	34.0	23.1	30.0	21.5	93.5	17.0	14.8	111.5
5	55.5	66.0	51.0	69.5	43.0	29.3	38.3	26.6	126.5	21.8	18.6	137.8
6	67.5	78.5	61.5	86.0	52.0	34.6	46.0	31.2	162.0	25.8	22.0	163.0
7	80.5	93.5	71.0	102.5	61.5	39.9	54.5	37.0	206.3	30.2	26.8	189.8
8	90.5	109.0	80.5	118.5	70.0	46.3	62.0	42.0	280.8	35.5	30.2	212.5
9	106.5	124.0	98.5	135.0	81.0	50.6	-	46.5		40.2	34.4	251.0
10	118.5	139.0	106.0	153.9	91.0	56.9	80.4	52.5		45.2	38.5	282.0
11	131.5	153.5	118.5	172.0	101.5	62.5	91.0	57.8		49.8	42.5	317.5
12	144.0	170.0	131.5	192.0	112.0	69.6	101.6	63.5		65.0	46.9	359.6
13	155.0	185.0	146.0	212.0	125.0	77.0	113.5	71.0		60.2	51.0	-

N°	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35	A36
D	23/6	24/6	24/6	24/6	24/6	25/6	25/6	25/6	25/6	25.6	25/6	25/6
C	To	To	To	To	To	To	To	To	To	To	To	To
D	·849	·849	·381	·851	4½	·3825	·3805	·380	·380	·381	·379	·378
T_1	84·6	58·4	57·4	57·9	57·0	60·8	58·8	59·0	58·4	60·0	58·6	58·0
T_2	97·2 (92·2?)	62·3	62·5	58·9	58·6	103·6	101·2	82·2	81·9	71·0	70·0	61·5
1	11·0	12·0	30·5	40·0	61·5	4·8	3·8	6·2	7·0	15·0	9·4	23·5
2	19·8	28·5	61·5	97·5	112·0	8·8	9·4	13·0	14·6	30·0	24·2	59·0
3	29·2	51·0	95·0	140+3	171·5	13·8	13·8	20·5	21·8	45·0	38·0	96·3
4	39·6	69·0	123·5	176·5+3	222·0	18·3	19·6	31·2	31·4	61·0	57·8	135·5
5	49·0	87·5	154·0	224·5+3	301·0	24·1	26·0	41·5	40·6	77·0	68·0	181·8
6	59·2	109·5	185·0	268·0+3	385·0	29·3	32·2	50·0	50·6	92·0	84·5	228·2
7	69·4	130·5	212·5	314·5+3	471·5	35·0	38·4	59·8	59·9	106·8	100·2	277·3
8	80·0	154·5	241·5	357·0+3	577·5	40·5	-	70·4	71·0	122·0	117·2	330·0
9	90·8	175·5	279·5	403·0+3	-	47·5	52·0	81·0	83·0	138·0	135·6	389·5
10	100·0	198·5	309·5	449·0+3		54·5	59·2	94·0	94·5	156·0	157·6	452·2
11	111·0	222·5	341·5	496·0+3		62·0	67·0	106·0	108·5	175·0	180·5	517·0
12	122·0	244·0	380·0	547·0+3		69·5	76·3	120·2	121·5	200·0	209·2	583·6
13	134·0	-	-	-		78·0	85·4	135·3	135·0	231·0	234·6	-

N°	A37	A38	A39	A40	A41	A42	A43	A44	A45	A46	A47	A48
D	25/6	26·6	26/6	26/6	26/6	26/6	26/6	26/6	26/6	26/6	26/6	26/6
C	To	To	To	To	To	To	To	To	To	To	To	To
D	·379	·378	·379	·387	·189	·189	·379	·191	·1905	·190	·1895	·189
T_1	58·4	58·1	57·9	57·5	62·5	59·5	58·0	57·0	58·0	59·9	58·5	57·2
T_2	61·8	69·0	69·1	60·0	99·0	96·8	61·9	84·8	62·5	69·9	70·5	60·8
1	23·0	15·2	15·2	35·5	-	7·4	31·5	10·0	9·1	-	13·5	42·0
2	49·5	31·8	29·5	81·0	15·0	14·8	64·0	27·4	23·1	36·0	37·1	88·5
3	81·0	47·8	44·8	122·5	24·3	24·0	97·2	36·6	36·5	61·8	59·5	166·3
4	117·5	63·2	60·2	166·0	35·2	33·3	135·2	50·2	50·0	89·9	85·9	251·2
5	154·6	78·6	76·0	211·0	45·0	44·5	175·3	66·3	66·8	122·5	116·2	362·0
6	190·0	93·2	92·0	251·0	57·4	55·6	216·2	84·0	84·2	159·5	150·0	483·6
7	226·0	107·8	108·0	298·6	-	67·5	258·2	101·9	101·3	202·8	185·6	-
8	262·2	120·8	123·2	362·5	84·4	80·2	308·2	128·0	120·0	262·2	228·2	
9	311·5	136·2	142·2	446·2	101·4	93·2	359·5	157·0	145·6	313·0	295·6	
10	376·0	149·6	163·0	532·8	120·8	110·0	417·6	195·0	180·3	473·0	401·5	
11	445·3	166·0	186·0	-	143·5	131·8	478·5	235·0	219·2	-	-	
12	518·5	192·4	213·0		170·2	156·6	542·5	284·2	266·0			
13	-	219·0	243·0		198·5	186·2	-		-			

Nº	A49	A50	A51	A52	A53	A54	A55	A56	A57	A58	A59	A60
D	26/6	26/6	27/6	27/6	27/6	30/6	30/6	30/6	30/6	30/6	1/7	8/7
C	To	To	To	To	To	To	To	To	To	To	To	Su
D	·1880	·061	·189	·1885	·189	·834	·837	·831	·838	·831	·8355	·862
T_1	57·5	57·5	57·9	58·2	60·5	59·5	58·5	88·7	58·3	57·6	57·7	65·1
T_2	60·5	86·0	81·9	61·8	84·0	105·5	87·5	96·0	58·8	61·3	60·6	"
1	46·0	13·4	7·6	17·0	10·3	3·5	3·9	9·2	68·0	14·4	19·2	8·4
2	98·5	39·4	17·0	70·0	21·6	7·5	9·1	18·5	152·0	39·2	41·5	17·2
3	148·0	80·0	26·0	145·0	36·5	11·2	14·3	28·8	222·5	50·9	65·8	26·4
4	227·0	151·0	47·5	277·2	49·0	14·6	20·3	39·0	306·0	66·0	91·2	35·0
5	317·0	198·2	67·8	498·0	66·4	18·2	25·4	50·1	386·4	88·2	119·2	44·8
6	389·0		88·4	-	83·6	22·3	30·7	60·1		110·9	148·0	52·6
7			111·5		102·8	26·0	36·7	71·8	503·0	136·0	176·9	61·4
8			143·6		123·6	30·0	41·4	84·1	598·5	159·4	206·4	70·0
9			161·6		153·6	34·2	46·7	93·3	683·5	185·6	234·5	79·1
10			227·5		189·5	38·2	52·3	103·9		211·5	263·9	87·6
11			279·5		233·0	42·1	58·5	114·5		236·3	293·5	96·3
12			341·2		289·0	46·4	64·3	126·5		264·8	323·5	105·9
13			-			52·2	70·3	137·5		290·5	358·0	114·5

Nº	A61	A62	A63	A64	A65	A66	A67	A68	A69	A70	A71	A72
D	8/7	9/7	9/7	9/7	9/7	9/7	10/7	10/7	10/7	10/7	10/7	24/7
C	Su	Su	Su	Su	Su	Su	Su	Su	Su	Su	Su	Su
D	·842	·854	·849	·857	·850	·872	·839	·846	·392	·380	·389	·854
T_1	65·0	64·0	63·8	64·5	62·9	62·9(s)	63·7	62·8	63·0	62·8	63·1	62·2
T_2	"	"	"	"	"	62·0	"	"	"	"	"	"
1	9·9	5·0	18·5	4·7	39·7	2·8	20·2	46·8	14·0	28·7	54·4	14·0
2	17·5	10·0	36·0	9·3	75·7	6·0	36·8	83·3	27·8	55·6	119·4	26·5
3	26·1	14·9	56·6	14·6	110·8	8·7	54·8	121·2	41·3	84·8	182·5	40·5
4	35·2	20·1	74·3	19·4	147·8	11·7		159·3	54·8	113·2	246·8	53·0
5	44·2	25·3	93·4	24·4	181·7	14·8	91·8	199·5	68·6	143·2	325·5	62·0
6	53·3	30·0	111·6	29·4	215·5	17·7	110·0	234·4	83·1	-	402·6	80·1
7	61·6	34·8	130·0	34·4	249·0	20·6	128·3	271·6	96·6	200·0	491·5	93·4
8	70·7	40·1	148·3	39·6	286·0	23·2	147·3	310·8	110·8	230·8	604·4	106·0
9	80·0	45·5	167·2	44·9	324·5	26·1	164·8	349·8	125·5	264·8	725·0	119·0
10	88·6	50·7	185·8	49·9	364·0	29·3	183·8	389·2	140·4	299·3		132·6
11	98·2	55·7	204·8	54·8	402·0	32·5	202·3	428·8	155·5	337·5		146·4
12	106·6	60·7	221·6	59·6	442·2	34·9	220·8	466·8	170·4	381·0		160·2
13	114·8	66·1	241·6	64·9		38·5	239·6		187·1			173·6

Nº	A73	A74	A75	A76	A77	A78	A79	A80	A81	A82	A83	A84
D	24/7	24/7	24/7	1/8	2/8	28/8	1/9	5/9	5/9	5/9	5/9	5/9
C	To	Su	Su	Su	Su	To	To	To	To	To	To	To
D	·861	·385	·180	·843	·4695	·840	·849	·840	·844	·844	·833	·848
T_1	62·4	62·2	62·2	61·3	62·0	60·7	82·8	63·4	62·7	62·3	62·9	62·9
T_2	68·0	"	"	"	"	99·3	87·9	85·0?	72·2	69·1	72·2	69·2
1	14·4	20·7	28·1	307	390	5·2	10·0	7·5	10·0	13·0	11·2	13·5
2	28·0	40·6	60·5	526	-	8·5	19·8	13·0	19·5	24·5	20·5	26·5
3	43·0	61·8	92·6	-	1800	12·6	30·5	18·8	28·5	36·2	32·0	40·5
4	57·5	81·4	130·0	-		15·5	40·8	24·8	36·7	48·0	41·3	53·2
5	63·6	100·8	172·0	-		20·3	52·9	31·0	46·0	61·0	52·3	66·0
6	90·7	121·3	226·0	2580		24·7	64·5	37·0	59·0	73·6	62·8	78·8
7	108·3	143·0	290·5			29·6	77·7	43·2	64·7	85·0	73·2	91·2
8	126·2	165·0	366·0			33·8	91·2	49·2	75·0	97·5	83·4	102·0
9	142·8	188·0				39·4	103·7	55·6	85·3	110·0	95·8	114·0
10	161·2	211·5				43·9	116·0	62·7	94·5	124·5	105·8	125·0
11	179·6	235·5				48·2	128·5	70·0	105·2	140·0	116·8	136·8
12	198·6	261·6				54·1	142·3	78·2	115·2	155·4	131·7	150·0
13	218·3	287·6				-	-					

Nº	A85	A86	A87	A88	A89	A90	A91	A92	A93	A94	A95	A96
D	5/9	5/9	5/9	17/10	17/10	17/10	21/10	21/10	21/10	21/10	22/10	23/10
C	To	To	To	Tu	Tu	Tu	Tu	Tu	Tu	To	Su	Su
D	·843	·845	·846	·843	·852	·852	·849	·849	·853	·869	·910	·088
T_1	62·6	62·8	62·8	56·8	56·0	56·1	55·3	56·4	56·7	54·7	89·9	64·6
T_2	67·7	68·0	67·2	65·5	81·9	82·2	90·5	89·9	66·9	66·3	"	"
1	14·5	13·2	12·7	16·7	7·7	7·7	5·7	6·2	12·5	-	-	8·4
2	26·0	27·5	26·0	30·7	14·7	14·7	11·7	12·3	26·0	21·0	5·3	17·2
3	40·5	43·5	39·8	45·2	22·8	21·5	17·7	18·3	39·0	33·4	8·3	29·4
4	54·8	57·1	55·4	60·1	29·6	29·6	23·0	24·0	51·6	45·7	10·7	43·6
5	67·5	74·5	71·5	75·7	37·3	37·0	29·5	30·8	65·4	56·6	13·3	57·2
6	82·0	90·2	-	90·2	44·0	43·7	34·5	36·5	78·6	66·5	15·8	75·2
7	96·8	107·0	103·0	104·5	51·7	51·0	41·3	43·0	91·3	76·7	18·6	96·3
8	113·5	124·0	119·7	119·8	59·0	58·6	47·3	48·7	104·8	87·0	20·8	121·2
9	129·2	142·0	137·0	134·2	66·5	65·5	53·8	55·5	118·2	98·0	23·0	166·8
10	147·8	160·0	153·0	150·0	75·2	74·0	60·0	62·0	132·5	108·5	26·7	217·5
11	167·0	180·5	172·6	-	82·2	81·5	65·3	67·0	145·4	-	29·3	-
12	187·2	198·5	195·0	182·2	89·6	88·7	71·5	73·5	159·7		31·6	348·3
13				198·1	97·5	96·5	77·7	79·5	174·0		34·5	-

Nº	A97	A98	A99	A100	A101	A102	A103	A104		A105	A106	
D	23/10	23/10	24/10	24/10	25/10	25/10	28/10	29/10		29/10	29/10	
C	Su	Su	So	So	So	So	So	Sa	Su	Su	So	Su
D	·184	·115	·869	·182 (·132?)	·867	·196	·850	·204		·080	·505	
T_1	64·9	64·7	65·0	64·7	67·5	67·0	62·0	61·4		61·4	61·4	
T_2	64·6(s)	64·3(s)	64·3(s)	64·3(s)	67·2(s)	66·5(s)	"	"		"	"	
								5·2	7·6	12·0	–	–
1	5·5	7·5	8·0	17·0	7·8	12·7	6·5	13·0	16·4	32·5	12·6	16·0
								21·2	–	57·0	–	–
2	12·4	15·9	15·2	35·3	14·7	26·7	12·7	29·3	–	94·0	25·5	29·3
								–	–	–	–	–
3	18·2	23·0	22·3	54·8	21·9	42·5	19·6	42·0	47·5	205·0	38·0	43·5
								–	–	–	–	
4	24·2	33·5	29·3	73·3	29·0	58·7	25·4	56·0	62·7	395·5	50·0	56·6
5	30·8	44·2	35·9	93·0	36·2	75·5	30·7	71·9			62·7	
6	36·0	59·0	43·4	120·4	42·7	94·0	37·3	88·5			74·7	
7	42·7	70·3	49·9	152·4	49·7	113·9	42·8	110·8			87·0	
8	49·2	87·2	56·4	192·0	56·7	143·5	48·2	138·6			100·0	
9	57·6	106·2	63·2	231·0	64·0	176·0	54·3	166·0			113·7	
10	66·0	127·0	70·0	280·5	71·3	214·0	60·2	197·6			127·7	
11	74·5	151·4	77·0	332·3	79·2	260·0	67·2	232·0			142·0	
12	82·5	179·4	–	401·7	86·5	300·5	73·5	265·0			156·8	
13	-		91·0	-								

Nº	A107		A108		A109		A110	A111	A112		A113	
D	29/10		29/10		29/10		29/10	29/10	29/10		3/11	
C	So	Su	So	Su	So	Su	So	Su	So	Su	So	Su
D	·251		·252		·110		·854	·1825	·064		·8625	
T_1	61·4		61·3		61·3		61·9	61·9	61·9		62·3	
T_2	"		61·5(s)		61·5(s)		"	"	"		62·5	
	7·2	11·3	7·2	10·5	10·6	15·7	–	4·4	–	9·4	7·5	–
1	16·7	22·1	16·7	20·9	23·7	31·5	4·7	9·4	19·7	19·7	14·0	-
	–	–	25·0	31·0	40·0	52·6	–	–	32·5	36·0	23·3	26·5
2	33·4	42·0	34·5	41·5	58·0	76·0	8·3	19·0	51·2	56·5	32·1	35·0
	–	–	–	–	–	–	–	–	77·7	82·0	–	–
3	51·5	64·0	51·3	63·5	103·0	139·3	11·7	28·0	105·6	113·3	47·0	51·6
	–	–	–	–	–		–	–	–		–	–
4	68·6	84·0	67·3	83·0	167·4		16·0	36·2	182·8		63·3	67·4
5	87·0		88·3		263·3		19·2	–	289·5		80·0	
6	105·4		109·2		364·0		23·7	53·5	·		94·5	
7	130·0		126·0				26·2	63·6			108·5	
8	157·9		151·0				29·7	77·6	·		124·6	
9	193·4		183·0				33·0	92·8			141·5	
10	235·0		220·0				36·9	110·0			156·7	
11	276·7		265·5				40·7	127·5			172·1	
12	319·5		305·0				43·8	147·3			189·2	
13							48·0					

Nº	A114		A115		A116		A117		A118		A120	A121
D	3/11		3/11		3/11		3/11		3/11		4/11	4/11
C	So	Su	So	Su	So	Su	So	Su	So	Su	So	So
D	·207		·0955		·858		·1845		·0955		·867	·239
T_1	62·3		62·6		62·9		63·0		63·0		62·3	63·0
T_2	62·5(s)		62·9(s)		63·1(s)		"		"		62·0(s)	62·7(s)
	16·5	20·0	23·0	17·0	7·9	–	13·7	18·2	22·4	28·4	–	4·3
1	31·0	37·0	57·0	31·0	14·7	–	29·0	36·8	56·0	62·5	4·3	8·3
	47·1	56·0	115·0	65·7	21·0	–	43·6	55·5	98·8	114·0	–	12·3
2	66·4	75·0	178·6	207·0	29·0	33·2	63·5	76·2	157·3	181·7	8·4	16·4
	–	–		334·0	–	–	–	95·2			–	–
3	101·8	112·0			44·0	49·0	101·4	117·6			12·5	24·0
	–	–			–	–	–	–			–	–
4	139·0	153·5			58·4	66·4	143·2	169·6			16·0	31·0
5	186·3				74·0		199·3				19·7	37·1
6	244·5				87·0		266·7				22·9	44·5
7	319·6				100·3		362·6				27·0	52·4
8	410·0				114·0						30·7	59·3
9	526·0				128·4						33·7	68·8
10					143·5						36·5	77·0
11					157·5						40·2	87·3
12					173·4						44·0	99·7
13											48·0	111·6

Nº	A122		A123	A124	A125	A126	A127		A128		A129	
D	4/11		4/11	4/11	4/11	4/11	4/11		4/11		5/11	
C	So	Su	So	So	So	So	So	Su	So	Su	So	Su
D	·0535		·6205	·3545	·1765	·8730	·2285		·0850		·7080 ·7075	
T_1	63·0		62·3	62·3	62·3	62·2	62·3		62·3		62·9	
T_2	62·7(s)		"	"	"	62·0(s)	62·6(s)		62·6(s)		63·4	
	8·4	11·2	–	–	4·0	–	6·1	–	9·8	12·0	–	–
1	18·4	23·8	4·5	5·6	9·4	6·7	12·7	15·4	19·6	24·6	7·4	–
	34·1	50·5	–	–	13·7	–	21·0	23·5	33·0	47·2	–	–
2	54·7	71·7	9·1	12·8	18·4	13·8	–	–	51·8	65·0	14·2	16·2
	–	113·0	–	–	–	–	–	–	–	–	–	–
3	125·5	163·0	14·0	18·8	27·0	19·0	38·7	44·7	96·0	124·4	21·7	24·0
	–		–	–	–	–	–	–	–	–	–	
4	230·5		18·0	25·0	35·0	25·4	52·0	59·6	168·7	208·0	28·5	
5			22·3	31·0	43·1	31·5	66·7		262·2		35·0	
6			26·5	36·5	52·7	37·4	78·6				41·7	
7			30·5	42·0	63·0	43·5	93·7				48·3	
8			34·8	47·5	78·8	49·3	112·0				54·8	
9			39·2	54·0	92·7	55·3	127·0				62·0	
10			42·7	60·7	109·8	61·0	162·7				68·7	
11			47·0	67·0	126·8	67·4	188·7				75·7	
12			52·2	74·0	146·7	74·6	213·8				83·5	
13			57·0	80·0		81·0	245·0				91·5	

Nº	A130		A131		A132		A133		A134		A135	
D	5/11		5/11		5/11		5/11		6/11		6/11	
C	So	Su	So	Su	So	Su	So	Su	So	Su	So	Su
D	·392		·872		·2420		·0715		·8575		·3115 ·3118	
T_1	63·0		61·7		61·6		62·0		60·2		62·0	
T_2	63·6(s)		61·0		61·0(s)		61·7(s)		62·2(s)		"	
	4·2	–	–	–	9·0	11·6	14·0	19·0	–	–	–	–
1	10·0	12·4	9·7	11·0	20·7	22·7	34·2	45·6	11·5	13·2	17·5	20·5
	16·0	–	–	–	29·4	34·5	66·0	95·0	–	–	–	30·5
2	21·0	–	18·3	21·2	39·6	43·3	170·0	219·0	21·5	24·7	34·2	39·4
	–	–	–	–	–	–	–		–	–	–	–
3	29·0	32·4	27·5	31·4	58·7	65·8	264·0		33·3	36·0	52·0	58·3
	–	–	–	–	–	–			–	–	–	
4	39·6	44·0	37·5	42·7	78·0	87·5			44·0	48·2	69·5	
5	48·8		47·0		98·0				54·6		88·0	
6	58·5		54·6		120·5				64·6		106·8	
7	69·0		64·2		145·0				74·8		125·3	
8	79·0		71·6		177·6				85·2		144·8	
9	89·0		82·2		218·9				95·5		168·0	
10	99·2		90·8		262·7				106·5		186·0	
11	111·3		101·0		309·0				118·5		224·5	
12	122·8		111·5		357·0				124·5		261·2	
13	–											

No	A136		A137		A138		A143	A144	A145	A146		A147
D	6/11		6/11		6/11		8/11	8/11	8/11	8/11		14/11
C	So	Su	So	Su	So	Su	To	To	Tu	Tu	To	To
D	·6255		·403		·1230		·734	·7235	·923	·573		·861
T_1	64·7		64·7		64·3		35·2	42·2	37·7	43·0		51·2
T_2	64·2(s)		64·2(s)		63·9(s)		61·1	69·2	53·0	68·6		96·4
	–	–	10·4	11·8	14·9	19·4	–	–	–	6·2		–
1	15·5	18·3	19·2	22·0	31·5	37·0	16·0	10·0	20·5	11·8		4·8
	–	–	28·5	32·6	51·3	65·5	–	–	–	–		–
2	31·2	35·0	39·5	44·5	73·0	101·0	28·0	17·0	38·0	23·0		8·3
	–	–	–	–	–	143·0	–	–	–	–		–
3	46·2	52·5	56·7	68·0	137·0	185·0	40·3	23·9	55·0	36·4	31·7	12·8
	–	–	–	–			–	–	–	–		–
4	61·5	70·4	78·2	92·7			54·5	31·4	73·4	47·5	42·2	17·0
5	77·3		98·7				67·1	39·6	91·3	59·5		19·6
6	92·2		118·3				80·0	47·5	108·5	71·3		25·0
7	107·2		–				93·5	56·7	125·5	84·0		29·4
8	121·0		160·0				107·0	66·6	143·3	94·5		33·7
9			184·0				122·0	76·5	160·8	106·4		38·0
10			210·3				138·0	87·0	177·5	119·0		42·5
11			236·5				152·5	97·4	195·5	131·0		46·5
12			288·0				167·7	108·3	214·0	143·6		50·7
13												56·0

Nº	A148	A149		A150		A151		A152		A153	
D	14/11	14/11		14/11		14/11		14/11		14/11	
C	To	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·874 / ·8735	·8765 / ·8755		·8805		·8835		·8740 / ·8735		·8855 / ·8850	
T_1	51·5	51·4		51·8		51·3		51·2		51·3	
T_2	94·7	79·5		79·7		72·5		72·0		66·6	
	–	–	–	–	–	–	–	–	–	–	–
1	4·5	7·0	8·0	7·0	8·2	8·0	10·0	8·1	10·0	10·0	12·4
	–	–	–	–	–	–	–	–	–	–	–
2	9·1	12·0	15·3	11·8	15·0	14·6	18·5	14·0	18·5	18·7	22·6
	–	–	–	–	–	–	–	–	–	–	–
3	12·5	18·0	22·5	18·0	–	22·2	27·5	23·7	28·3	28·7	34·3
	–	–		–	25·5	–	–	–	–	–	–
4	16·0	–		22·0		–	36·5	30·4	36·8	37·5	45·5
5	20·1	29·4		29·4		–		–		47·4	
6	25·0	35·3		35·0		43·0		46·3		56·3	
7	29·6	41·8		40·0		51·4		52·5		65·7	
8	34·7	47·3		46·2		59·0		60·3		75·7	
9	39·5	55·5		52·2		66·1		67·5		85·2	
10	43·6	59·8		59·5		73·5		75·5		94·3	
11	47·4	66·3		65·4		81·0		83·5		104·6	
12	52·2	73·3		72·8		89·7		92·6		116·0	
13	58·0	80·2		80·3		98·1		101·5		127·0	

Nº	A154		A155		A156		A157		A158		A159	
D	14/11		15/11		15/11		15/11		15/11		17/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·880		·8780		·8715 / ·8710		·8850 / ·8845		·8825		·8855	
T_1	51·6		51·9		51·6		51·2		51·3		71·5	
T_2	66·6		62·1		61·8		51·0		57·1		93·9	
	–	–	–	–	–	–	–		–	–	–	–
1	10·2	12·6	11·9	14·7	12·1	13·5	19·0	22·0	16·0	19·4	6·2	8·0
	–	–	–	–	–	–	–	–	25·2	29·2	–	–
2	18·7	22·9	22·4	28·4	24·0	29·0	39·5	42·3	35·7	41·0	11·3	14·0
	–	–	–	–	–	–	–	–	–	–	–	–
3	27·5	34·0	34·3	43·2	35·6	43·7	55·4	63·6	55·0	62·0	–	21·0
	–	–	–	–	–	–	–	–	–	–	–	
4	37·2	45·0	45·7	57·0	48·0	58·0	73·0	83·5	73·7	83·0	–	
5	47·4		–		60·4		90·7		91·4		27·7	
6	55·3		68·4		73·5		107·1		109·7		33·0	
7	64·4		74·5		86·3		125·5		128·4		38·5	
8	74·3		92·0		99·0		141·3		148·3		44·0	
9	83·4		104·6		110·7		160·0		169·6		49·0	
10	92·5		115·8		124·5		178·8		191·0		55·4	
11	103·0		127·7		139·0		199·0		–		60·5	
12	113·4		140·1		154·0		221·0		234·0		66·0	
13	124·7										74·5	

Nº	A160		A161		A162		A163		A164		A165	
D	17/11		17/11		17/11		17/11		17/11		17/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·8725 ·8720		·8880		·8810		·8815 ·8810		·8895 ·8890		·3960	
T_1	72·6		70·3		71·0		87·9		87·2		54·1	
T_2	90·3		80·2		80·7		94·6		93·0		93·4	
	–	–	–	–	–	–	–	–	–	–	–	–
1	6·8	8·5	9·5	11·8	9·5	11·5	11·0	12·4	12·5	14·0	7·0	9·0
	–	–	–	–	–	–	–	–	–	–	–	–
2	12·7	16·0	18·0	22·2	18·1	22·7	22·0	23·9	23·8	27·3	12·4	17·3
	–	–	–	–	–	–	–	–	–	–	–	
3	18·6	23·0	27·5	33·0	27·0	34·0	32·7	35·7	34·7	39·2	–	
	–		–	–	–	–	–	–	–	–	–	
4	–		37·0	44·0	–	44·3	43·5	47·6	45·4	52·3	23·7	
5	31·3		–		–		53·9		56·5		31·0	
6	37·5		54·5		54·0		64·5		68·0		37·5	
7	44·1		63·5		63·0		76·2		79·8		44·3	
8	50·7		72·2		72·5		85·5		92·0		51·8	
9	57·3		81·0		82·0		96·3		103·7		58·4	
10	63·3		89·7		90·5		107·0		116·0		65·5	
11	70·7		99·0		100·5		118·5		128·6		73·0	
12	78·6		108·7		111·5		131·5		143·0		81·5	
13			119·3		123·2		143·0					

Nº	A166		A167		A168		A169		A170		A171	
D	17/11		18/11		18/11		18/11		18/11		20/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·4000		·3965		·3980		·3995		·410		·4115	
T_1	54·7		56·1		57·0		53·5		53·9		53·6	
T_2	93·0		80·0		77·6		97·0		98·6		85·0	
	–	–	–	–	–	–	–		–	–	–	–
1	6·5	8·8	8·5	12·0	9·4	13·8	5·0		5·8	7·7	7·2	9·1
	–	–	–	–	–	–	11 –		–	–	–	–
2	12·7	17·2	16·0	24·5	17·0	25·3	10·9	16·2	10·9	–	14·0	19·0
	–	–	–	–	–		–		–	19·0(E)	–	–
3	19·4	27·0	–	36·0	–		–		15·5		–	–
	–		32·7	–	–		–		–		–	–
4	–		41·8	48·0	35·1	38·0	21·8	31·8	–	30·7	28·7	39·6
5	32·5		51·2		44·6	50·5	–		25·8		36·7	
6	–		60·3		55·0		–		–		44·5	
7	39·0		70·0		65·3		39·5		39·0		52·4	
8	45·6		80·0		76·2		45·5		44·6		60·0	
9	53·3		89·5		86·8		52·7		52·0		68·2	
10	60·0		100·0		97·8		58·7		57·5		76·7	
11	67·4		112·2		110·0		64·5		64·7		85·4	
12	76·0		124·7		124·3		72·8		71·6		95·7	
13	85·0				138·7		80·4		79·6		106·3	

N°	A172		A173		A174		A175		A176		A177	
D	20/11		20/11		20/11		20/11		20/11		20/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·4100		·413		·4080		·4040		·4145 ·4140		·4070	
T_1	53·5		53·8		53·9		54·0		54·7		75·0	
T_2	83·5		73·7		73·0		65·3		66·2		90·6	
	–	–	–		–	–	–	–	–	–	–	–
1	7·2	9·8	9·3	12·5	9·8	12·7	10·6	17·3	12·0	18·7	8·5	11·5
	–	–	–		–	·	–	28·3	–	29·3	–	–
2	14·0	20·5	17·5		18·2		24·5	–	24·6	–	16·0	23·6
	–	–	–		–		–	48·0	–	48·3	–	–
3	21·5	–	–		27·7		39·4	–	38·3	–	–	–
	–	–	–		–		–	78·1	–	–	–	–
4	30·0	41·0	38·0		39·5		54·7		53·5	78·0	36·5	48·0
5	39·3		47·7		50·4		70·0		70·2		46·0	
6	47·5		58·4		–		87·0		86·0		55·6	
7	56·5		68·3		71·0		103·9		101·5		65·5	
8	64·2		80·0		82·7		120·0		118·0			
9	73·0		90·0		92·2		–		134·5			
10	81·5		101·7		104·7		154·5		161·0			
11	91·5		113·0		116·7		172·0		168·0			
12	102·0		126·4		133·0		195·0		193·0			
13	112·5											

N°	A178		A179		A180		A181		A182		A183	
D	20/11		24/11		24/11		24/11		24/11		24/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·4100		·4070		·4050		·4060		·4060 ·4055		·4070 ·4065	
T_1	75·2		86·3		82·5		82·9		83·8		83·9	
T_2	91·2		94·0		94·0		94·8		95·1		94·8	
	–	–	–	–	–	–	–	–	–	–	–	–
1	9·0	11·8	12·0	16·7	12·0	14·3	9·8	14·0	10·6	14·0	10·6	14·0
	–	–	–	–	–	–	–	20·8	–	–	–	–
2	17·6	23·5	23·5	34·0	22·4	28·5	18·6	–	20·5	28·0	22·0	29·1
	–	30·3	–	–	–	–	–	34·0	–	–	–	–
3	27·4	–	37·0	51·0	34·0	43·0	29·5	–	31·5	–	34·0	43·4
	–	–	–		–		–	–	–	–	–	–
4	36·2	48·0	48·8		44·7		39·5	53·5	42·5	55·0	44·7	57·0
5	–		65·3		57·0		49·5		–		56·0	
6	55·0		82·0		70·0		59·0		66·5		68·5	
7	65·2		98·7		82·4		69·5		79·5		80·6	
8	75·0		117·5		96·5		79·4		92·0		93·0	
9	85·4		134·5		109·4		92·0		105·7		106·4	
10	97·0		150·0		124·1		103·9		119·4		120·7	
11	110·0		172·0		139·3		117·6		136·0		136·5	
12	125·0		191·5		153·5		133·0		156·1		156·4	
13					169·0		147·5		166·4		169·5	

Nº	A184		A185		A186		A187		A188		A189	
D	24/11		24/11		24/11		24/11		24/11		25/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·2145		·2010		·186		·2065		·2210		·	
T_1	52·4		52·3		52·2		55·6		55·4		52·9	
T_2	96·0		95·3		94·2		95·9		84·5		82·3	
			–	–	–	–	–	–	–	–	–	–
1			–	12·2	7·0	12·3	5·8	11·2	8·5	13·6	9·0	16·3
			–	–	–	19·0	–	–	–	20·5	–	23·9
2		24·0	13·9	–	14·5	–	–	–	17·4	–	20·7	–
		29·4	–	28·8	–	31·4	–	28·4	–	35·5	–	37·7
3		34·7	23·0	–	24·5	–	23·0	–	26·7	–	31·5	–
		–	–	–	–	–	–	–	–	–	–	–
4		45·6	–	47·0	–	50·4	–	47·0	–	57·0	42·3	60·5
5			40·2		43·2		41·5		50·3		53·9	
6			50·0		56·0		–		63·7		67·5	
7	59·4		60·5		67·7		61·6		76·5		81·0	
8	71·0		71·3		80·0		73·2		89·7		95·7	
9	81·6		83·7		93·5		83·7		103·5		110·5	
10	93·5		95·7		106·9		95·7		119·2		128·0	
11	111·7		110·7		121·0		113·0		–		153·5	
12	131·5		132·3		152·3		135·3		167·0		182·5	
13			153·3		178·5						213·5	

Nº	A190		A191		A192		A193		A194		A195	
D	25/11		25/11		25/11		26/11		26/11		26/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·2150		·2095		·2115		·2160		·2165		·2170	
T_1	52·6		54·7		54·7		52·0		52·0		53·2	
T_2	82·7		84·5		82·6		74·9		74·5		65·3	
	–	–	–	–	–	–	–	–	–	–	–	13·7
1	12·5	–	8·5	14·5	8·0	14·0	8·7	–	8·5	18·5	12·0	26·5
	–	24·2	–	22·0	–	23·5	–	–	–	–	20·1	
2	–	–	18·5	–	18·7	–	–	–	20·0	38·0	31·1	41·6
	–	40·0	–	36·2	–	37·5	33·7	46·0	–	–	–	71·2
3	37·5	–	29·0	–	30·6	–	–	–	32·6	56·7	55·0	84·6
	–	–	–	–	–	–	49·6	–	–	–	–	–
4	51·0	63·5	40·5	59·0	42·6	61·0	66·3	74·3	50·0	75·2	78·6	114·5
5	–		52·3		54·0		83·7		65·5		103·5	
6	77·0		64·2		67·5		102·0		81·5		131·2	
7	95·2		77·6		83·2		121·0		97·5		159·4	
8	117·6		93·0		98·2		142·4		115·3		193·3	
9	146·0		107·3		114·7		164·0		134·7		226·0	
10	175·2		124·2		–		200·5		155·0		286·7	
11	209·7		144·6		154·7		282·2		178·7		381·2	
12	251·5		173·5						219·5		484·5	
13			203·0									

Nº	A196		A197		A198		A199	A200-3 OBSERVATIONAL (SEE NOTES)	A204		A206	A208-10 OBSERVATIONAL (SEE NOTES
D	26/11		26/11		26/11		26/11		28/11		28/11	
C	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu	To	Tu
D	·2165		·2125 ·2120		·2170 ·2165		·2160+		·1170		·0545	
T_1	53·7		76·2		76·3		85·3		53·7		54·3	
T_2	64·9		91·9		93·2		92·3		87·0		81·7	
	–	–	–	–	–	–	6·6	–	–	–	–	–
1	14·0	27·0	7·5	14·0	9·5	16·0	14·7	21·0	8·6	18·0	17·5	43·2
	24·9	42·0	–	24·2	–	24·3	–	–	15·5	29·0	30·2	–
2	35·6	56·5	19·1	33·0	22·0	–	34·0	48·3	23·0	39·9	47·0	154·5
	–	73·5	–	–	–	41·5	–	–	–	49·9	–	237·7
3	58·4	–	29·5	51·4	–	–	55·2	74·2	37·4	–	97·5	
	–	–	–	–	–	–	–	–	–	–	–	
4	82·9	119·0	43·3	70·5	46·7	68·2	76·6	102·4	–	94·0	179·4	
5	112·2		58·5		60·3		104·2		73·5		289·2	
6	142·5		77·5		74·5		135·5		–			
7	171·5		95·6		90·8		173·5		116·2			
8	207·4		114·8		118·4 (8½")		217·0					
9	245·4		141·0		129·5							
10	321·0		168·5		158·2							
11	407·5		201·0		187·5							
12	510·0		237·3									
13												

Nº	A211	A212	A213	A214	A215	A216	A217	A218	A219	A220	A221	A222
D	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	2/12	2/12	2/12	2/12
C	Tu	Tu	Tu	Tu	Tu	Tu	Tu	Tu	So	So	So	So
D	·8840	·4150	·2115	·120	·863	·4075	·1010	·2115	·409 (AVERAGE)	·408 (AVERAGE)	·1230	·1770
T_1	50·6	50·0	50·5	51·3	54·5	54·8	57·3	56·8	64·4	64·3	64·3	64·3
T_2	89·8	89·8	88·6	87·3	60·2	60·6	63·0	67·3	63·9	64·1	63·9	64·3
	–	–	6·9	10·5	10·6	20·2	31·6	22·0	–	–	5·2	–
1	5·7	9·2	14·0	20·5	19·8	35·0	72·0	42·5	7·6	7·3	10·7	9·0
	–	–	20·4	31·0	–	50·6		63·0	10·0	–	16·2	14·0
2	11·7	17·8	–	41·5	39·5	65·0		83·5	13·2	14·0	22·7	18·6
	–	–	33·3	–	–	–		–	–	–	–	–
3	17·5	26·4	39·9	63·6	57·5	96·0		126·0	18·6	19·2	31·7	27·6
	–	–	–	–	–	–		–	–	–	–	–
4	23·0	35·0	53·0	91·7	77·3	123·7		178·0	24·5	25·6	50·2	38·0
5	29·4	43·5	66·2	121·2	97·2	155·0		231·5	30·6	32·4	68·7	47·6
6	35·3	52·5	79·0	154·0	117·0	189·3		298·5	37·3	38·4	89·5	59·0
7	41·3	61·6	–	191·6	136·8	221·2		383·5	42·7	44·0	112·0	72·5
8	46·8	71·0	100·8 109·7		157·2	254·0			48·5	50·2	143·3	89·6
9	52·6	80·3	128·5		177·3	288·0			54·7	56·3	179·2	106·2
10	59·9	89·3	149·0		197·6	326·0			60·6	61·9		126·0
11	64·7	99·2	168·5		217·2	363·0			67·0	67·3		147·5
12	70·8	108·4	189·6		238·0				75·8	74·0		172·2
13	76·7	117·7	207·0		258·0					79·4		197·0

Nº	A223		A225		A226		A227		A231		A233	A234
D	3/12		3/12		3/12		3/12		4/12		5/12	5/12
C	To(B)	Tu(B)	To(B)	Tu(B)	To(B)	Tu(B)	To(B)	Tu(B)	To(B)	Tu(B)	To(B)	To(B)
D	·2130		·2170		2190		·2165		·1265 ·1270		·8935	·8860
T_1	57·8		58·0		57·7		58·0		51·0		50·8	49·1
T_2	69·0		69·9		69·9		70·6		86·9		91·5	93·2
	-		8·9		8·0	-	9·3	-	5·7	-	-	-
1	11·6		20·8		17·6	21·8	18·3	21·2	13·0	17·2	6·0	6·0
	22·0		31·4		26·4	35·2	28·3	33·2	20·4	26·7	-	-
2	34·7		43·0		·	48·2	38·7	46·5	30·3	37·0	11·5	11·4
	-	66·0	-		-	-	-	-	41·5	47·0	-	-
3	59·3	79·5	66·2	76·0	57·0	-	62·4	76·0	51·5	58·2	17·3	16·4
	-		-		-	-	-	-	-		-	-
4	84·0		91·0		82·3	103·0	90·1	104·2	78·0		22·5	21·0
5	110·8		119·8		107·5		116·8		111·0		26·0	25·2
6	140·3		152·2		136·5		149·0		154·6		31·5	30·5
7	172·5		192·5		167·0		185·3		-		36·5	35·0
8	208·0		241·2		200·6		228·0		295·3		41·4	39·5
9	257·0		299·2		241·7		281·0				46·0	44·0
10					296·0		347·0				50·5	48·8
11					354·5		421·6				56·0	53·0
12							574·0				60·8	57·8
13											66·4	62·5

Nº	A235		A236	A237	A238	A240		A241		A242	A244	
D	5/12		4/12	5/12	6/12	8/12		8/12		8/12	11/12	
C	To(B)	Tu(B)	To(B)	To	To	So	Su	So	Su	To(B)	So	Su
D	·2145		·8660 ·8656	·8775 ·8780	·860 ·8595	·2210		·7150		·876 ·875	·400	
T_1	50·3		51·6	49·9	49·8	64·7		65·0		50·7	65·4	
T_2	88·7		91·7	94·9	94·8	64·9		-		93·0	"	
	5·7	-	-	-	-	8·5	-	-	-	-	8·5	9·0
1	11·6	12·7	5·3	5·2	4·5	17·2	22·0	11·0	-	5·8	14·0	17·0
	17·1	19·6	-	-	-	27·8	34·0	-	18·0	-	21·0	24·5
2	23·3	26·0	9·8	8·5	8·5	37·8	45·5	22·4	24·4	11·0	27·4	33·0
	-	-	-	-	-	-	-	-	-	-	-	-
3	34·4	38·6	13·6	12·5	13·0	56·4	70·5	32·5	36·2	16·0	39·0	50·0
	-	-	-	-	-	-		-	-	-	-	-
4	45·9	51·4	18·3	16·0	16·3	78·0		43·5	47·2	21·5	52·5	66·1
5	58·2		23·5	20·2	20·0	98·7		53·2		25·0	-	
6	70·0		28·5	24·7	24·8	121·4		63·5		29·5	78·0	
7	82·7		33·0	29·0	29·2	149·8		73·8		34·2	91·2	
8	-		37·5	33·8	34·6	183·5		83·5		38·6	104·0	
9	116·0		42·5	37·6	39·0	227·0		93·5		43·3	117·6	
10	136·6		46·3	42·5	42·6	278·0		104·6		48·2	133·5	
11	159·5		51·5	47·5	47·6			115·2		52·5	151·5	
12	185·0		56·8	52·3	52·3			127·5		57·0	171·5	
13	211·3		62·0	57·2	57·7			137·5		63·0		

Nº	A245		A246		A247		A248		A249		A250	
D	11/12		11/12		11/12		18/12		18/12		18/12	
C	So	Su	So	Su	So	Su	To(B)	Tu(B)	To(B)	Tu(B)	To(B)	Tu(B)
D	·4000		·1875		·1880		·410		·4075		·2275	
T_1	65·3		65·1		65·3		88·3		83·0		93·3	
T_2	"		65·1		64·7		51·9		52·3		53·0	
	-	11·0	10·0	-	-	12·6	-		-	-	5·2	
1	-	18·0	20·1	24·9	19·5	25·1	8·9		8·3	-	10·2	
	-	26·0	29·8	38·5	34·5 (1¾')	37·6	13·5		-	13·6	-	
2	-	-	42·2	51·6	-	51·8	17·7		16·3	-	20·1	24·2
	35·2	42·8	-	65·0	50·1	62·5	-	24·0	-	-	-	-
3	-	51·5	62·5	79·5		-	-	-	23·2	26·3	29·8	35·8
	-	-	-	-		-	-	-	-	-	-	-
4	58·9	68·5	87·3	106·5		106·1	33·2	38·3	30·4	34·6	39·2	47·5
5		85·5	115·0			135·6	-		-		-	
6		102·3	145·5			168·3	49·0		45·6		58·8	
7		119·7	178·0			212·4	57·0		-		69·0	
8		137·2	216·5			265·7	65·5		59·7		-	
9		155·5	267·4			326·0	73·6		67·2		92·9	
10		173·0	334·7			392·0	-		75·0		108·5	
11		-	413·5			477·5	91·7		87·5		124·7	
12		209·3	515·0			596·5	100·5		91·5		142·6	
13							107·2		100·5		162·6	

Nº	A251	A252		B1	B8	B9	B10	B13	B14	B21
D	18/12	18/12		11/7	19/7	22/7	22/7	23/7	23/7	25/10
C	To(B)	To(B) ⇄	Tu(B)	Su	Su	Su	Su	Su	Su	So
D	·897	·878 ←? ↗		·603	·615	7"	·615	·557	· 7⅛"	7 9/16"
T_1	93·8	67·2		64·0	49·0	39·0	40·5	93·1	91·2	66·5
T_2	52·5	50·8		·	50·0	39·7	40·0	92·8	92·0	67·2
				5·9	3·6	3·3	3·8	3·6	3·6	4·0
1				10·4	7·2	6·2	7·0	6·7	6·8	9·4
				14·8	10·3	9·4	10·0	10·0	10·4	14·0
2				19·7	13·7	12·6	13·3	13·2	13·6	18·5
				23·9	16·6	16·1	16·6	16·6	17·2	23·2
3		21·4		27·6	20·0	19·4	20·0	19·8	20·6	28·0
		-		34·1	23·3	22·6	23·4	23·2	24·0	
4		34·3	31·1	38·9	26·8	25·6	26·6	26·7	27·2	
5		45·0	40·6							
6	30·5									
7										
8										
9	47·5									
10										
11										
12	58·0	117·0								
13										

A1 :- Barrier lifted in two secs. from zero – and for succeeding tests till amended. Wedge uniform to 9' then delayed on far side

A2 :- Drag far side A3 :- Drag near side A8-11 :- See end of notes

A12 :- Discarded A13 :- Leak at gate – discarded

A16 :- Leak – discarded, barrier lifted in 1 sec (to zero)

A38 : Fan caused far side drag (as A1 + 2)

A39-49 :- It was observed during these tests that about 9' the surface tended to come to standstill and the wedge tip to 'dive' slightly – sometimes forming roller

A79 :- Barrier lifted at zero.

A94 :- Depth is for short length at removal of barrier; longer length 2/10 in. below.

A95 :- 20 lb salt in 1·880 ft small mixing tank for A95-98

A99 :- 5 lb salt in 2·512 ft large mixing tank for A99-102

A103 :- 7 lb/2·580 ft large tank A103-5

A106 :- 3 lb/ 2·580 ft large tank A106-9

A110 :- 20 lb/2·585 ft large tank A110-112

A113 :- 1·5 lb/2·710 ft. large tank A113-115

A116 :- 1·5 lb/2·740 ft large tank A116-119

A120 :- 20·4 lb/2·730 ft large tank A120-123. No trace of waves at interface – just turbulent mixing

A121 :- Very good example of non-breaking wave case

A123 :- 20·4 lb/2·745 ft large tank A123-125

A124 :- Waves changing into turbulence at interface.

A127 :- 7 lb/2·705 ft large tank A126-128

A129 :- 7 lb/2·735 ft large tank A129-130

A131 :- 3 lb/2·745 ft large tank A131-133

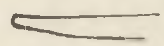
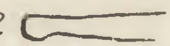
A134 :- 3 lb/2·720 ft large tank A134-135

A136 :- 1·5 lb/2·730 ft large tank A136-138

A139 :- 4 lb/1·078 ft small tank A139-141 These tests were run to show whether the perspex barrier produced uneven fronts due to its spring. This was found to be so, but could be avoided by care.

A158 :- Tendency to 'dive' from about 10' - Nose blunted from 10'.

A175 :- Surface moving for 2·5' infront of front at 9'

A176 :- Change from wedge  to bulbous wedge  very noticeable when surface comes to rest infront of wedge.

A178 :- Good even wedge - bulb from 9' or so.

A190 :- Drops of wetting agent at random in flume - had noticeable effect on front.

A192 :- A few drops of wetting agent behind tip caused roller formed about 10' to be ironed out.

A196 :- Perfect roller with 3 complete turns seen, started to form about 9'

A200 :- 52·5°F basic - 97·0°F in small side. 0·885' depth. Strong wedge advance full of turbulent mixing. Very little sign of surface tension advance. Surface moved only about 1' in advance up to about 4' but at 7' to 8' was 2' or so in advance. Tip dropped at end but did not form roller.

A201 :- 52·5°F - 92·0°F as A200 - 0·403' depth. Slight but definite elongation infront of wedge at start. Finished by about 3' as separately observable feature. 1' surface movement at 4' 3' by 8'. Dived from 10' with roller forming. Definite turbulent mixing in wedge front.

A202 :- 51·5°F - 92°F as A200 - 0·213' depth. Definite elongation to about 3'. Dimple  rather than roller from 3' to 5'. Movement up to 4' ahead a 7'. Virtually no mixing at 7'. Slight dive starts at 10' - roller by $10\frac{3}{4}$'. Roller all way with underflow.

A203 :- 53·5°F - 85°F as A200 - 0·097' depth. Very pronounced run forward continued till about 6'. 2½' + 4½' under and over are about simultaneous. Deteriorates into finest wedge imaginable; 0 at 8' to less than ½ depth at 0'

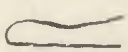
A204-5 :- Bad runs - not used

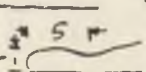
A207 :- 52.5°F - 62.8°F ; 0.408' depth. Little visible mixing and practically no signs of surface advance. Moving surface well ahead by 4', but front moving slightly faster. Dimple at 8' (not roller) Roller from 10½' as surface stops.

A208 :- 51.8°F - 64.5°F ; 0.872' depth. Little sign of surface tension advance. Fair amount of mixing in wedge. - repeat due to visitors.

A209 :- 51.5°F - 64.5°F ; 0.705' depth. Slight surface tension advance stopped by 1.5'. 3' and 2.5' simultaneous over and underflow. Definite mixing but not pronounced. Surface moving 3-4' ahead at 7'

A210 :- 51.5°F - 65°F ; 0.195' depth. Definite surface tension advance. True wedge caught up by about 4'. Smooth advance at 5' with surface moving about 2' ahead. 2.5' at 7'. The surface was held up at 8' and the wedge immediately dived.

A211 :-  Depression but not true roller of slower moving cases.

A212 :- 

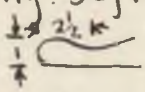
Again slight depression but never true roller.

A213 :- Still only slight dip till near end - 9' on roller more pronounced

A214 :- Slight dip till 5' but changes to 2 to 1 roller by 6'.

A215 :- Slight dip but no sign of true roller - some mixing.

A216 :- Little mixing. Definite bulb at 7', but not roller. Bulb deeper by 9'

A217 :- Bulb again 

. Test disturbed by downpipe plug.

A218 :- True roller formed about 7½'.

A219 :- 15 lbs salt in 2.625' large tank A219-222. Depth varied at start - Short length 0.413', longer length 0.408. Typical pointed wedge with some mixing till 9'-10', when surface drag formed roller No sign of surface tension effect.

A220:- Short length 0.4060', longer length 0.085' at start. Swirl of mixing 3'-7' rather than bulb. No S.T. advance. Fair amount of [mixing bulb.
A221:- Advanced faster than surface with tendency to
Thin wedge at 7'; very small rollers formed at 9'
A222:- 7'-8' roller starts; 9.5' good roller
A223:- 8.5' dips; 8.75' roller; was very smooth at interface by 7'. Showed S.T. advance, but more or less clear by 2.25'. Not quite balanced.
A224:- Too much wetting agent. Overflow held back to less than underflow. Very noticeable surface run back.
A225:- 1 dropperful wetting agent per 9 cu ft. A225-7. Roller from [7.5'
A226:- Trace S.T. advance; 8.5' dives; 9' roller [No S.T. advance.
A227:- Roller forming at 8'. No S.T. advance seen.
A228:- Very uneven wedges - Discard.
A229:- Ditto. A230:- Poor wedges from combination of too little depth and too little density diff. But no signs of S.T. advance (Test was 64.3-74.1 at 0.0885 ft with S.T. balanced.
A231:- 6 dropperfuls W.A. in 2.7' large tank A231-235.
A233 + 234:- No sign of S.T. advance; otherwise no difference from saline case or non-treated thermal. Pronounced turbulence and very sharp point to wedges (overflow)
A235:- Roller from 10.5'
A237:- Slight but definite S.T. advance observed till about 8'
A238:- S.T. advance not observable by 8'. A239 - Discarded
A240-241:- 3lb salt/2.68' of large tank combined with 21 drops W.A. in 2.58'. A240 - moderate; A241 good wedges
A242:- 4 dropperfuls of W.A. in 2.6' of large tank. S.T. balanced
A243:- 3lb salt in 2.725' of large tank A243-247.
A246:- 9.5' - tendency to roller. Still only slight roller by 11'.
A248-251:- S.T. balanced at 52-93°F (in A248 overbalanced?)

A252 :- S.T. balanced

B1 :- $\Delta\rho = 0.00579$ gm/m.l.

B6 :- $\Delta\rho = 0.00595$ gm/m.l.

B9 :- $\Delta\rho = 0.00629$ gm/m.l.

B10 :- $\Delta\rho = 0.00596$ gm/m.l.

B13 :- $\Delta\rho = 0.00606$ gm/m.l.

B14 :- $\Delta\rho = 0.00569$ gm/m.l.

B21 :- $\Delta\rho = 0.00265$ gm/m.l.

Runs A8-11. For these runs the flume was filled to a depth of 4½" (.375') in the usual way, with the warmer water in the shorter length. The barrier was then cracked open and filling continued on the cold side. Some mixing occurred between the cold water underlying the warmer water and the warmer water. Temperature traverses at the middle of the short length of the flume, immediately prior to the lifting of the barrier, are given below. The second temperature in the tables represents in this case the warm water temperature at the start of the 'lifting'.

A8: Final Depth 10⅛" 10⅛"/76.3 9½"/76.5 8"/75.0
6"/69.0 4½"/60.8 3"/60.0
A9 : F.D. 10⅛" 10⅛"/75.3 9"/75.0 8"/75.0 7"/74.0
6"/70.5 5"/61.5 4"/58.8 3" 58.5 0"/58.5
A10: F.D. 5 13/16 5 13/16/73.5 5"/74.5 4"/74.0
3"/73.5 2"/71.0 1"/65.0 0"/61.5
A11 : F.D 5⅝" 5⅝"/75.0 5"/75.5 4"/75.0 3"/74.3
2"/72.0 1½" 68.0 1"/65.5 ½"/62.0 0"/60.0

16.2 Recordings for test series E (and e)

Again recordings are in the form of tables and notes. The following abbreviations have been used in the tables.

No. - test No. (small e signifies surface tension balanced)

D - Date (1959 omitted)

C - Code indicating position of introduction box: A:- facing up flume from gate with open end at + 11 ft. 0 in., floor 0.5 ft. above bottom. B:- as A but 0.25 ft. above bottom. C:- facing up flume with open end at + 4 ft. 8 in., floor 0.25 ft. above bottom. D:- as C but floor 0.35 ft. above bottom.

D - Total depth in feet

T_1 - Basic temperature, ^oF

T_2 - Inflow temperature, ^oF

Q - Flow in cusecs.

The times (in seconds) for the tips of the fronts to reach the various distances from the open end of the introduction box (with zero time as indicated) are then given.

The notes follow the tables.

Nº	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
D	15/1	16/1	16/1	20/1	20/1	20/1	20/1	20/1	21/1	21/1	22/1	22/1
C	A	A	A	A	A	A	A	A	B	B	B	B
D	·675	·675	·675	·675	·675	·675	·675	·675	·3375	·3375	·3375	·3375
T_1	52·7	55·4	56·6	59·4	60·7	61·2	61·5	61·7	52·8	54·2	57·2	58·0
T_2	77·0	78·2	78·5	79·9	73·7	67·7	74·1	91·0	77·0	76·3	78·7	79·5
Q	·0242	·0201	·0201	·0201	·0201	·0202	·0201	·0201	·0125	·00633	·00633	·00633
1	0	0	0	0	0	0	0	0	0	0	0	0
2	11·4	9·0	10·5	12·5	12·8	18·5	11·6	9·2	19·2	18·0	12·5	22·0
3	22·8	22·0	20·9	26·4	26·4	36·1	26·0	19·2	32·2	37·1	26·7	40·5
4	34·5	34·7	-	36·4	40·0	56·0	38·7	28·7	43·3	55·4	37·0	56·2
5	43·8	46·7	-	45·4	52·0	76·0	51·0	36·7	57·7	76·2	49·3	76·2
6	54·7	56·7	55·2	54·0	65·0	97·3	63·7	45·2	72·0	97·7	59·3	96·2
7	64·2	67·3	66·0	63·5	77·0	111·1	-	52·7	84·9	118·2	74·2	116·0
8	74·7	78·2	77·0	74·0	89·4	129·2	75·6	-	99·8	-	89·7	-
9	84·2	89·3	89·0	84·2	102·2	147·3	101·3	70·4	114·7	169·4	104·0	163·7
10	94·7	100·7	101·0	95·2	114·8	162·5	114·5	79·7	130·8	194·7	121·2	188·0
11	104·7	112·3	111·6	104·3	127·7	181·7	126·0	-	146·0	222·0	140·3	211·3
12	115·2	123·7	123·6	115·7	141·2	201·7	139·2	95·4	164·0	252·3	159·5	239·0
13	127·0	135·7	135·5	127·2	154·2	220·2	-	-	182·3	282·3	-	265·8
14	138·5	148·0	148·5	137·7	168·0	241·0	165·7	113·9	202·0	313·6	201·3	291·8
15	148·6	159·5	160·0	148·4	182·7	-	179·3	122·6	221·4	346·0	221·5	321·0
16·5	165·7	179·0	179·0	166·4	206·7	288·7	201·6	137·0	254·3	397·5	261·8	336·0

Nº	E13	E14	E15	E16	E17	E18	e19	e20		e21	e22	e23
D	22/1	22/1	22/1	22/1	23/1	23/1	6/2	6/2		6/2.	6/2	6/2
C	B	B	B	B	B	B	A	A		C	C	C
D	·3375	·3375	·3375	·3375	·3375	·3375	·675	·675		·3275	·3275	·3275
T_1	58·5	59·8	61·8	62·5	62·0	62·8	60·0	60·3		61·5	61·8	62·5
T_2	79·0	81·8	82·8	84·2	85·1	82·6	80·3	80·6		81·5	81·7	82·0
Q	·00745	·00660	·00785	·00760	·00695	·00755	·020	·020		·0071	·0071	·0071
1	0	0	0	0	0	0	0	0	6"	0	0	0
2	18·0	17·5	13·0	13·7	12·0	12·5	12·2	12·2	1'-2"	10·2	10·0	12·2
3	36·5	33·5	26·0	29·5	23·0	29·0	23·5	23·7	1'-8"	-	18·7	21·7
4	53·3	50·0	38·5	43·0	36·6	46·0	34·0	34·2	2'-8"	36·0	33·7	36·5
5	72·5	66·8	54·2	55·8	51·3	62·8	43·5	45·3	3'-8"	51·5	49·0	52·0
6	91·0	85·0	70·3	-	63·3	79·0	52·7	55·5	4'-8"	71·0	70·0	68·0
7	110·8	103·0	85·0	82·4	-	95·0	62·0	67·5	5'-8"	91·2	87·5	89·5
8	135·0	122·7	-	98·0	94·0	113·9	-	78·0	6'-8"	110·9	107·5	108·5
9	154·3	143·7	121·8	113·5	107·5	131·8	83·7	88·7	7'-8"	-	130·0	132·2
10	177·3	164·0	142·0	130·6	123·0	153·3	95·0	98·5	8'-8"	158·5	153·0	156·0
11	202·0	186·3	162·5	146·2	138·0	175·6	106·0	110·3	10'-2"	199·7	193·5	196·5
12	227·2	201·7	182·8	161·7	153·0	196·6	117·8	122·0				
13	253·4	237·3	-	-	170·2	221·3	130·0	-				
14	280·3	265·2	229·5	-	186·2	241·3	142·8	147·0				
15	307·5	292·3	255·3	209·5	201·2	272·7	154·5	158·0				
16·5	351·6	337·2	295·5	247·3	225·0	319·0	175·9	182·5				

No	e24	e25	e26	e27	e28	e29
D	7/2	7/2	7/2	10/2	10/2	10/2
C	C	C	C	D	D	D
D	·3375	·3375	·3375	·4725	·4725	·4725
T_1	60·7	61·8	62·4	60·5	61·2	61·7
T_2	81·7	81·5	82·4	81·3	82·6	82·1
Q	0071	·0149	?	·0118	·0118	·0118
6"	0	0	0	0	0	0
1'2"	10·5	6·2	10·2	7·0	7·3	7·5
1'8"	19·7	9·0	21·0	15·0	16·2	15·5
2'8"	37·3	26·0	45·6	27·5	28·7	28·7
3'8"	52·5	39·0	71·5	40·4	43·0	40·5
4'8"	69·3	52·0	97·0	54·3	56·5	52·0
5'8"	88·8	67·0	123·2	67·0	67·2	65·2
6'8"	109·8	82·5	155·0	78·6	81·0	79·5
7'8"	128·8	-	190·5	94·6	96·0	92·5
8'8"	154·3	110·0	227·5	109·3	110·5	107·5
10'2"	169·0	134·5	289·7	133·5	136·0	131·0

E1:- With tip at 16'-6", Surface temp 2'-3" back = 76·0°F

E2:- Uneven wedge; little surface movement ahead. At end 76·5°F 18" back from tip, 77·5°F 4' back.

E3:- Uneven wedge ⇒̲; change from one side to other after 3' No S.T. spread from 8' on 77·0°F 18"; 77·7 4' back at end

E4:- Better wedge, surface does move though not quite as fast as flow. The straightness and levelness of flow from the box is apparent. 78·5°F 3'; 79·5°F 7' back at end

E5:- No visible difference from previous cases but depth must be greater 73·7°F 4' back at end

E6:- Slope down from entrance. Very noticeable change to deeper layer and wedge. 66·0°F 12" back 67·2°F 3' back at end.

E7:- 72·5°F 18" back, 73·2 3' back at end. See also after E 8

E8:- Flow lifted before reaching end of entrance box. Thinner than 7. 88·5 °F 2·5' back at end. With tip at 7' depth from bottom of overflow to bottom is at 6' is 7¼", at 5' is 7½", at 4' is 7" With tip at 12', bulge depth is 7⅛", at 11' is 7½", at 10' is 7¼" at 9' is 7"

E7 (contd) Tip at 7', depth at 6' is 6¼", at 5' is 6¼", at 4' [is 6½"
Tip at 12', bulge 5¾", at 11' is 6⅝", at 10' is 6⅜", at 9' is 6½", at 8' is 6½"

E9:- Good wedge, but good bit thicker than entry depth 74·5 °F 3' back, 75·7 °F 4' back at end. Tip at 7', bulge 3", after rise slopes down to 2⅝" about 4'. Slopes from entrance to 2⅝" at 1'. Tip 12', bulge 2⅞", after rise back about 3⅛"

E10:- Slight slope down, good wedge. 70.0°F 18" back, 73.5°F 4' back at end. Tip at 7', bulge $3\frac{1}{4}$", after rise slopes down to $3\frac{1}{8}$" at about 4'. Slopes down from entrance to $2\frac{5}{8}$" at 1'. Tip at 12', Bulge $3\frac{1}{8}$", after rise back about $3\frac{1}{4}$".

E11:- Pronounce S.T. advance with no bulge. 77°F 18" back, 77.0°F 5' back at end. Tip at 12', no bulge, 3" back $3\frac{5}{8}$", at 11' is $3\frac{1}{2}$" then back at $3\frac{1}{2}$"-$3\frac{3}{8}$".

E12:- Little trace of S.T. advance. 73°F 18" back 76.5°F 5' back at end. Tip at 7', bulge $3\frac{1}{8}$" — rise — back at $3\frac{1}{8}$". Tip at 12', bulge $2\frac{7}{8}$", at 11' is $3\frac{1}{8}$" and back at this.

E13:- Good even wedge and appeared to be good run. Not much sign of S.T. advance. 71°F — 18" back, 71°F(?) 6' back at end. Later surface temps 77°F at 13' 78.5°F at 7'. Tip at 7' bulge $3\frac{1}{8}$". Tip at 12' bulge $2\frac{7}{8}$" at 11' is 3" and back at this.

E14:- 72.0°F at 18" back 80 at 5' back at end. Later surface temps. 79°F at 15', 81°F at 4'. Tip at 7', bulge $3\frac{1}{4}$", rise $3\frac{1}{2}$", at 5' $3\frac{1}{4}$". Tip at 12', Bulge $3\frac{1}{4}$", rise $3\frac{3}{8}$", 11' is $3\frac{1}{4}$", 10' is $3\frac{1}{8}$", 9' is $2\frac{7}{8}$".

E15:- Not much signs of S.T. advance. 77.1°F 2' back, 81.1°F 6' back at end. Tip at 7', bulge $3\frac{1}{2}$", rise $3\frac{5}{8}$", at 5' is $3\frac{3}{8}$".

E16:- S.T. advance. 78.0°F 3' back, 80.7°F 7' back at end.

E17:- Very much S.T. advance. 81.0°F 4' back, 82.5°F 7' back.

E18:- Normal case with slight bulge. 77.5°F at 3', 81.5°F at 7' from end.

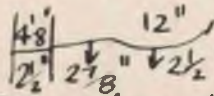
e19:- Poorish start to front. 79.5°F on surface at far end after expt. Tip at 7' similar to e20 at 7'.

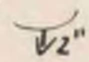
e20:- V.G. front. 80.0°F on surface at far end after expt. Tip at 12' (8"; 7", 6"). Tip at 7' (8"; $6\frac{1}{4}$", $6\frac{1}{4}$") $6\frac{1}{2}$" at 5' then slope back to 6" at box.

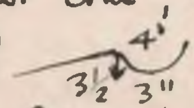
e21:- 80.0°F on surface later. Tip at 6'-8" (5"; $3\frac{1}{4}$", 3"); at 3'-8" (5"; $3\frac{1}{4}$", $2\frac{7}{8}$")

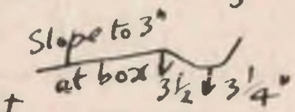
e23:- 81·0°F on surface later.

e24:- 80°F on surface later.

e25:- 80·5°F on surface later. Tip at 6'-8" 

; at 3'8" 

e26:- 72·0°F in wedge tip near end, 78·0°F 3' back. Very small roller when tip at 6'8" 

; at 3'8" 

e27 :- 80·5°F on surface at far end after expt.

e28 :- 81·3°F on surface at far end after expt.

Nº	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10	g11	g12
D	12/2/59	12/2	12/2	13/2	13/2	16/2	16/2	16/2	16/2	16/2	16/2	16/2
C	P	P	P	mx1	mx1	mx2.1	mx2.1	mx2.1	mx2.1	mx1.8	mx2.0	mx1.95
T_1	62.5	62.7	63.3	62.2	63.0	62.2	62.2	62.2	62.8	62.3	63.0	63.5
T_2	82.3	82.5	81.5	82.2	82.5	83.0	83.2	83.0	83.5	83.2	83.3	84.2
Q	.0337	.0337	.0337	.00066	.00066	.00274	.00274	.00274	.00274	.00158	.00193	.00181
0	0	0	0	0	0	0	0	0	0	0	0	0
2	11.2	10.2	10.3	4.8	4.7	-	-	-	-	-	-	-
3	18.3	17.0	17.3	8.6	8.9	4.8	-	5.0	4.8	5.5	5.0	5.6
4	26.0	24.9	23.8	12.7	13.5	7.5	7.0	7.5	7.5	8.4	7.5	8.5
5	32.5	33.5	32.6	17.5	19.0	9.8	9.5	9.4	10.2	12.3	10.0	10.2
6	43.3	44.5	43.5	23.0	24.5	-	12.3	12.2	12.7	15.7	12.3	13.9
7	55.8	57.8	55.5	28.4	32.5	15.5	14.3	16.0	16.3	19.0	15.2	17.7
8	68.9	71.7	69.3	36.3	42.5	18.4	17.2	-	19.7	23.7	19.3	22.2
9	83.5	83.7	82.1	45.2	52.3	24.0	20.7	23.0	23.5	29.0	23.3	26.3
10	103.0	99.8	100.2	55.8	63.8	30.2	26.4	27.8	27.2	35.6	27.8	32.1
11	121.4	116.2	119.5	68.0	76.0	38.0	32.0	33.2	33.0	42.7	31.8	38.4
12	140.0	134.5	139.5	83.9	91.2	45.5	38.0	38.7	38.4	49.5	36.6	44.4
13	164.5	153.0	157.5	104.0	112.0	53.2	44.0	46.0	43.7	57.8	43.6	51.2
14		170.0	181.3	122.8	132.5	61.2	48.0	50.5	49.0	64.7	51.5	57.2
15				140.7	153.2		53.2	57.4	54.2	74.0	59.5	
16				157.5	169.5		59.5	66.0	61.3		67.0	
17				177.4	187.0		66.0	74.0	70.2			

Nº	g13	g14
D	16/2	16/2/59
C	mx1.95	mx1.95
T_1	63.5	63.8
T_2	84.0	83.6
Q	.00181	.00181
0	0	0
2	-	-
3	4.5	5.2
4	7.9	7.5
5	10.2	10.3
6	13.2	13.6
7	16.9	16.8
8	19.7	21.7
9	24.3	27.0
10	31.2	32.5
11	36.0	38.5
12	40.0	44.2
13	49.0	50.3
14	56.7	57.2
15	64.3	65.6
16		
17		

16.3 TEST SERIES G

All tests carried out with surface tension difference balanced out. 'C' signifies code; with P indicating full size tests as shown in FIG. 7.18 with a total depth of 10 in. and 2 in. in introduction box. All reduced scale tests were 1/5 horizontal scale and are indicated mx1.8, where a 1.8 exaggeration is used in the particular test. T_1 and T_2 are the basic and introduced water temperatures. Q shows the introduced water flow in cusecs. The times to the various distances are then given, equivalent model distances being used for the reduced scale tests. This simplifies comparison and plotting, as in FIG. 7.20.

16.4 Current Meter Calibration Recordings

Min. current meter and Ott meter placed about 2" apart at approx 5 in. depth in 6 in of water in 18 in. wide flume.

No	Velocity by timing	Prop. revolutions by counting	Deflection on meter	Ott meter - time for 50 revs.
1	9.2, 9.5, 8.6, 8.8, 8.2, 9.1 } 1ft. 0.112 ft/sec.	33.8, 33.8, 34.7, 34.8 } 20revs. 0.584 revs per sec.	0.06 scale C 0.28 scale A	
2	4.1, 4.2, 4.1 } 1ft 0.241 ft/sec.	10.6, 10.4, 10.1, 10.4 } 20revs. 1.92 revs. per sec	0.20 scale C 1.00 scale A	
3	7.0, 6.8, 6.5, 6.7, 7.1, 6.8, 7.15 } 3ft 0.437 ft/sec	7.35, 7.1, 7.4, 7.4 } 20revs. 2.74 rev/sec (too fast?)	0.42 scale C 0.80 scale B	33.45, 33.1, 33.6 } 0.128 m/sec or 0.420 ft/sec
4		5.3, 5.3, 5.5, 5.2 } Suspect	0.62 scale C	19.1, 19.0, 19.2, 18.9 }
5	5.0, 4.8, 5.0 } 3ft 0.61 ft/sec		0.61 scale C	19.3, 19.2, 19.0, 19.7 } 0.192 m/sec or 0.630 ft/sec
6	4.1, 3.8, 3.6, 3.7, 4.0 } 3ft 0.79 ft/sec		0.77 scale C	13.8, 13.3, 13.0, 13.0 } 0.245 m/sec or 0.802 ft/sec
7	8.1, 8.05, 8.5, 8.0 } 3ft 0.368 ft/sec	7.5, 7.7, 7.3 } 20 revs 2.68 rev/sec (suspect)	0.36 scale C 0.69 scale B	48.3, 49.1, 47.8, 48.4 } 0.110 m/sec or 0.36 ft/sec
8	37.6, 35.7, 31.5, 34.5, 32.5 } 2ft 0.0582 ft/sec	77.8, 43.0, 57.1 } 5 revs 0.0845 r/sec.	0.02 scale C	
9	15.3, 14.3, 15.0, 14.3, 15.0, 14.6 } 2ft 0.135 ft/sec	12.4, 12.7, 13.0, 13.0 } 10 revs 0.780 r/sec	0.10 to 0.09 scale C	
10	17.3, 17.9, 17.8, 18.0, 18.0 } 3ft 0.1685 ft/sec	12.7, 12.7, 12.7, 12.8 } 15 rev 1.18 r/sec.	0.10 to 0.09 Scale C	
11	14.0, 13.7, 13.8, 13.7, 14.1, 13.7 } 3ft 0.218 ft/sec	11.1, 11.5, 11.3, 11.4, 11.0 } 20 rev 1.78 r/sec	0.20 Scale C	
12	9.9, 9.8, 10.1, 9.9, 10.0 } 3ft 0.305 ft/sec	16.0, 17.2, 17.5, 18.1, 17.9 } 50 rev. 2.82 r/sec	0.29 Scale C	

16.5 Recordings for test series H

The recordings are in the form of notes giving temperatures and flows, and reproductions of the oscillograph recording strip for the various tests, the latter having been mounted on quarto paper before copying. Some detail is perhaps lost, especially in the case of originally poorer recordings, but the essential detail can be read, and the method has allowed the preparation of the necessary five copies with reasonable economy in effort and cost.

Throughout the tests the introduction box was positioned with the open end facing downstream at plus 6 in. in the larger flume, the box bottom being 0.5 ft. above the flume bottom. The total depth was maintained at 0.625 ft. throughout series H.

For test H(a) the speed of the recording camera was 1 in. per sec. and thereafter was 0.5 in. per sec.

During tests H(a) - (e) the bare recording probes were positioned as follows, the distance from the edge of the box being given first and the distance from the right hand side of the flume (facing downstream) thereafter (Depths are given on the recording strip reproductions.)

Probe 1	In box		Probe 9	18 in.	8 in.
Probe 2	6 in.	3½ in.	Probe 10	30 in.	3½ in.
Probe 3	6 in.	7½ in.	Probe 11	30 in.	8½ in.
Probe 4	6 in.	13 in.	Probe 12	42 in.	8 in.
Probe 5	12 in.	3½ in.	Probe 13	42 in.	13 in.
Probe 6	12 in.	9 in.	Probe 14	54 in.	5½ in.
Probe 7	12 in.	13 in.	Probe 15	54 in.	8½ in.
Probe 8	18 in.	3 in.			

For tests H2 - 17 the damped recording probes were positioned 18 in. from the end of the box (apart from Probe 1 in the box) and the depths were:-

Probes 2 - 9 uniformly spaced from 3 in. deep to ½ in. deep, and Probe 10 at the surface. Probe 11 was left bare and was used for subsidiary recordings, again at 18 in. as detailed on the recordings.

The flows were as follows (cusecs):-

Flows No.	Lower flow	Upper flow
1	0.357	0.0894
2	0.1785	0.0447
3	0.0893	0.0223
4	0.0447	0.0112

In the notes the lower flow temperature is always given first.

The oscillograph recordings were mounted for copying so as to be read left to right and top to bottom with the volume turned to the normal second reading position.

The tests were carried out during the first half of June, 1959.

H1 FLOWS 1

(a) 61·1°F - 75·0°F (

(b) 62·1°F - 75·2°F (62·6°F at finish)

(c) 63·3°F - 75·7°F (63·7°F at finish)

(d) 64·6°F - 76·7°F (64·8°F at finish)

(e) 64·0°F - 77·5°F (64·0°F at finish)

H2 FLOWS 1 63·0°F - 75·8°F

H3 FLOWS 1 64·3°F - 71·6°F

H4 FLOWS 1 64·8°F - 91·3°F

H5 FLOWS 1 62·0°F - 69·3°F

H6 FLOWS 1 62·3°F - 66·5°F

H7 FLOWS 1 62·8°F - 76·0°F

H8 FLOWS 1 63·5°F - 94·0°F

H9 FLOWS 2 62·6°F - 75·6°F

H10 FLOWS 2 63·4°F - 68·3°F

H11 FLOWS 2 63·6°F - 65·5°F

H12 FLOWS 2 63·7°F - 94·7°F

H13 FLOWS 3 65·1°F - 95·7°F

H14 FLOWS 3 63·3°F - 68·4°F

H14(a) FLOWS 3 Small temp. diff.

H15 FLOWS 3 63·8°F - 77°F ? (0·0015 density diff.)

H16 FLOWS 4 65·3°F - 90·5°F

H17 FLOWS 4 65·6°F - 71·8°F

H18 FLOWS 2 61·0°F - 74·5°F

H19 FLOWS 2 63·0°F - 70·8°F

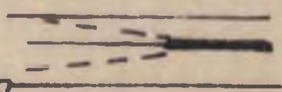
H20 FLOWS 2 63·5°F - 66·5°F

H21 FLOWS 2 63·5°F - 85·7°F

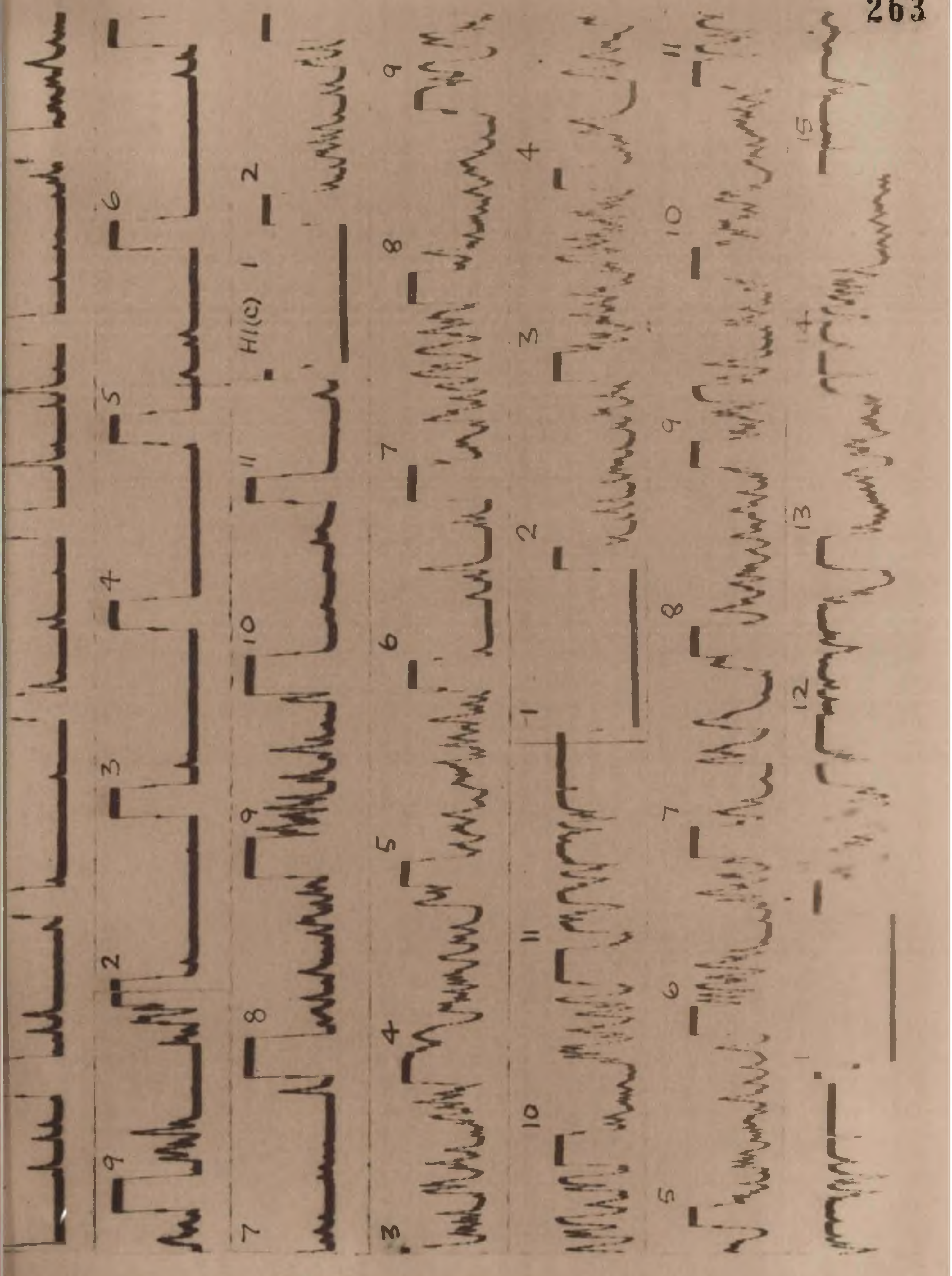
H22 FLOWS 2 65·8°F - 58·8°F (Reversed case)

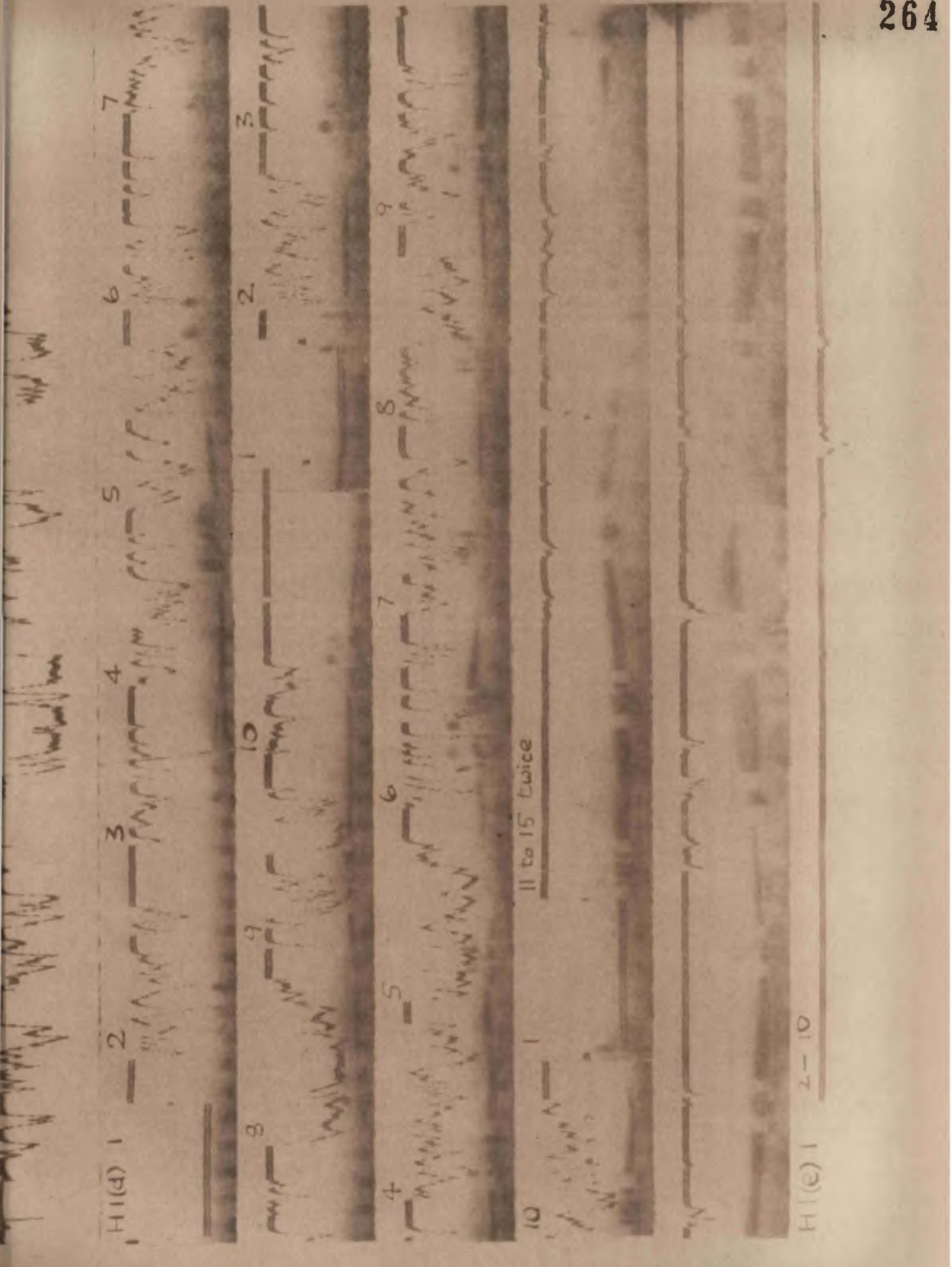
H23 and 24 FLOWS 2 63·0°F - 66·5°F and 63·5°F - 65·5°F.

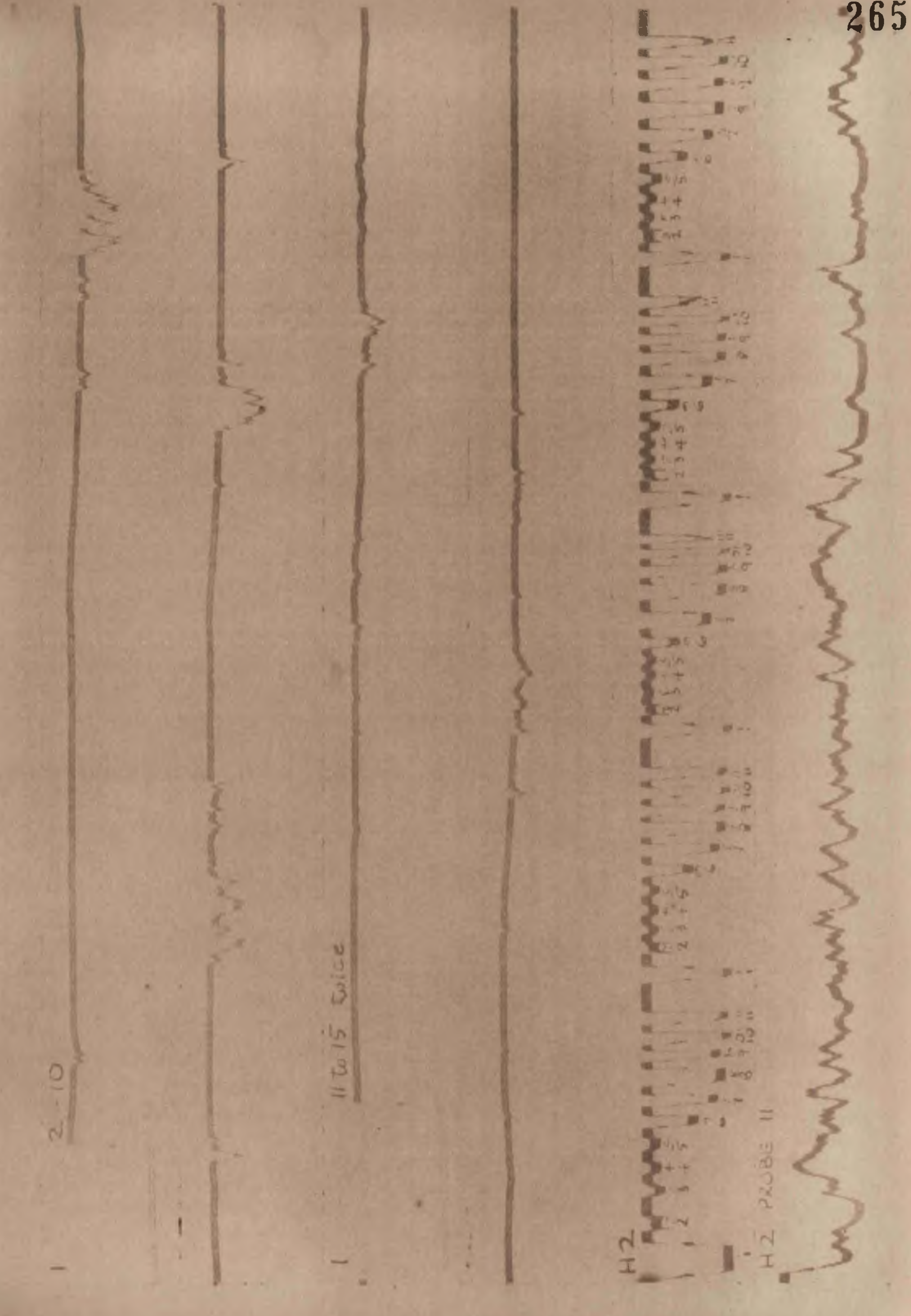
In both these runs the mixing died away after 4'6" and heated top flow continued to end of flume. at this flow stratification is obviously very sensative to the slightest. density difference.

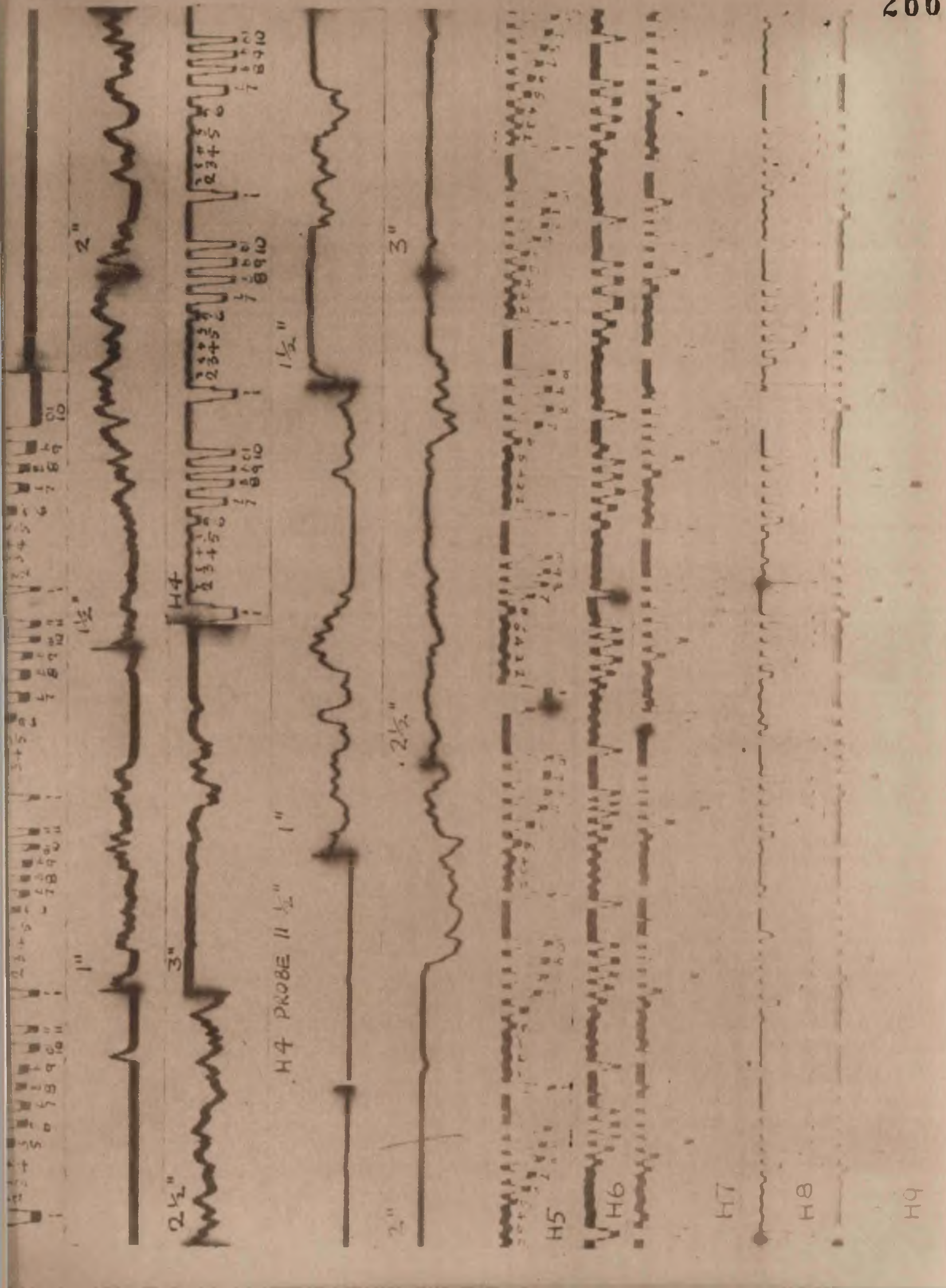
H25 Lower flow rather over 0·5 cusecs (60°F) and a upper flow of 85°F put in by eye, top depth being about 1 m. mixing occurred right through top flow from the point of confluence in the typical 'Jet' manner  Statification still maintained to the end of the flume mixing much less after first few feet.

H26 Bed of 3/4" pebbles put on flume bottom. for first six feet from the edge of the box. VISUAL comparison between roughened and unroughened part did not show any greater diffusion of dye stream But repeat of H25 seemed to give greater draw down of surface (coloured) water once it was initially pulled away from the interface.

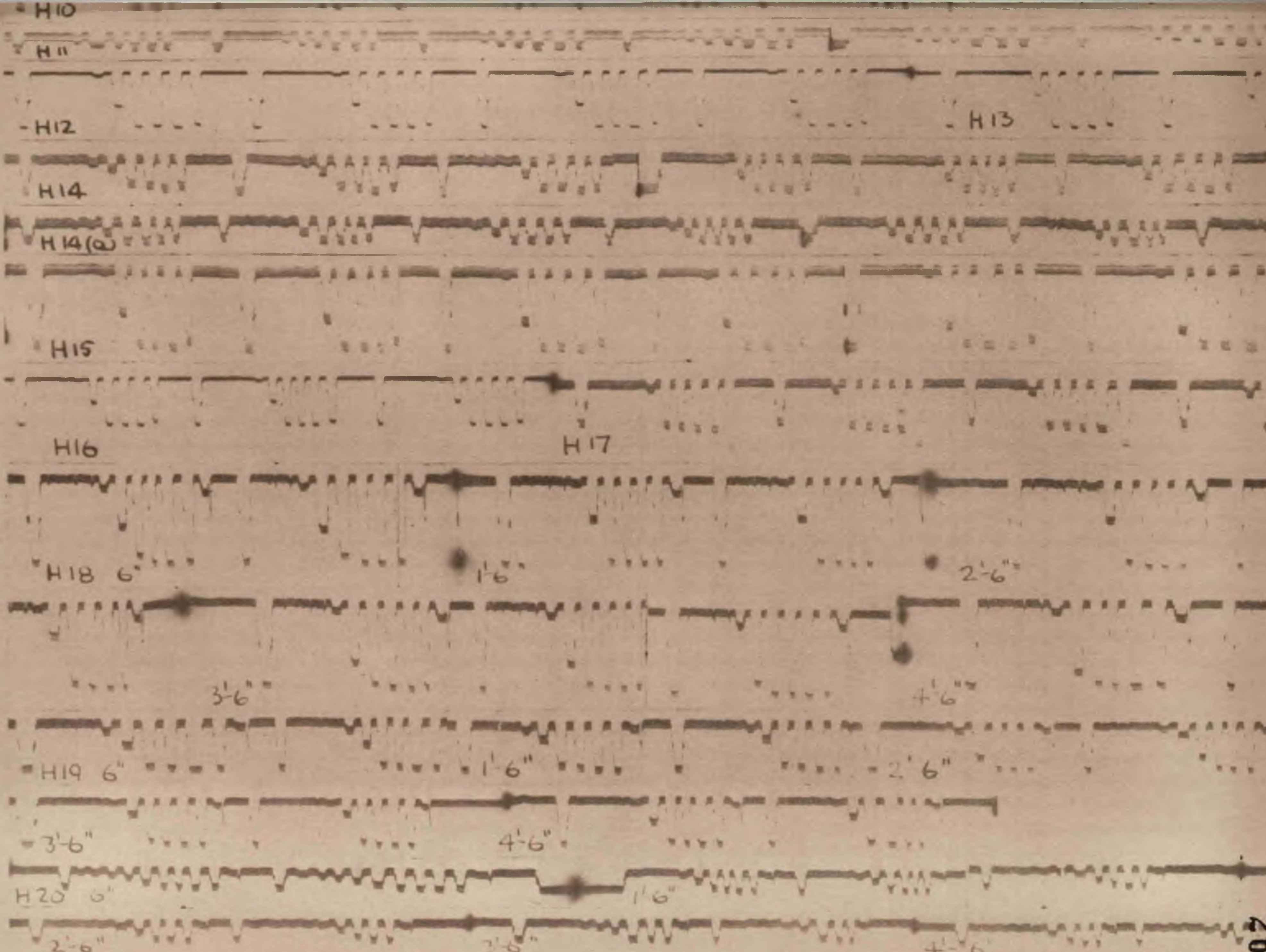


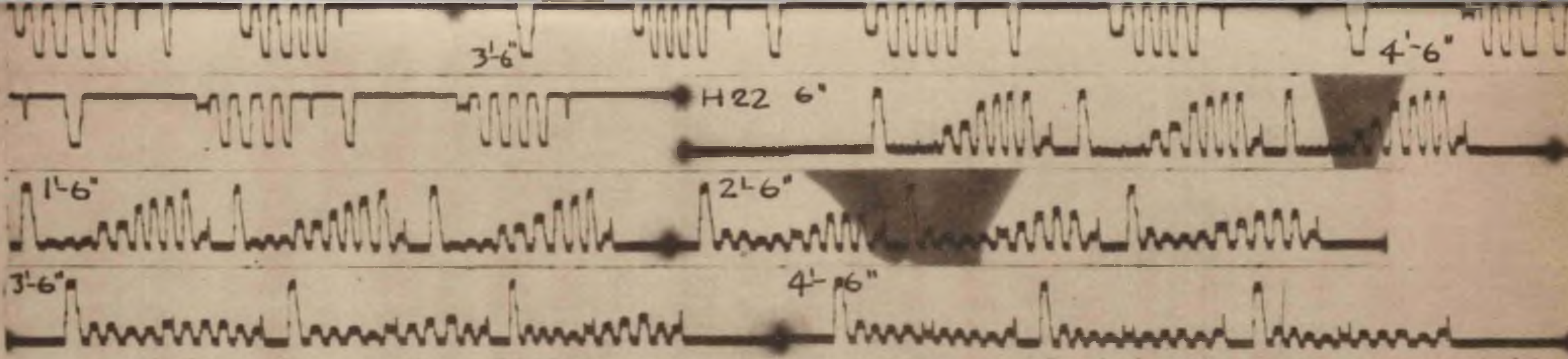

H1(d) 1
11 to 15 twice
H1(e) 1
2 - 10


2-10
11 to 15 twice
H2
H2 PROBE II



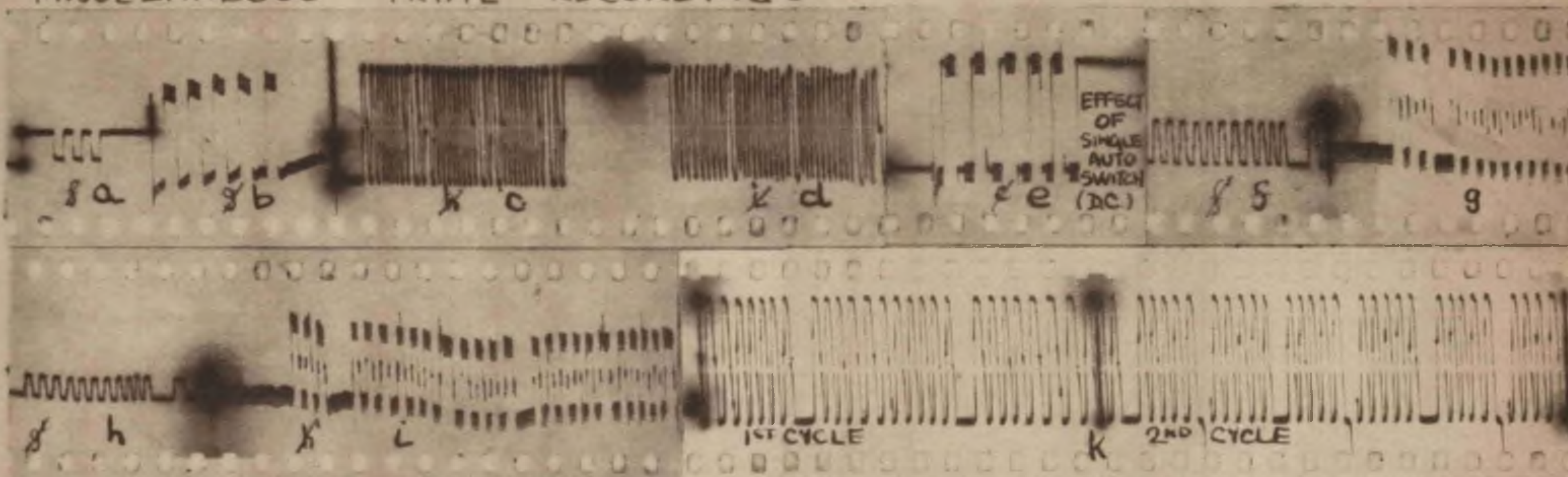
H4 PROBE 11 ½"
H4
H5
H6
H7
H8
H9


H10
H11
H12
H13
H14
H14(a)
H15
H16
H17
H18 6"
1'6"
2'6"
3'6"
4'6"
H19 6"
1'6"
2'6"
3'6"
4'6"
H20 6"
1'6"
2'6"
3'6"
4'6"



END OF RECORDINGS FOR TESTS H

MISCELANEOUS TRIAL RECORDINGS



(a) to (d) with 7 junction thermopile system of chromel - alumel. - two circuits only
(a) 66.4 - 69.0°F D.C. (b) 66.4 - 69.0°F A.C. (c) 63.8 - 74.8°F, 0.25 in/sec recording D.C. and 1 rev/sec on switch (d) as (c) but 0.5 in/sec and turning switch as fast as possible. (f) to (i) with 4 junction thermopile chromel-constantin:- two circuits only (f) 64.2 - 68.8°F D.C. (g) 64.2 - 68.7°F A.C. (h) 64.2-66.7°F D.C. (i) 64.2-66.7°F A.C. (k) agreement between probes (4 junction chromel-constantin) at start of tests H.

16.6 Recordings for test series J.

The recordings are in the form of tables and notes. The following abbreviations have been used in the tables.

No. - Test No.

D - Date (1959 omitted)

C - Configuration of flume etc. (as shown below)

D - Total depth (in feet) (N.B. in small scale tests this refers to the actual depth).

T_1 - Lower flow temperature. °F

T_2 - Upper flow temperature. °F

Q - Upper and lower flows indicated by No. (as shown below). Thereafter the times for a surface float to reach the various distances from the introduction box (as shown) are given (in seconds).

The notes follow the tables.

Configurations

In both larger and smaller flumes the entry box was positioned at -2ft. 0in. (facing downstream) throughout the tests. (In the smaller flume scaled down full size distances and depths were used at all times except for the total depth given under D in the tables and the distances above the bottom noted here).

Configuration A:- Larger flume with bottom of box 0.5 ft. above flume bottom.

Configuration B:- $\frac{1}{4}$ horizontal scale model of A in smaller flume with 1.8 vertical exaggeration; i.e. bottom of box 0.225 ft. above flume bottom.

Configuration C:- Natural $\frac{1}{4}$ scale model of A in smaller flume:- i.e. bottom of box 0.125 ft. above flume bottom.

Configuration D:- A with $4\frac{1}{4}$ in. x $2\frac{7}{8}$ in. block across flume at +7 ft. (9 ft. from box) with $4\frac{1}{4}$ in. side vertical.

Configuration F:- D with block at zero ft. (2 ft. from box).

Flows

The lower flows of each pair are given first (cusecs)

Larger flume (R.N.$_{65}$ indicates Reynolds Number for flume at 65°F based on the total depth and total flow and the whole wetted perimeter).

Flows No.	Lower flow	Upper flow	Mean Velocity (ft./sec.)	R.N.$_{65}$
1	0.357	0.0894	0.476	14,200
2	0.1785	0.0447	0.238	7,100
3	0.0893	0.0223	0.119	3,550
4	0.0447	0.0112	0.0595	1,775
9	0.714	0.0596		
10	0.357	0.0298		

Smaller flume Each pair of flows was for a normal Froude law - $\frac{1}{4}$ horizontal scale model of one pair of the larger flume flows, and the intention is indicated thus:- 3 x 1.8 means Flows 3 simulated with 1.8 vertical exaggeration.

Flows No.	Model	Lower flow	Upper flow	Mean velocity (ft./sec.)	R.N.$_{65}$
5+	2 x 1.8+				
6	2 x 1.8	0.01335	0.00334	0.159	1,450
7	3 x 1.8	0.00667	0.00167	0.0785	725
8	3 x 1.0	0.00279	0.00069	0.0595	445
11	10 x 1.8				

+Flows 5 were incorrect attempt at flows 6 and were too small, being 1.49/1.59 of 6 (Slide rule slip). The error was immediately apparent in the velocity measurements.

Nº	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12
D	10/9	10/9	10/9	10/9	10/9	10/9	11/9	11/9	11/9	11/9	11/9	11/9
C	A	A	A	A	A	A	A	A	A	A	A	A
D	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625
T_1	62·5	62·5	62·5	65·2	66·7	66·7	65·4	65·5	65·5	65·5	65·7	67·0
T_2	62·5	62·5	62·5	88·0	89·0	89·0	65·4	65·5	65·5	65·5	90·0	90·5
Q	1st	1st	1st	1st	1st	1st	2nd	2nd	2nd	2nd	2nd	2nd
0	0	0	0	0	0	0	0	0	0	0	0	0
1	2·5	2·3	2·3	2·7	1·4	2·0	5·0	4·3	3·8	4·0	4·2	3·8
2	5·0	5·0	4·4	5·0	4·3	4·7	8·7	8·3	8·1	7·8	7·7	7·6
3	7·6	7·4	6·8	7·0	6·7	7·2	12·7	12·3	12·0	12·0	12·2	13·3
4	9·7	9·8	-	8·8	8·7	9·5		16·3	15·3	15·3	16·0	-
5	12·0	12·0	-	11·2	11·0	11·6		20·0	20·1	19·7	19·3	19·0
6	14·7	14·3	-	13·2	13·7	13·0		24·0	23·7	23·0	23·3	24·6
7	16·7	16·0	-	15·2	14·8	15·2		28·0	27·0	26·2	27·3	27·5
8	18·0	18·0	16·7	16·0	17·5	17·0		33·7	31·0	30·0	31·0	70·8
9	19·9	20·2	19·1	19·0	19·2	19·0		36·4	34·9	33·7	34·5	36·2
10	21·8	-	21·4	21·4	21·3	21·6		40·2	38·1	38·1	38·4	38·4
11	24·3	24·3		23·0	23·2	23·2		44·4	41·7	42·0	-	42·2
12	26·2	26·7		24·4	26·5	25·5		48·8	45·3	45·6	45·5	-
13	27·7	28·7		26·2	27·3	27·0		52·3	49·1	49·0	48·9	49·2
14	29·8	30·8		28·5	29·3	28·7		56·0	52·6	54·0	52·2	52·8

Nº	J23	J24	J25	J26	J27	J28	J29	J33	J34	J35	J38	J39
D	12/9	12/9	12/9	12/9	14/9	14/9	14/9	15/9	15/9	15/9	15/9	15/9
C	A	A	A	A	A	A	A	A	A	A	A	A
D	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625
T_1	67·3	67·3	67·3	67·3	64·3	64·7	65·7	65·2	65·2	65·2	65·7	65·7
T_2	67·3	67·3	67·3	67·3	89·0	88·0	91·0	65·2	65·2	65·2	81·0	81·0
Q	3rd	3rd	3rd	3rd	3rd	3rd	3rd	4th	4th	4th	4th	4th
0	0	0	0	0	0	0	0					
1	-	8·0	6·0	7·0	-	10·0	9·3					
2	17·0	15·7	14·7	-	18·7	18·3	17·0					
3	26·0	23·2	18·7	20·2	27·3	24·5	25·2					
4	32·7	31·5	26·0	26·5	34·6	31·7	33·0					
5	40·5	39·0	33·0	33·7	41·7	39·7	40·2					
6	47·6	46·7	40·4		49·0	46·7	47·3					
7	55·2	55·0	48·0		56·3	54·7	54·6					
8	62·0	65·0	55·3		63·0	62·3	61·5	0	0	0	0	0
9	68·0	72·3	62·4		70·0	71·5	68·3	14·1	15·7	15·7	11·2	10·5
10	74·5	80·1	70·1		76·8	79·6	74·6	27·3	29·5	31·3	21·0	21·3
11	81·5	87·5	77·5		-	87·2	81·5	40·5	44·0	45·7	31·5	31·7
12	88·0	94·3	85·0		90·3	94·0	87·0	52·3	57·9	58·5	41·6	42·0
13	94·5	100·7	-		97·0	102·0	94·4	63·0	73·0	79·5	51·7	51·3
14	101·0	108·0	101·3		103·7	107·0	100·8	74·5	87·0	87·5	61·8	61·0

No	J42	J43	J44	J45	J46	J47	J48	J49	J50	J51	J52	J53
D	16/9	16/9	16/9	16/9	16/9	16/9	16/9	16/9	16/9	16/9	16/9	16/9
C	A	A	A	A	A	A	A	A	A	A	A	A
D	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625	·625
T_1	65·7	65·7	65·7	65·7	65·7	66·0	66·0	66·0	66·5	66·7	66·7	66·7
T_2	65·7	65·7	65·7	65·7	65·7	67·8	71·0	74·5	81·7	92·0	92·0	92·0
Q	4th	4th	4th	4th	4th	4th	4th	4th	4th	4th	4th	4th
0				0	0	0		0	0	0	0	0
1				17·5	17·5	14·0		11·5	11·7	8·5	10·4	11·0
2				34·0	33·2	29·0		24·9	24·0	9·0	22·0	22·0
3				50·0	50·0	42·5		37·6	35·0	28·7	32·2	33·7
4				65·5	65·0	56·0		51·0	47·1	38·6	44·0	46·7
5				82·0				64·5	59·5	49·0	55·6	58·8
6				97·8				75·5	73·0	58·3	67·5	69·7
7				112·4				87·0	85·5	67·2	78·0	87·3
8	0	0	0	127·5			0	100·5	99·5	76·3	88·0	97·2
9	13·7	14·9	15·3	141·0			18·0	112·5	110·0	86·9	100·0	109·0
10	26·8	29·5	32·5	154·5			34·3	123·2	120·5	96·5	111·0	121·3
11	39·0	45·0	48·0	169·0			50·0	134·0	131·2	107·5	121·7	133·4
12	53·5	60·5	63·5	182·7				146·0	141·5	117·0	132·5	142·0
13	67·0	76·0	80·2	197·5				158·0	152·0	127·8	144·0	-
14	80·0	91·0	95·7	211·5				170·5	162·7	138·0	153·0	-

No	J54	J55	J56	J57	J58	J59	J60	J61	J62	J63	J64	J65
D	16/9	18/9	18/9	18/9	18/9	18/9	18/9	18/9	18/9	18/9	18/9	18/9
C	A	B	B	B	B	B	B	B	B	B	B	B
D	·625	·28	·28	·28	·28	·28	·28	·28	·28	·28	·28	·28
T_1	66·7	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0
T_2	92·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0	65·0
Q	4th	5th	5th	5th	5th	5th	6th	6th	6th	6th	6th	6th
0	0	0	0					0	0	0	0	0
1	9·4	2·0	-						2·4	2·5	2·5	
2	18·6	3·6	3·7		0	0			4·7	4·4	4·0	
3	30·7	5·3	6·7		1·7	2·0			6·2	6·4	5·7	
4	43·2	6·7	8·0		-	-			7·5	8·2	7·5	
5	54·9	8·4	9·4	0	4·8	5·7	0		9·6		8·7	
6	67·3	10·3	11·0	2·2	-	-	-		11·0		10·0	
7	80·3	13·0	12·9	4·8	8·4	8·7	4·0		-		-	
8	92·7			-	-	-	-	12·4	12·9	12·1	12·7	
9	105·6			6·8	11·5	11·5	7·0			-	-	
10	116·2			-	-	-	-	15·6		15·6	16·0	
11	127·0			11·5	14·3	-	10·0			-	-	
12	137·3			-	-	-	-			18·3	18·6	17·5
13	147·7			13·5	17·4	17·9	12·7			-	-	-
14	156·5				19·9					21·0	21·5	20·3

Nº	J66	J67	J68	J69	J70	J71	J72	J73	J74	J75	J77	J78
D	18/9	18/9	18/9	18/9	21/9	21/9	21/9	21/9	21/9	22/9	22/9	22/9
C	B	B	B	B	B	B	B	B	C	C	C	C
D	·28	·28	·28	·28	·28	·28	·28	·155	·155	·155	·155	·155
T_1	66.0	66.0	66.0	66.0	64.7	64.8	65.5	65.5	66.5	66.5	67.0	67.0
T_2	87.0	87.0	87.0	87.0	64.7	66.8	72.5	88.5	66.5	66.5	84.0	84.0
Q	6th	6th	6th	6th	7th	7th	7th	7th	8th	8th	8th	8th
0	0	0	0	0	0	0	0	0	0	0	0	0
1	2.4	2.4	–	2.6	4.0	3.7	4.0	4.2	7.2	7.9	5.5	5.1
2	4.0	4.4	4.7	4.4	7.5	7.5	7.0	7.1	13.0	15.3	10.0	8.7
3	5.9	6.0	–	6.0	10.5	10.3	9.6	10.0	18.3	–	14.7	13.3
4	7.0	–	8.0	7.5	13.6	13.7	12.9	12.5	–	23.2	19.0	17.0
5	–	9.0	–	6.2	15.9	–	15.0	15.5	26.4	26.4	23.0	21.2
6	10.0	–	10.7	10.4	18.4	19.3	17.7	17.7	31.4	29.4	26.8	25.4
7	–	11.0	–	–	22.0	22.5	20.2	20.2	33.5	32.7	29.6	29.4
8	12.7	–	13.3	12.8	23.8	24.7	22.4	22.4	36.5	35.6	34.0	33.0
9	–	13.9	–	–	26.7	27.4	25.5	25.2	40.0	38.5	37.5	36.6
10	15.3		15.3	16.8	29.0	29.8	27.7	27.7	43.1	42.0	41.0	40.7
11	–		–	–	32.2	32.5	31.0	–	44.9	46.7	44.6	44.6
12	17.6		18.8	18.7	35.7	35.2	32.5	32.4	50.1	48.3	48.1	47.5
13	–		–	–	37.2	37.6	35.2	34.5	53.0	51.2	51.3	50.6
14	20.5		20.7	21.0	39.4	39.8	38.0	37.0	55.5	53.3	54.5	53.6

Nº	J79	J80	J81	J82	J83	J84	J85	J86	J87	J88	J89	J90
D	22/9	22/9	22/9	22/9	22/9	22/9	22/9	22/9	22/9	24/9	24/9	
C	C	C	C	C	C	C	C	C	C	A	A	
D	·155	·155	·155	·155	·155	·155	·155	·155	·155	·542	·542	No missed
T_1	67.0	67.0	67.0	67.0	67.0	67.0	67.0	67.0	67.0	66.0	66.0	
T_2	91.0	91.0	88.0	88.0	67.0	67.0	61.0	87.0	87.0	66.0	66.0	
Q	8th	8th	8th ‡	8th ‡	8th ‡	8th ‡	8th ‡	8th ‡	8th ‡	9th	9th	
0	0	0	0	0						0	0	
1	5.0	3.5	4.0	4.0						–	–	
2	9.0	7.6	7.7	7.7						–	–	
3	13.4	11.4	12.3	12.4						·	5.0	
4	17.6	14.3	15.6	15.9						4.5	–	
5	20.0	18.4	19.3	19.7	0	0	0	0	0	–	–	
6	23.7	22.0	23.0	23.6	3.4	4.2	4.0	3.5	3.8	7.0	7.7	
7	27.0	25.7	26.5	27.0	6.7	8.0	7.5	6.5	7.0	8.3	–	
8	31.7	29.0	29.7	31.6	9.9	11.9	10.5	10.0	10.6	–	–	
9	34.0	33.0	33.0	34.0	12.7	14.2	14.0	13.0	13.5	10.0	10.5	
10	37.5	36.0	36.8	37.4	15.7	17.9	17.2	16.0	16.5	–	–	
11	41.2	40.0	39.6	41.3	18.1	21.4	20.6	19.3	20.0	11.5	–	
12	44.0	44.0	43.0	44.3	21.4	24.7	–	22.5	22.9	–	13.0	
13	46.7	47.7	46.0	47.5	23.9	28.2	26.0	24.7	25.5	14.0	–	
14	49.5	49.7	48.7	51.3	26.5	–	29.3	27.2	28.3		15.5	

N°	J91	J92	J93	J94	J94A	J95	J96	J97	J98
D	24/9	24/9	24/9	24/9	24/9	24/9	25/9	25/9	25/9
C	A	A	B	A	A	B	A	D	F
D	·542	·542	·244	·542	·542	·244	·625	·625	·625
T_1	66·5	66·5	66·5	64·0	64·0	64·0	66·4	66·4	68·0
T_2	90·0	88·0	87·0	64·0	64·0	64·0	83·2	83·2	84·2
Q	10	10	11	10	10	11	3	3	3
0				0	0				
1				4·0	·				
2				·	4·3				
3				7·7	·				
4				9·8	·				
5				12·0	10·0				
6				14·0	·				
7				·	13·7				
8				18·2	·				
9					18·0				
10									
11					22·7				
12									
13					25·5				
14					27·6				

J1 :- Colour reaches bottom by 4' (from edge of box) - good mixing. Very definite turbulence in box and in main stream.

J2 :- Colour in fainter dilution reaches bottom about 3.5'. But more concentrated at top down flume till about 11' when fairly well mixed

J3 :- Float touched side

J4 :- Definite change to layering, but no distinct interface. Strands of colour, only, reach bottom.

J7 :- Still turbulent in box and below. Mixing of strands to bottom by 4.5'. Main body stays on top.

J8 :- Repeat J7 Mixing pretty thorough by 10'-11'. Very little difference in velocity from surface to 1" from botton as observed by dye.

J11 :- Initial vortex action quickly suppressed Very definite layering. But flow still quite turbulent in upper layer and certainly in lower layer.

J12 :- Little difference in velocity, top to near bottom, even up to within 1 ft of overfall

J13 :- (J13 - 19 - 2nd Flows observational runs) 67.5°F - 80°F Still definite layer - hardly distinguishable from J12 by eye.

J14 :- 68.0°F - 76.5°F Interface slightly less distinct.

J15 :- 68.0°F - 74.5°F Again.

J16 :- 68.3°F - 72.0°F Layer to end of flume but strands stretch down. twards bottom by end of flume.

J17 :- 68.6°F - 71.0°F Mixing still inhibited by very indistinct interface by end. Some strands reach near bottom by 6'

J18 :- 68.6°F - 69.2°F Mixing but still concentrated towards top by end of flume

J19 :- 68.7°F - 67.6°F (Reverse case) Pretty well mixed by 10' - a most decided change.

J20 :- (J20–21 1st Flows observation runs) 68.7°F - 78°F Hits bottom by 5' but does maintain greater proportion of upper flow towards top right along the flume.

J21 :- 68.7°F – 84.0°F. Tending to statification, with streamers down. 81.0°F just below surface at end of flume.

J22 :- Flows ·1150 cusecs above – ·460 cusecs below. (Max possible upper flow) 69.5°F – 84.3°F. Tending to statification still, with streamers down – 82.0°F on surface at end of flume.

J23 :- (3rd flows) Mixing still reaches bottom by 4.5', though greater concentration does stay on top. Perhaps density effect of $KMnO_4$ coming in slightly. Still very uniform velocity down flume to within 3/4" or so of bottom, where flow is distinctly laminar. Still very little from withdrawal at top right up to 14'.

J27 :- Flow still just turbulent over introduction box. Velocity distribution certainly not laminar. Very little mixing after box; waves are suppressed. Lamination down flume growing thinner? Flows still both turbulent.

J28 :- Upper layer appears to move slightly faster near end; dye shows this up. Lower lair uniform speed till near bottom.

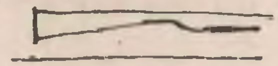
J30 :- 67.5°F – 72.5°F Interface less distinct at box only though waves definitely break.

J31 :- 67.5°F – 69.5°F Interface indistinct all way. As temp difference brought down to zero, the line of lower edge of mixing moved down to hit bottom at 4'-6"

J32 :- 67.5°F – 66.0°F (Reversed case) – Colour hits bottom by 3'.

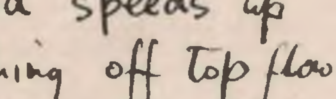
J33 :- (4th Flows) Touches bottom by 4'. Huge (in nature of expt.) slow waves or eddies break each way. Velocity down flume still far from parabolic.

J36 :- 4th Flows 65.2°F both. Bottom withdrawal. Dead water starts about 14', as does noticeably modification of velocity distribution.

J37 :- As J36 but 65.3°F – 78.0°F Definite speed up of top water with thinning; then meeting with extending wedge It was not attempted to reach stability, but dead water fairly quickly reached 5'. Eventual shape 

J38 :- Top layer very noticeably thins and speeds up Top layer is approaching laminar. Upon switching off top flow a thin layer of the heated water maintained itself on the surface for a considerable time. It was slowly thinned by being swept laminarly downstream by the turbulent flow below.

J40 (back to 2nd flows) 66.0 – 82.0 Shut off <u>Little</u> tendency to lie on surface and hot water fairly swiftly swept clear. Lower flow breaks through at entrance box

J41 :- (bottom withdrawal 2nd flows) 67.2°F – 80°F No real build up occurred, merely dead water to about 13' with separation layer within the hot water 

J47 :- (4th flows) Mixing suppressed but interface not quite sharp Little sign of thinning.

J48 :- Slight lift (1/8" in 1½") The wake at the level of the bottom of the box, with laminar flow, moves noticeably slower than main body of top and bottom layers

J49 :- Definite lift and sharp interface with slight undulations

J50 :- at 0'/1¼" at 1'/7/8". at 3'/1" at 4'/1 3/8" at 5'/1 1/8" then about 1¼" (Thickness of upper layer)

J51 :- Lifts from floor of box, upper layer tending to parabolic velocity distribution (from inspection) Slight swirl.

J55 :- Froude law simulation of flows 2 in small flume (¼ horizontal size) with 1.8 vertical exaggeration. Flows too low by 1·49/1·59 due to slip for J55-59. Streamers touch bottom by 4·5' (Equivalent model distance) Flows pretty well mixed by 10'. Quite good simulation to eye. Velocity still fairly uniform from top to near bottom – turbulent. Eddies visible at box just as in full scale test.

J60 :- Flow corrected. Visually same as J55

J66 :- Very clear stratification but with indefinite interface from bottom of introduction box.
Little further mixing. No change in velocity distribution

J70 :- Simulating 3rd flows. Mixing occurs with streamers reaching bottom by 4·5 – 3·5. Little stratification by 10' Still turbulent with no tendency to parabolic velocity dist.

J71 :- Still 'wake' mixing but thereafter stratification to end of flume.

J72 :- Still 'wake' mixing (less) and greater stratification No velocity dist. change observable.

J73 :- Very slight occassional mixing only but wake not smooth till 8' or 9' No vertical velocity distribution change

J74A :- Natural model of flows 3. 64·0°F – 66·5°F But reverse case. Touches bottom about 2·5' Very well mixed by 7' or 8'

J74 :- touches about 3·5' to 4' Definite tendency for top water to stay on top down flume.

J75 :- 1/16" dia floating balls used for timing.

J76 :- Bottom withdrawal. Surface stops over whole length of flume.

J77 :- Slight mixing at start, thereafter clear interface

J79 :- Now clearly visible speed up of top water. Not affected by pattern of nails in bottom (reaching to just short of interface), or even by vibrated mesh just d/s of edge of box. A slight 'haze' soon settles out.

J81 (J81-87. Estimated upper flow due to trouble in setting. Remained constant.) 3/8" pebbles covered 25% area from edge of introduction box. No visible speed up of surface water.

J83-85 Even temps with bottom roughened as for J81-82

J86-87 Seemed to be velocity discontinuity (to eye) but did not show up clearly with float.

J88 :- Colour reaches bottom about 4.5'. Ott meter times for 50 revs. with prop 2:1

	at 4'	at 11'
Surface	14.1, 14.7, 13.7 14.3	13.1, 13.7
2" above bottom	14.7, 14.4	16.1, 16.5, 15.1, 15.9

J91 :- Again colour reaches bottom by about 4.5'. But definite layering at 13' where 75.0°F on surface 68.0°F 2" up.

J92 :- Some reaches bottom + 4'6" - 5'6" but most stays on top, i.e. 78°F on surface, 67°F 2" up at 13'.

J93 :- Again some reaches bottom by 5'-6' but most stays on top 77°F on surface at 13' 68°F 2" up (Equivalent measures) This is quite amazing.

J94 :- 4.5' hits bottom. pretty well mixed by 8'

J95 :- Reaches bottom about 4.5'. Not quite so well mixed at 8' as J94

J96 :- Surface temperature 82.5°F on surface at 12'.

J97 :- 82.7°F at 9', 78°F (average of fluctations) at 11', 74°F at 13' and 73°F at 14'.

J98 :- Speeds up over block and mixes well as slowing occurs at 4' to 5'. Well mixed by 8' with

only traces of visible stratification. (Because the upper flow is coloured, a greater impression of mixing than in fact obtains) Little further mixing after 8'.
At 2' 83.8°F; at 4' fluctuating about 80°F; at 6' 77°F; at 8' 75°F; at 11' 74°F and at 14' 73.5°F all on surface. 2" above bottom 71.5°F at both 11' and 14'.

16.7 Current-meter recordings during tests H and J

Configuration A, flows 2, depth 0.625 ft, during H tests

Miniature current meter timed for 10 revolutions.

Depths are from surface.

<u>At edge of introduction box.</u>

Surface	5.0, 5.4, 4.6.		
3/4 in.	5.2, 4.7, 4.8	4½ in.	4.7, 4.7, 4.5.
1½ in.	7.7, 7.3, 7.6	6 in	5.7, 5.6, 5.2
2¼ in.	5.0, 4.8, 5.3	Bottom (AS NEAR AS POSSIBLE)	6.9, 7.2, 6.5, 7.7, 5.9
3 in.	4.7, 4.6, 4.7.		5.9, 6.2.

<u>1'-6" from edge of box – both 64.5° F.</u>

Surface	4.2, 3.8, 4.4, 4.4	3 in	4.5, 4.2, 4.2
3/4 in.	4.6, 4.2, 4.4, 4.4	4½ in.	4.0, 4.0.
1½ in.	4.8, 5.7, 5.0, 4.9, 5.0	6 in.	4.1, 4.3, 4.5, 4.2
2¼ in.	4.1, 4.1, 4.1,	Bottom.	5.7, 5.7.

<u>4'-6" from edge of box – both 64.5° F.</u>

Surface	4.3, 4.2	3 in.	4.4, 4.2, 4.4.
1½ in.	4.7, 4.6, 4.9.		

<u>Repeat 4'-6" from edge of box – both 64.5° F.</u>

Surface	4.2, 4.3.	3 in.	4.4, 4.4, 4.4.
1½ in.	4.7, 4.6, 4.7.		

<u>1'-6" from edge of box – 62.7° F Lower – 75.7° F upper.</u>

Surface	4.3, 4.1, 4.4	3 in.	5.3, 5.1, 5.0, 5.2
3/4 in.	4.7, 4.8, 4.4, 4.4	4½ in.	4.8, 4.8, 5.0, 5.0.
1½ in.	5.9, 5.9	6 in.	5.0, 5.5, 6.2, 6.3, 6.0. 4.4, 4.7, 5.0, 4.6
2¼ in.	5.2, 5.1, 5.0, 4.9	Bottom.	5.4, 5.8, 6.3.

<u>4'-6" from edge of box – 63.7° F Lower – 76.4° F.</u>

Surface	4.2, 4.0, 4.4, 4.1	4½ in.	4.6, 4.5, 4.5
1½ in.	5.8, 5.5, 5.7, 5.7	6 in.	4.2, 4.3, 4.5, 4.6.
3 in.	4.3, 4.1, 4.3	Bottom.	7.3.

Further miniature current meter recordings (during J tests)
Configuration A, flows 2, depth 0.625 ft, again 10 revs.

4'-6" from edge of introduction box, both 67.0°F

Surface 4.2, 5.1, 4.3, 5.1, 5.5, 4.6, 5.2
1½ in. 4.8, 5.3, 5.1
4½ in. 4.5, 4.7, 5.5, 4.9, 4.8, 4.5, 4.8.
Bottom. 6.5, 6.5.

12'-0" from edge of introduction box, both 67.0°F.

Surface 4.3, 4.3.
4½" in. 4.5, 4.2
Bottom. 6.5, 6.5.

Still 12'-0" from edge of box, flows 4, 67°F. - 85°F.

Surface 11.4, 12.0
1½" in. 15.0, 16.0.
4½ in. 15.0, 16.0.

16.8 Recordings for test series M

The recordings are in the form of notes giving temperatures, flows and configurations (the flows and configurations were largely those used in tests series H and J but are relisted here together with those pertaining to series M only.) The notes are followed by the reproductions of the oscillograph recording strip.

Throughout the tests the probes were positioned in a line across the middle of the flumes, at the distances given on the recording strip, and sufficiently spaced to have little effect on the flow, (approximately 1 in.) The depths were as follows (heights from flume bottom):-

M1 - M9 - Surface, $6\frac{1}{2}$ in., $5\frac{1}{2}$ in. $4\frac{1}{2}$ in., $3\frac{1}{2}$ in., $2\frac{1}{2}$ in., $1\frac{1}{2}$ in., and $\frac{1}{2}$ in. ($\frac{1}{2}$ in. probe went out of action during tests)

M10 - M39 - Surface, $6\frac{1}{2}$ in., $5\frac{1}{2}$ in., $4\frac{1}{2}$ in., $3\frac{1}{2}$ in., $2\frac{1}{2}$ in., and 1 in.

M40 - M41 - Surface, 2 $^9/16$th in., 2 $^1/16$th in., 1 $^9/16$th in., 1 $^1/16$th in., 1 $^9/16$th in., and 2 $^1/16$th in.

M43 - M47 - Surface, $1\frac{5}{8}$ in., $1\frac{1}{8}$ in., and $\frac{5}{8}$ in., simulating surface, $6\frac{1}{2}$ in., $4\frac{1}{2}$ in., and $2\frac{1}{2}$ in.

M48 - M50 - Surface, $2^{15}/16$ in., $2^1/16$th in., and $1\frac{1}{8}$ in., simulating surface, $6\frac{1}{2}$ in., $4\frac{1}{2}$ in. and $2\frac{1}{2}$ in. For tests M43 to M50 a fifth probe was used to give the initial temperature difference.

Configurations (end of box always at - 2 ft. 0 in.)

Larger flume

Configuration A:- bottom of box 0.5 ft. above flume bottom.

Configuration E:- as A with $4\frac{1}{4}$ in. x $2\frac{7}{8}$ in. block across flume at zero ft. (2 ft. from end of box) and $4\frac{1}{4}$ in. sides vertical.

Configuration F:- as E with $2\frac{7}{8}$ in. sides of block vertical.

Configuration G:- bottom of box 2 5/16th in. above flume bottom, ¾ in. mesh and down pebbles on floor of flume from end of box downstream (Fig. 16.1) with largest stones removed. 5/16th in. was allowed as 'dead' in assessing the flow area, thus with flows 2 the total depth was 2 13/16th in., 2 in. below and ½ in. above the box bottom.

Smaller flume

Configuration B:- ¼ hor. scale, 1.8 vert. exaggeration model of A.

Configuration C:- Natural ¼ scale model of A.

Configuration H:- Natural ¼ scale model of E.

Configuration J:- Natural ¼ scale model of F.

Configuration K:- ¼ hor. scale 1.8 vert. exaggeration model of E.

Configuration L:- ¼ hor. scale, 1.8 vert. exaggeration model of F.

Flows (in cusecs)

Larger flume

Flows No.	Lower flow	Upper flow
1	0.357	0.0894
2	0.1785	0.0447
3	0.0893	0.0223
4	0.0447	0.0112

Smaller flume Each pair of flows was for a normal Froude law - ¼ horizontal scale model of one pair of the larger flume flows.

Flows No.	Simulating	Upper flow	Lower flow
6	Flows 2, 1.8 exag.	0.01335	0.00334
12	Flow 2, Natural	0.00558	0.0014

In the notes the following arrangement is adopted:-

M13	1	F	88.7	64.7	64.7
				65.2	64.5

which signifies that for test M13 Flows 1 were combined with configuration F. The upper flow temperature was 88.7°F, and of the lower flow and the reference bucket 64.7°F at the start of the recordings and 65.2°F and 64.5°F respectively after the last reccrdings. (The second line temperatures were not taken for some of the earlier tests, and where otherwise omitted, were the same as the first line temperatures). Where the total depth differed from 0.625 ft. it is noted.

As for tests M, the oscillograph recordings were mounted from left to right and top to bottom, as is obvious from the numbering. The recording speed was 0.5 in. per second throughout.

The tests were carried out between the 3rd and the 18th November, 1959.

TEST	FLOWS	CONF	UPPER	LOWER	BUCKET.
M1·2	replaced – aiming at flows 1 conf A & max dens diff.				
M3(a)	1	A	87·3	63·0	63·0
(b)			89·0	65·0	65·0
M4(a)	1	E	89·3	66·3	66·3
(b)			90·5	68·0	68·0
M5(a)	1	A	78·1	64·3	64·3
(b)			78·6	65·1	65·1
M6	2	A	72·9	65·5	65·5
M7	2	E	73·5	66·1	65·9 65·5
M8	2	E	79·5	66·5	66·5 66·2
M9	2	E	90·0	67·3	67·3 67·0
M10	error (0.370 V) under	E	70·7	63·4 63·4	63·4 63·0
M11	2	E	71·5	63·9 63·9	63·7 63·4
M12	2	F	71·8	64·2 64·2	64·1 63·9
M13	1	F	88·7	64·7 65·2	64·7 64·5
M14 (Check on M13)	1	F	88·8	64·7	64·7
M15	1	E	89·1	65·9 66·3	65·9 65·7
M16	1	A	75·0	67·7	67·7 67·5
M17	1	A	AIMED At DENS DIFF. 0.00168	68·2	68·1 68·0
M18	1	A	91·0	68·7	68·7 68·6
M19	1	A	approx. 73·0 (0·00042)	69·5	69·5
M20	3	E	71·5	69·9	69·7
M21	3	F	71·4	69·9	69·5
M22	3	A	71·3	69·9	69·2
M23	3	A	62·4	60·2 60·2	59·7 59·6
M24	3	E	62·4	60·2	60·2 60·4
M25	3	F	62·7	60·6 60·6	60·5 60·2
M26	3	F	65·4	61·2 61·2	61·2 61·1
M27	3	F	69·6	61·2 61·2	61·0 61·0
M28	3	F	76·2	61·9 62·0	61·9 61·9

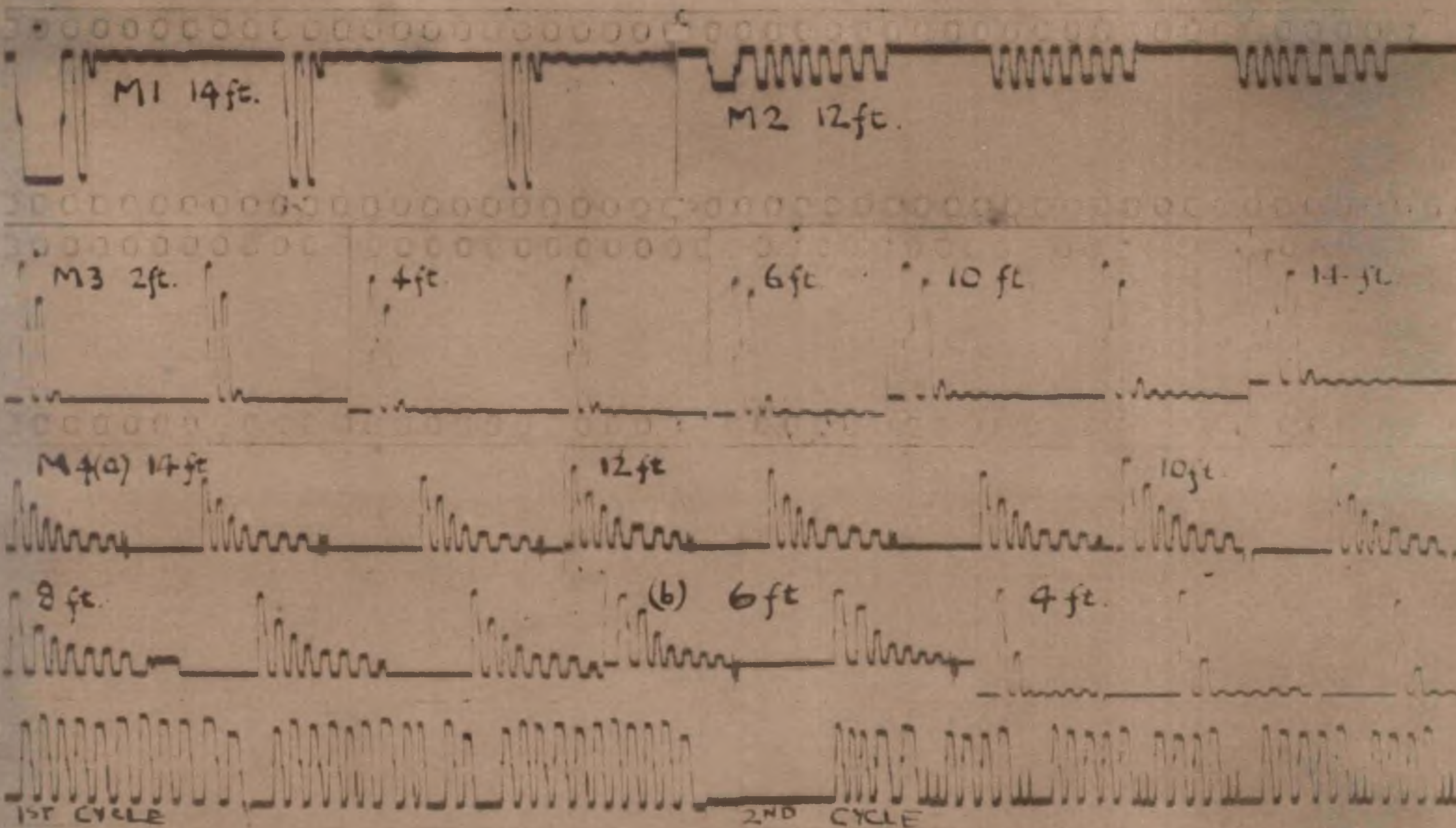
TEST	FLOWS	CONE	UPPER	LOWER	BUCKET
M29	3	F	86·7 87·2	62·7 62·5	62·3 62·0
M30	2	F	71·5 71·2	63·9 63·8	63·8 63·7
M31	2	E	67·3 67·1	64·3 64·1	64·1 64·0
M32-35	REPLACED	BY	M37-39.		
M36	4	E	62·35 62·3	61·35 61·9	61·9 61·9
M37	4	E	62·5 "	62·0 "	62·0 "
M38	4	A	62·5 "	62·0 "	61·9 "
M39	4	E	62·5 62·7	62·0 62·1	61·8 61·75
M40	2	G	80·0	63·8	63·8

2 13/16" total depth (5/16" dead) Head loss from −1ft. to +4ft = 2 5/8 × 1/38·5 In.

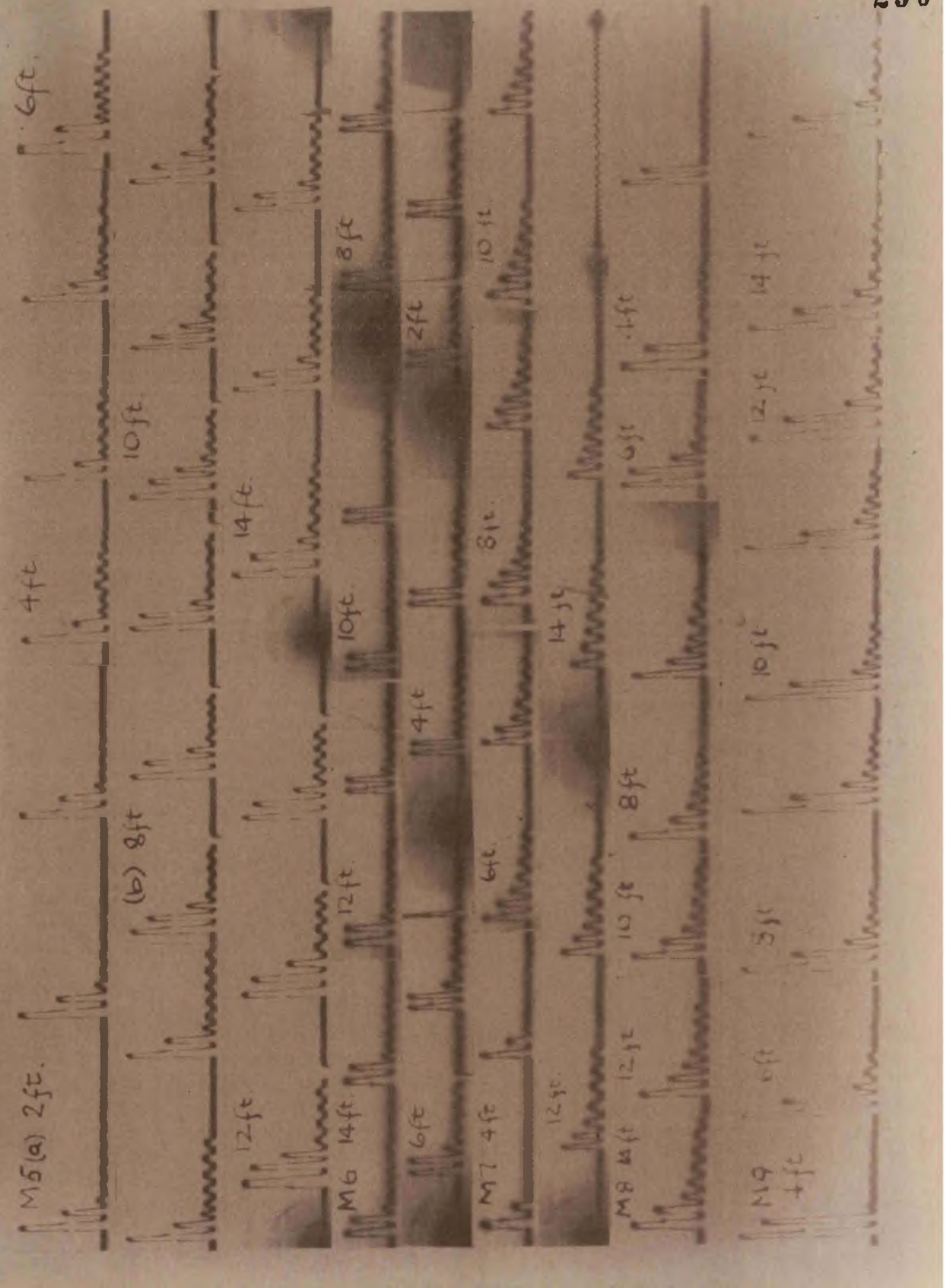
TEST	FLOWS	CONE	UPPER	LOWER	BUCKET
M41	2	G	73·1	64·7	64·7
M42	2	G∓ (PEBBLES REMOVED)	70·2	65·4	65·2

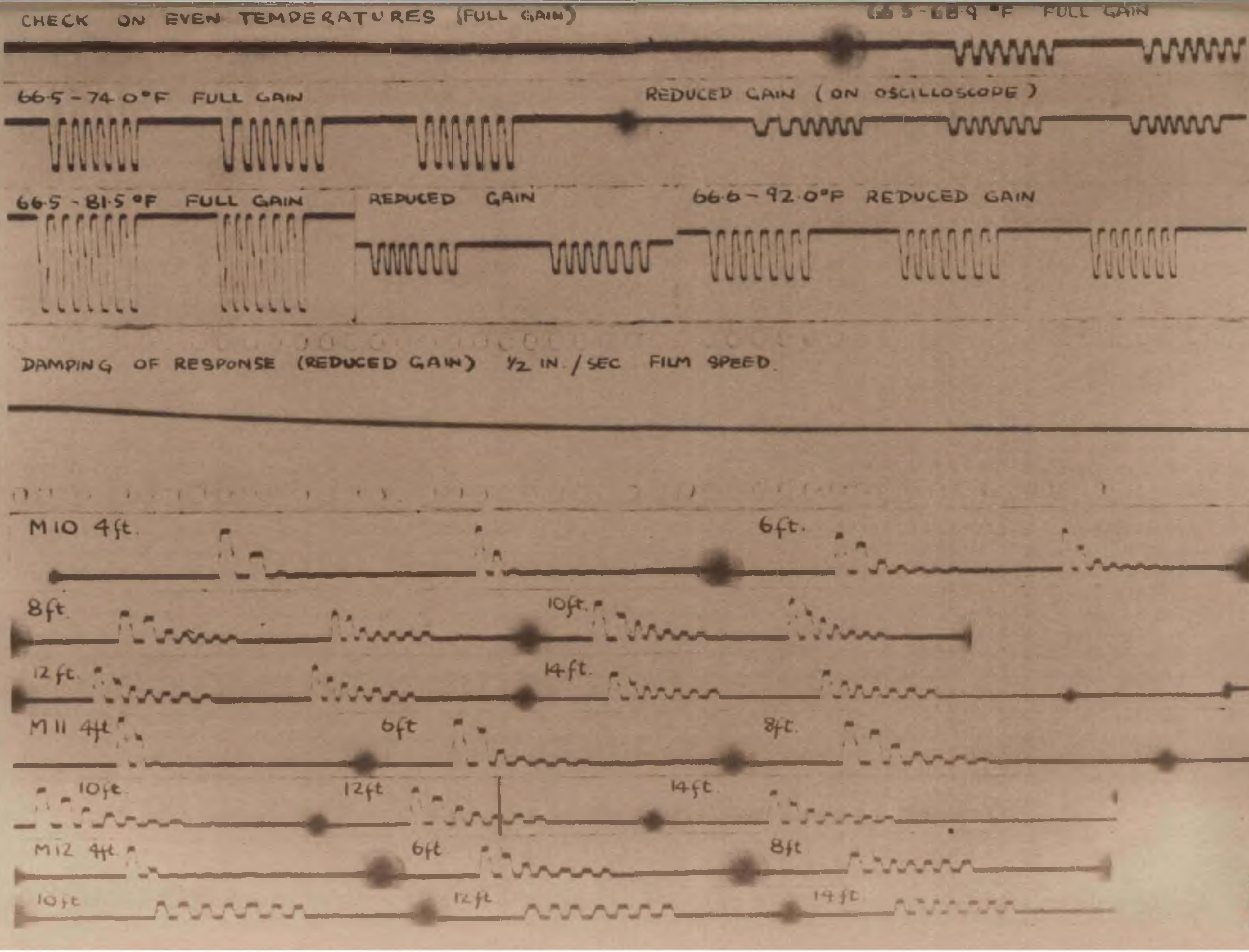
ENTRY MIXING AGAIN PREDOMINATES & THERE IS LITTLE CHANGE FROM G.

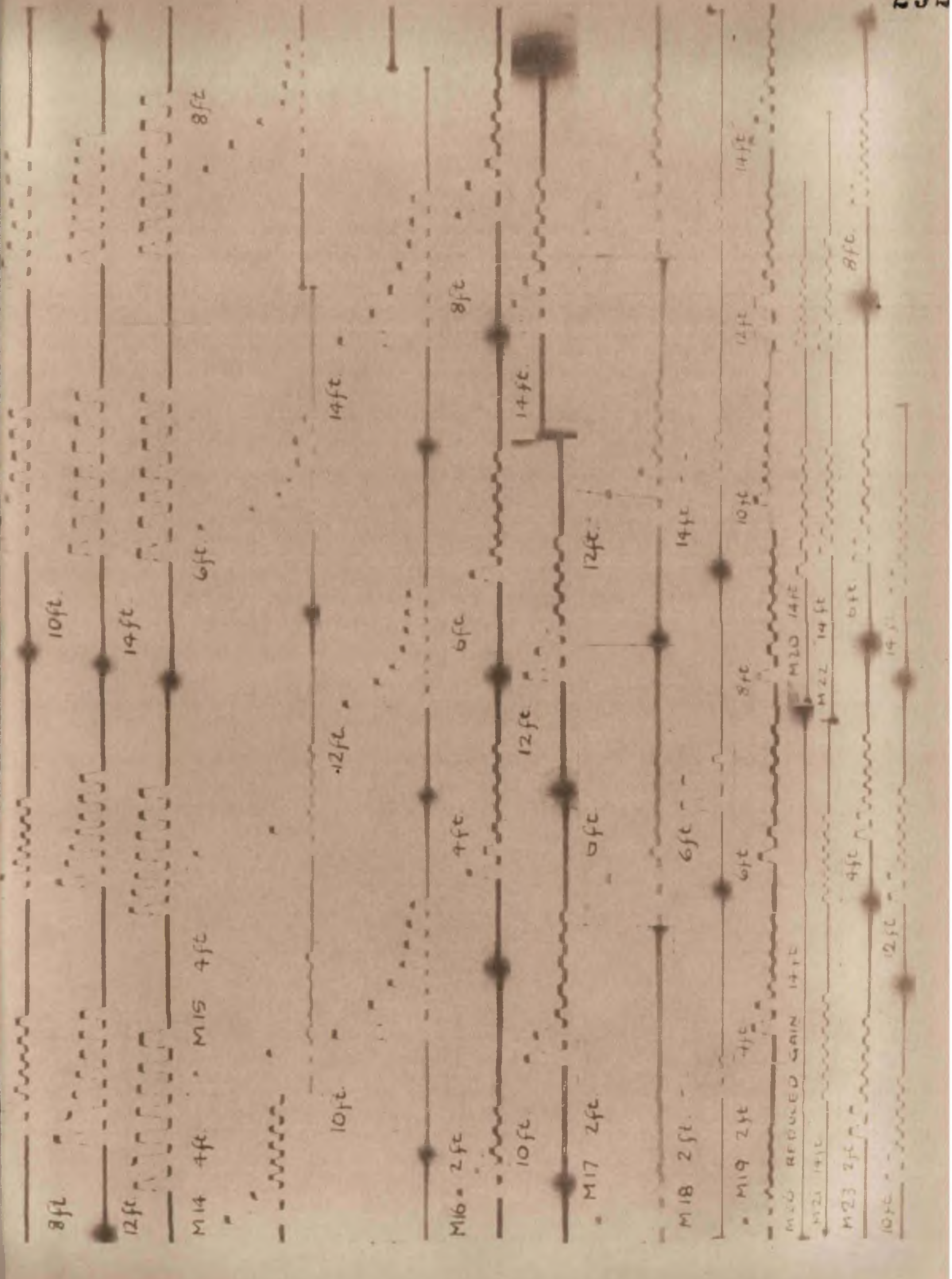
TEST	FLOWS	CONE	UPPER	LOWER	BUCKET
.M43	12	C	71·5	64·3	64·3
M44	12	H	"	"	"
M45	12	J	"	"	"
M46	12	H	78·0	64·5	64·5
M47	12	J	"	"	"
M48	6	B	72·1	65·0	65·0
M49	6	K	"	"	"
M50	6	L	"	"	"

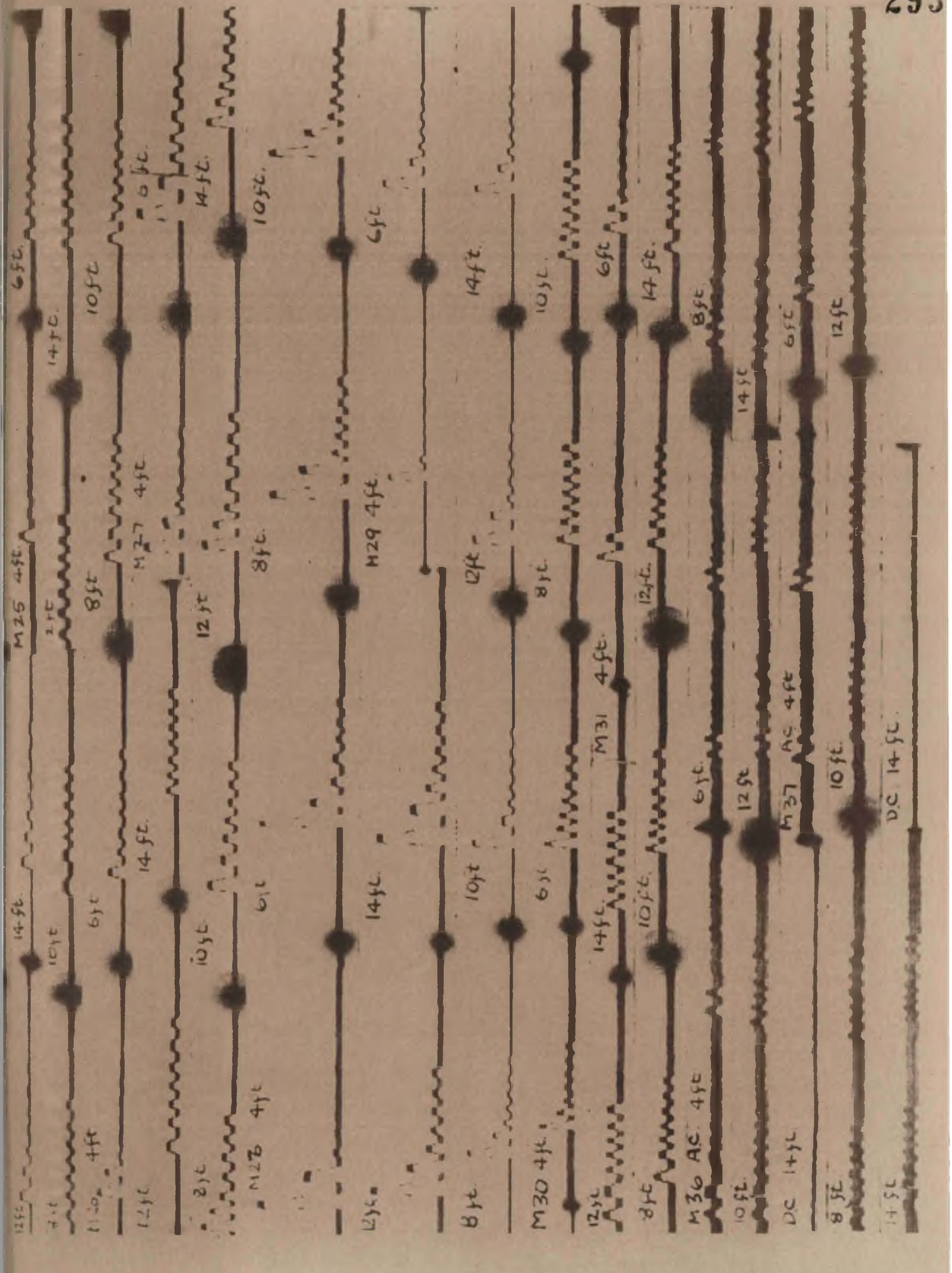


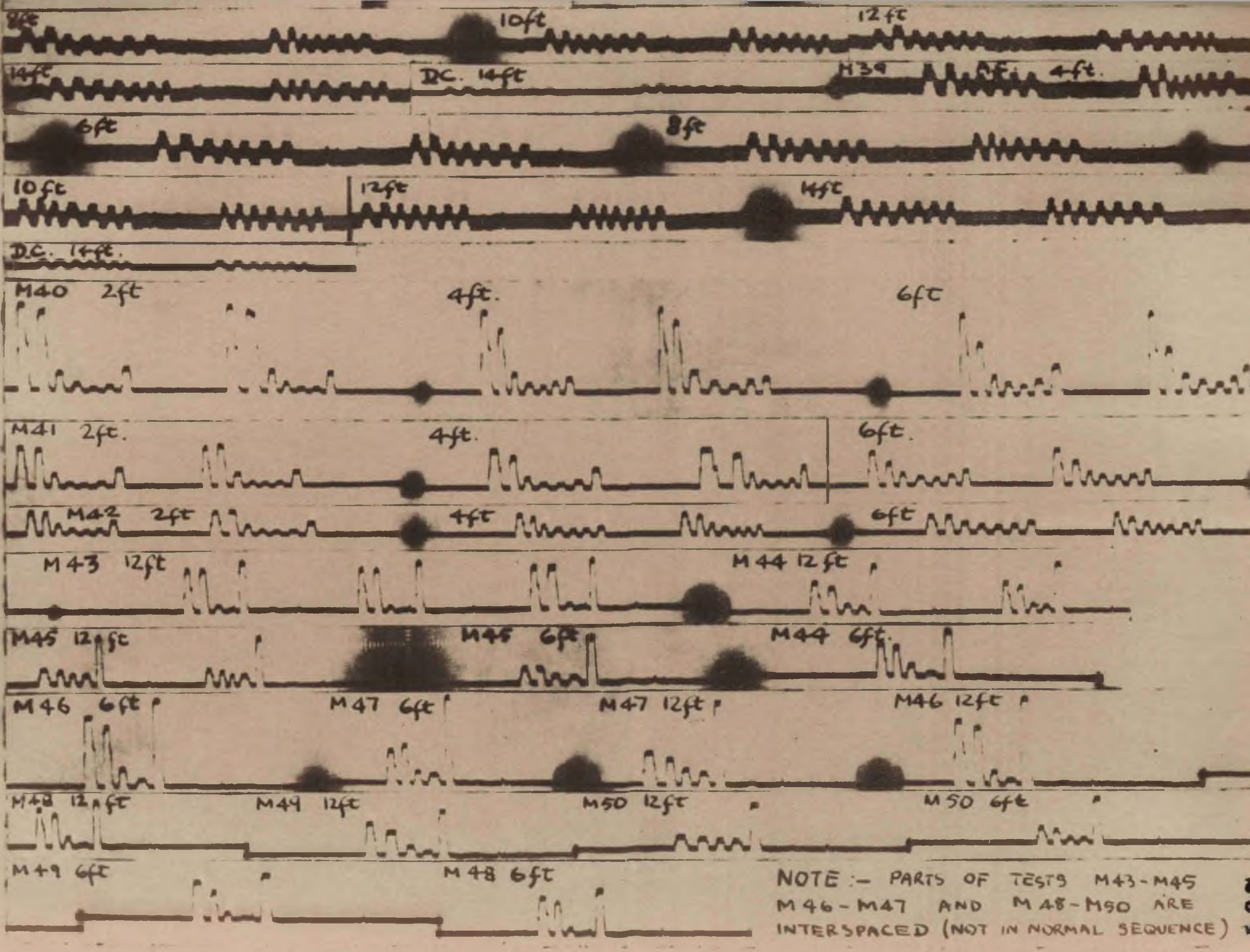
EFFECT OF ELECTROLYTIC ACTION ON PROBES (SEE 5.2.10)


M5(a) 2ft.
4ft
6ft.
(b) 8ft
10ft.
12ft
14ft.
M6 14ft
12ft
10ft
8ft
6ft
4ft
2ft
M7 4ft
6ft
8ft
10ft
12ft
14ft
M8 14ft
12ft
10ft
8ft
6ft
4ft
M9 4ft
10ft
12ft
14ft


CHECK ON EVEN TEMPERATURES (FULL GAIN)
66.5 - 68.9 °F FULL GAIN
66.5 - 74.0 °F FULL GAIN
REDUCED GAIN (ON OSCILLOSCOPE)
66.5 - 81.5 °F FULL GAIN
REDUCED GAIN
66.6 - 92.0 °F REDUCED GAIN
DAMPING OF RESPONSE (REDUCED GAIN) 1/2 IN. / SEC FILM SPEED.
M10 4ft.
6ft.
8ft.
10ft.
12ft.
14ft.
M11 4ft.
6ft
8ft.
10ft.
12ft
14ft.
M12 4ft.
6ft
8ft
10ft
12ft
14ft


M14 4ft
M15 4ft
M16 2ft
M17 2ft
M18 2ft
M19 2ft
M20 REDUCED GAIN 14ft
M21 14ft
M22 14ft
M23 2ft


M25
M27
M28
M29
M30
M31
M36 AC
M37
DC


8ft
10ft
12ft
14ft
D.C. 14ft
M39
4ft.
6ft
8ft
10ft
12ft
14ft
D.C. 14ft.
M40 2ft
4ft.
6ft
M41 2ft.
4ft.
6ft.
M42 2ft
4ft
6ft
M43 12ft
M44 12ft
M45 12ft
M45 6ft
M44 6ft.
M46 6ft
M47 6ft
M47 12ft
M46 12ft
M48 12ft
M49 12ft
M50 12ft
M50 6ft
M49 6ft
M48 6ft
NOTE :- PARTS OF TESTS M43-M45
M46-M47 AND M48-M50 ARE
INTERSPACED (NOT IN NORMAL SEQUENCE)

16·9 Recordings for test series N and P

The recordings are in the form of notes and reproductions of oscillograph recordings strip, in both cases test N comes first. The tests were carried out 19th - 26th Nov. 1959.

For tests N the probes were positioned as follows :-

1 in shorter length.
2 at 6" in longer length
3 at 3'-6" in longer length
4 at 7'-0" in longer length
5 at 10'-6" in longer length

Test No.	Depth (ft).	T_1 (°F)	T_2 (°F)	Probe depths (in above bottom). 3	4	5
N1	0·400	55·0	86·5	½	½	½
N2	0·400	55·5	86·5	2⅞	2½	2⅛
N3	0·800	55·0	59·7	3	3	3
N4	0·800	55·0	88·1	bottom	4	1
N5	0·200	57·5	84·5	¼	¼	¼

For tests P1-4 the probes were located (full size dimensions):-

1, 2, 3 } ℄ of tank {
1 — 3ft from box at surface.
2 — 3ft from box 2½ in. below surface
3 — 7ft from box at surface.

Test No	Scale	Flow (cusecs)	T_1 (°F)	T_2 (°F)	Pail (°F)	$\Delta\rho$ (gm/m.l.)
P1.	Full	0·0363	66·0	83·0	66·5	0·00229
P2	Full	0·0363	66·5	83·5	67·5	0·00232
P3‡	1/5 (1·95 Vert Exag)	0·00193	67·8	84·0	65·5	
P4	1/5 (1·95 Vert Exag)	0·00193	67·8	83·5	66·0	

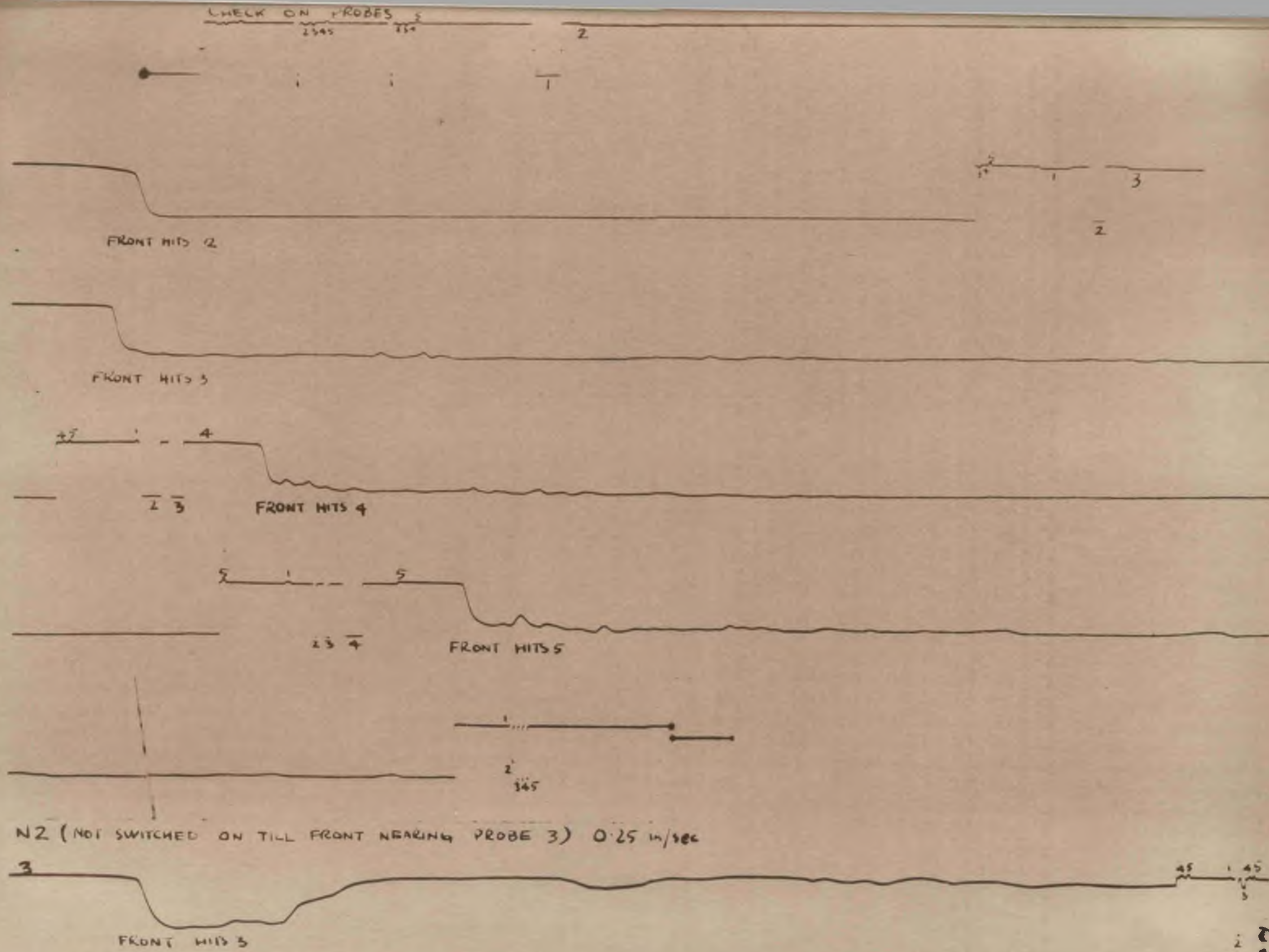
‡ Possibly some of the 'pail' probes were out of the water.

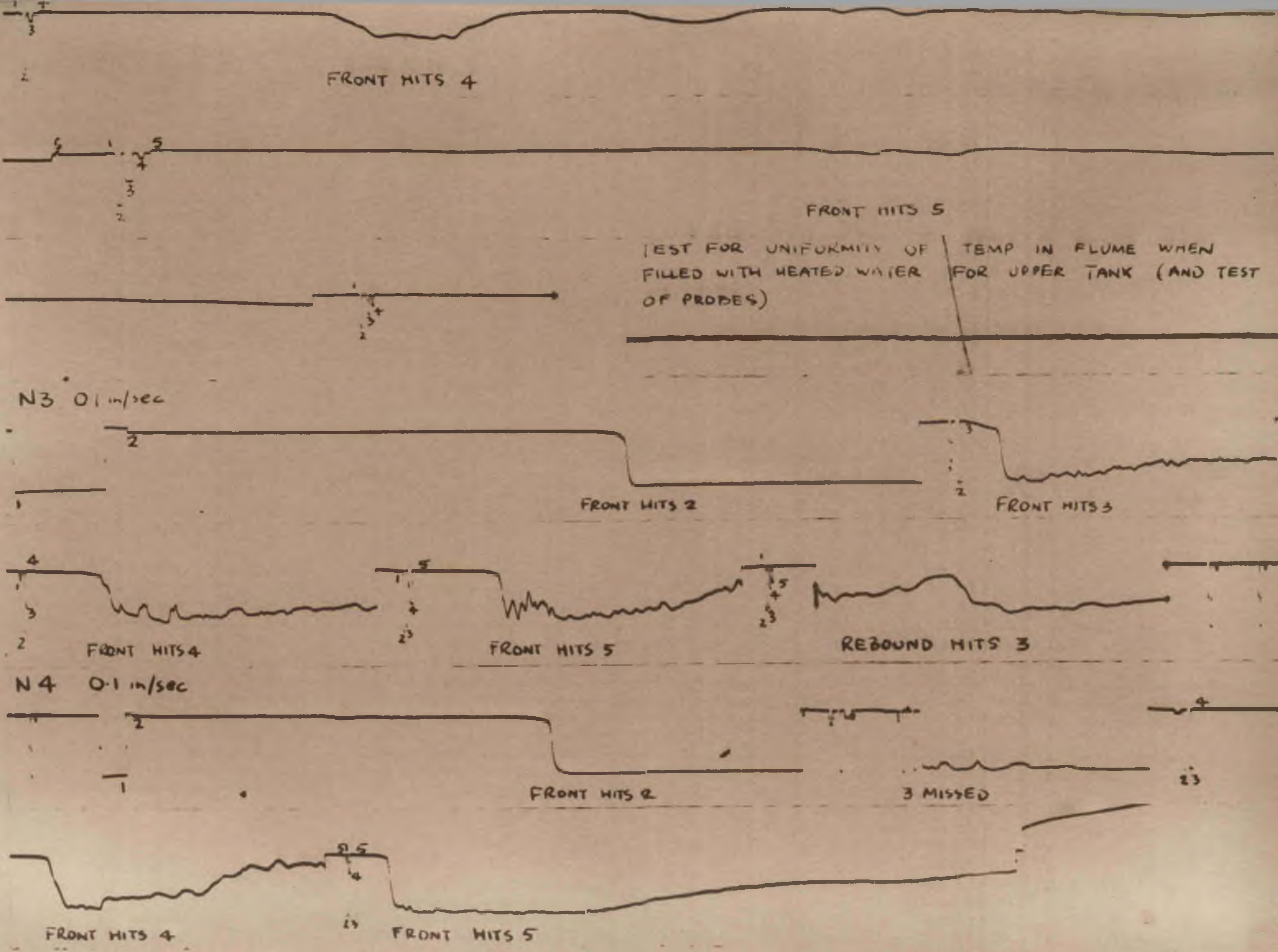
For tests P5-8 the location of the probes is dealt with in the body of the thesis.

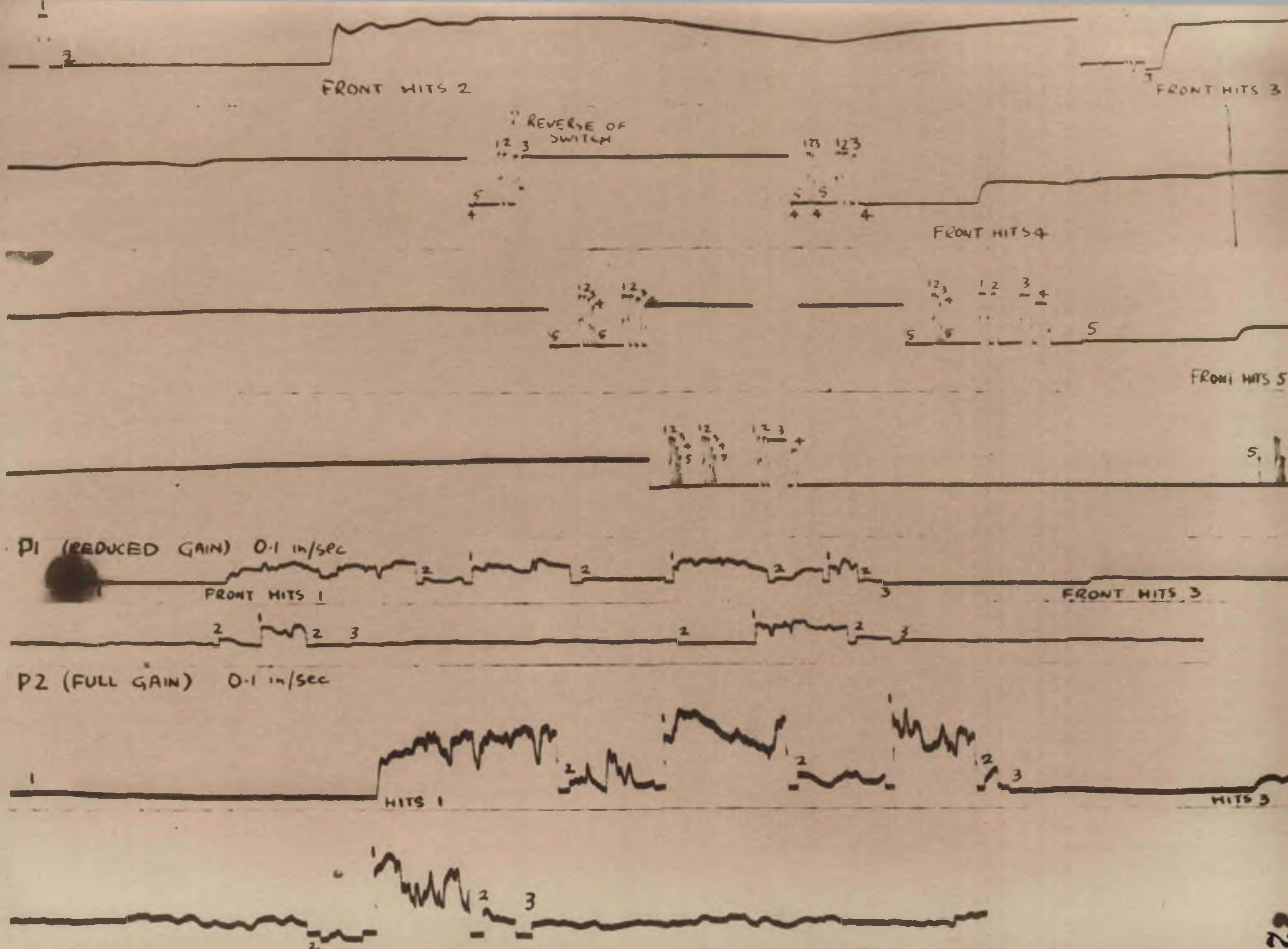
TEST No	SCALE	FLOWS (CUSECS) MAIN	INTRODUCED	T_1 (°F)	T_2 (°F)	Rail (°F)
P5	FULL	0·240	0·1028	66·5	83·5	66·5
P6	"	0·240	0·1028	67·5	84·0	68·2
P7	"	0·240	0·1028	69·2	85·0	68·7
P8	1/5 (1·95 VERT EXAG)	0·0127	0·00546	68·0	84·0	65·1

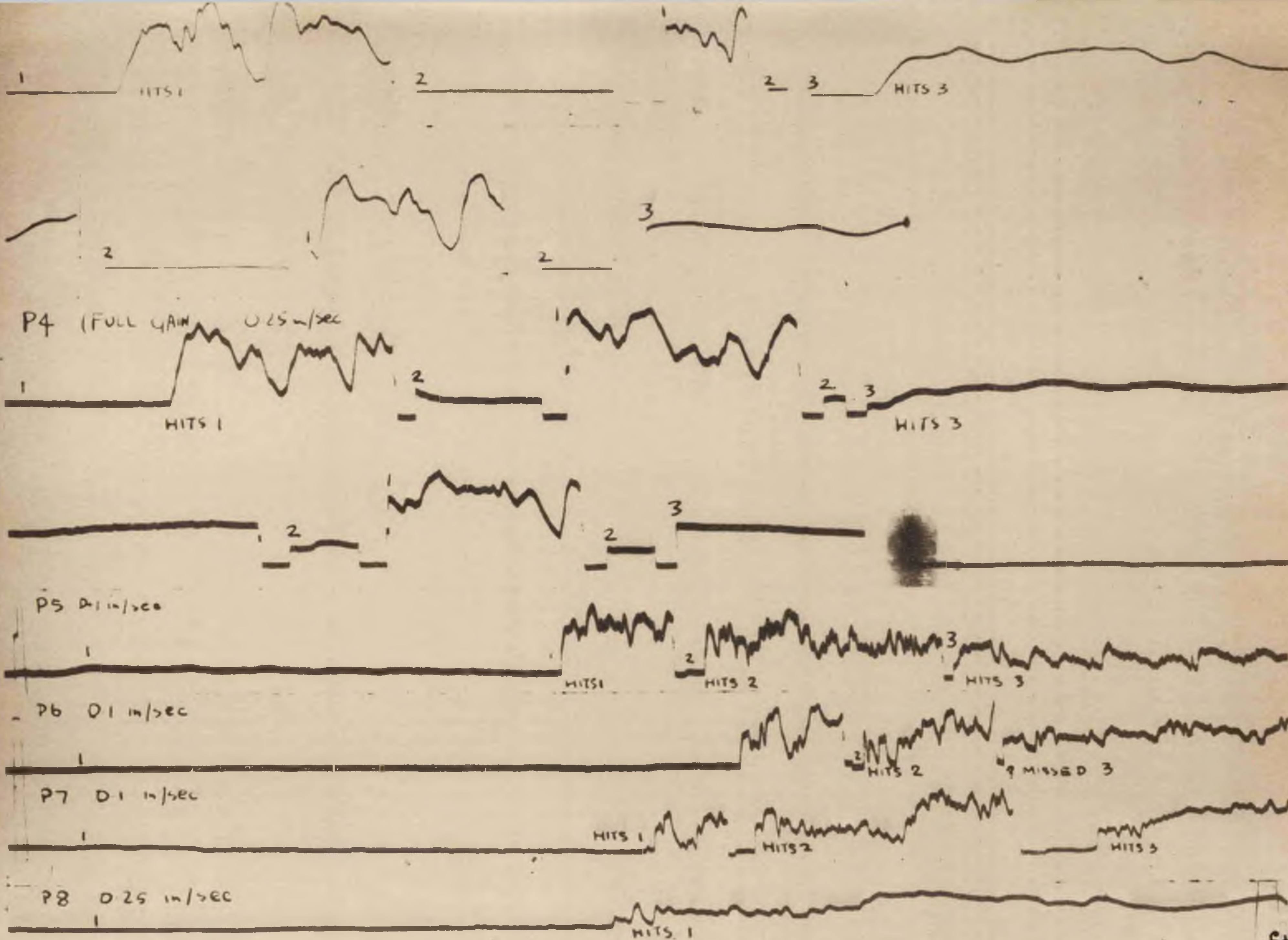
P5–P7 Λ MARKED ON RECORDING STRIP AT 0 SECS

P8 Λ " " " " " 25 SECS.


CHECK ON PROBES
FRONT HITS 2
FRONT HITS 3
FRONT HITS 4
FRONT HITS 5
N2 (NOT SWITCHED ON TILL FRONT NEARING PROBE 3) 0·25 in/sec
FRONT HITS 3


FRONT HITS 4
FRONT HITS 5
TEST FOR UNIFORMITY OF TEMP IN FLUME WHEN FILLED WITH HEATED WATER FOR UPPER TANK (AND TEST OF PROBES)
N3 0.1 in/sec
FRONT HITS 2
FRONT HITS 3
FRONT HITS 4
FRONT HITS 5
REBOUND HITS 3
N4 0.1 in/sec
FRONT HITS 2
3 MISSED
FRONT HITS 4
FRONT HITS 5


FRONT HITS 2
FRONT HITS 3
? REVERSE OF SWITCH
FRONT HITS 4
FRONT HITS 5
P1 (REDUCED GAIN) 0.1 in/sec
FRONT HITS 1
FRONT HITS 3
P2 (FULL GAIN) 0.1 in/sec
HITS 1
HITS 3


HITS 1
HITS 3
P4 (FULL GAIN 0.25 in/sec
HITS 1
HITS 3
P5 0.1 in/sec
HITS 1
HITS 2
HITS 3
P6 0.1 in/sec
HITS 2
MISSED 3
P7 0.1 in/sec
HITS 1
HITS 2
HITS 3
P8 0.25 in/sec
HITS 1

17. APPENDIX 2 - NOTATION (GENERAL)

Note: The notations used in the sections on Economics and Heat Losses are local to these sections and are listed in them.

A	Area
B	Breadth
d	An internal depth
F	Force
g	Gravitational acceleration
H	Total depth
H^1	Part of the total depth
K	Ratio V_o/V_Δ
L, l	Length, often extension length
Lo	Length of shorter section in lock flows
M	Mass
m	Mean value (when used as subscript).
R_Δ	Densimetric Reynolds number
R_Δ'	Local densimetric Reynolds number
Ri	Richardson number
T	Time
V	Velocity, volume
Vo	Initial velocity of lock flow, with additional subscript (o) or (u) indicating overflow or underflow.
V_Δ	Densimetric velocity.

m, s and d are used as subscripts to indicate various lengths as shown in Fig. 10.1.

ρ	Density.
$\Delta\rho$	Small density difference.
$\Delta\rho'$	Small density difference reduced from $\Delta\rho$ initially obtaining.
μ	Coefficient of dynamic Viscosity.
ν	Coefficient of kinematic Viscosity.

18. APPENDIX 3 - OUTFALL STUDIES

18.1. Introduction

18.1.1. Concurrently with the operation of the main Kincardine model, some studies of the circulating water outfall arrangements were made using a $^1/_{24}$ natural scale model. A crest level of minus 1 ft. O.D. combined with a length of 80 ft. had been selected for the weir necessary to preserve the syphonic recovery of the system at lower water levels. This weir was to be sited at the end of the culverts immediately before the discharge into the River Forth, which has an extreme low water level of minus 11.0 ft. O.D. Borings had shown that, at the position chosen for the outfall, gravel underlay the silt banks characteristic of the Forth. It was thought desirable to avoid eroding this gravel as far as possible; the gravel started about minus 14 ft. O.D. and at a water level of minus 11 ft. O.D., the mean velocity of the flow of 925 cusecs spread over 80 ft., would be 3.85 ft./sec., assuming no erosion of the gravel, a not unreasonable velocity. This assumed that the silt bank, which sloped from about minus 7 ft. O.D., to minus 11 ft. O.D. along the line of the outfall (oblique to the river bank line) would be washed out in front of the outfall so as to form a channel into deeper water (Kincardine Paper, Fig. 2). But the formation of a large pit in the gravel was another matter; if this were to be continually filled with silt at higher river levels then washed out at low water, progressive local regime changes might result.

18.1.2. The model tests consisted of discharging a flow corresponding to full load flow (on a Froude law basis) over a 50 ft. equivalent model length of spillway (with appropriate adjustment for the reduced length) and into a pool at minus 11 ft. O.D. equivalent level with a minus 14 ft. O.D. bed formed with washed building sand. (100, 97, 93, 82, 41 and 5% by weight passing

B.S. Sieve Sizes 3/16, No. 7, No. 14, No. 52 and No. 100). No attempt was made to represent the actual configuration of the silt banks. Various stilling basin shapes and devices were tested for 25 minutes per test, corresponding to 2 hours prototype time, and thereafter the centre line scour profile was recorded and a photograph taken showing the scour. There was a great variation in amount of scour between suitable and unsuitable spillway profiles. Tests K9 and K5, Figs. 18.1 2 and 3 illustrate this. The stepped spillway of Test K9 was adopted and has been constructed at Kincardine Power Station. Slightly better results were obtained with arrangements including blocks, but the difference was thought insufficient to justify this construction (Test K.15, Figs. 18.1 and 4). With certain arrangements a three dimensional flow and scour pattern developed as typified by Test K2 (Figs. 18.1 and 5).

18.1.3. The Author was curious regarding several uncertainties which remained after the foregoing tests.

(a) How would the results have varied had a better sand for scour models, e.g. Leighton Buzzard,[18.1] been used? (References are at the end of this section)

(b) If sectional tests had been made in a flume, might the three dimensional effects (as found in Test K2) have been suppressed, so leading to the possible adoption of such a profile because of a uniform result similar to the centre line scour actually obtained? The shape was simple and at the centre line the scour was well away from the structure.

(c) The various spillways tested had been built up as shown in Figs. 18.6 and 7. Though greater flexibility was so obtained than had each been formed complete, there was still the thought that money could have been saved had a greater range of the main slope part been available. All those used were to a slope of 3 in 2 and, because of their length, the accuracy required in construction and the curve at top and bottom, were relatively costly to have made; perhaps three pounds each.

(d) Would the spillway shape ever have an effect on the dispersion pattern of the heated water, and could this be investigated with heated water in a model experiment?

(e) It had appeared, both from observations during the main model tests and while erosion was going on in the scour model, that although the shape of the outfall determined the scour shape, it was mainly the scour shape that determined the flow pattern of the discharged water, as far as discharge into still water was concerned. Thus in the main model experiments, where there was a fixed moulding of the outfall scour, the spillway shape appeared largely immaterial. Was this true in general as regards model experiments?

(f) To what extent could model and prototype results be expected to agree?

18.1.4. As a sideline to the main work described in this thesis, some experiments were carried out to elucidate some of these points.

18.2. <u>Brief consideration of theoretical design method</u>

18.2.1. A great deal has been written on the theoretical design of stilling devices and on experimental verifications of theory. Several papers appear each year and recently a whole book has been devoted to energy dissipation.[18.2] No claim is made that the literature has been carefully searched by the Author in this case.

18.2.2. Despite the effort that has been spent on the establishment of general principles, it is generally agreed that unless a particular design can be directly related to previous tests it must be checked by a hydraulic model. In fact for the Kincardine spillway, the design was simply based on model experiments, the shape selected being similar to one tested by Burns and White[18.1] during basic studies. The drop was slight, but the restriction on scour was extreme.

18.2.3. The practical hydraulic approach to the theory is typified by King[18.3] (1929) and recent practical design studies have been based on this approach by Bradley and Peterka.[18.4] In contrast the hydromechanic approach is typified by a recent paper by Rouse and others.[18.5]

18.2.4. Q, the flow per foot width at low water is 925/80 = 11.55 cusecs. Using Bradley and Peterka's findings the velocity of flow on reaching an apron at - 14 ft., can be estimated as 28.6 ft./sec., as shown on Fig. 18.8, at a depth of 0.40 ft. The corresponding depth after a hydraulic jump would be 4.3 ft. and the lengths of jump given by Elevatorski's[18.2] and Bradley's and Peterka's[18.4] methods (based on experimental evidence) would be 26.6 and 26.0 ft. respectively, as calculated on Fig. 18.8.

18.2.5. A recalculation, supposing a tail water level of minus 11.0 ft. O.D., gave a floor level of minus 15.5 ft. O.D., V_1 as 29.4 ft./sec., D_1 as 0.39 ft., D_2 as 4.5 ft. and L as 27.5 ft. (Bradley and Peterka's method).

18.2.6. For erodable beds the whole length of the jump must normally be protected. To reduce the length stilling and dissipation devices must be adopted. Bradley and Peterka's studies were not available at the time of the Kincardine model experiments. The solution based on their findings would have been a fairly complicated arrangement of blocks ~~and~~ on top of the horizontal apron dropped, as described in 18.2.5, to maintain the conjugate depth after the jump. The length would be about 16 ft.

18.3. Experiments

18.3.1. A flexible sheet was constructed to fit the small flume ($4\frac{1}{2}$ ins. wide), by cementing alternative lengths of $\frac{1}{8}$ in. dia. stubs ($4\frac{1}{4}$ ins. long) and $\frac{1}{8}$ in. square rubber between two sheets of $\frac{1}{8}$ in. thick rubber. The outside strips at the ends were, of course, of rubber and longitudinal lengths of rubber made up the width and allowed a seal to be formed. With this sheet spillway slopes and curves could be laid over hardboard profiles, which were simple to cut. Fig. 18.9 shows the general arrangements for testing. Leighton Buzzard standard sand[18.6] was used throughout (100% passing 18 mesh B.S. sieve, and less than 10% a 25 mesh sieve) and in all tests stability appeared to be reached by the end of the 25 minute test. Levels were as for the earlier tests and the same scale ($^1/_{24}$) was used. At the end of each test a photograph was taken with the intention that these should show the spillway shape, the sccur, and the general nature of the flow. The grid used to show the scour depth was 2 equivalent ft. vertically and 5 ft. horizontally.

Fig. 18.10 (Test L1) shows the equivalent of Test K9.

Fig. 18.11 (Test L2) shows the effect with the general shape of Test L1 and three nuts laid as shown and accupying about $^2/_5$ of the total width. From previous experience such nuts were known to be slightly more effective than equivalent rectangular blocks. The scour as Test L1 is dotted.

Figs. 18.12 and 13 (Tests L3 and L4) show the effect of the omission of one step, without and with the nuts. In the previous series of experiments, such omission, without nuts or blocks, had caused a noticeable increase in scour.

Figs. 18.14 and 18.15 (Tests L5 and L6) show tests of the original test K2 arrangement, without and with nuts.

18.3.2. A series of tests were arranged with progressive reduction of the length of the structure from the weir crest:-

Fig. 18.16 (Test L7) shows a similar arrangement to Test K9, the shape actually built. The equivalent of six feet has been saved by increasing the slope of the weir and reducing the width of the smaller steps.

Figs. 18.17 and 18 (Tests L10 and L11) show the extreme case tested, without and with nuts. Here the nuts had to be joined by a brass strip, being swept away by the force of the stream if left separate.

18.3.2. Using a fixed bed at minus 14. O.D., a test was carried out as a combined verification of the design method used in 18.2.4. and 5 and of the model results generally. Fig. 18.19 (Test L12) shows the jump at a tail water level just sufficient to hold it at the foot of the spillway. The equivalent depth is 40 ft. instead of 4.3 ft, as given by calculation, and by inspection ~~of~~ the length of jump, defined as the length of the slope or the end of the bed flow whichever gives the greater length, was about the position of the figures on the side of the flume, equivalent to 26 ft. The tail water level was lifted to 6 ft. equivalent depth as shown in Fig. 18.20 (Test L13). This would approximate to dropping the bed to about minus 17.5 ft. with tail water at minus 11.0 ft. O.D. The lift from the bed did not come nearer the spillway. Indeed, continuing right up to minus 1.5 ft. O.D., the point of lift tended to move away from the spillway and the water nearer the spillway was intensely turbulent throughout its depth.

18.3.3. Still using the fixed bed at minus 14.0 ft. O.D., for a length of 48 ft. then with a slope of 1:7.5 for 30 ft. down to the edge of the dropped bottom of the flume (Fig. 4.11), a test was carried out with the spillway water at 75°F. and a bottom flow of 60°F. rising from the dropped bottom section. The tail water level was lifted to minus 1.5 ft., O.D. The cold water did not penetrate beyond the lip of the drop. Keeping the level the same, the flow was halved and the spillway temperature raised to 85°F. Penetration occurred to within 36 ft. (equivalent of the bottom of the spillway) i.e. 12 ft. on to the flat fixed bed. At this point the penetration was balanced by the bed flow, which lifted and separated there.

18.4. Discussion

18.4.1. The results so far as they clarify the uncertainties listed in 18.1.3, can be summarised using the same heading letters.

(a) The original results would not have been materially different if Leighton Buzzard sand had been used.

(b) The three dimensional effect was suppressed in the flume, but the scour was still considerable, though away from the structure.

(c) It appears that a slightly shorter and cheaper spillway would have been equally suitable to that adopted.

(d) At full flow the spillway shape, within wide limits, would not have an effect on the dispersion even near the point of drowning, the pulled back water being made up entirely of the outfall flow.

(e) No progress was made in this direction, although the hypothesis seems reasonable. The statement under (d) above is, of course, conditional on the scour pattern being unchanged between alternative spillway shapes.

(f) The corelation with the flat apron requirements as described in 18.2.4 and 5 and 18.3.2, affords some evidence of the probable accuracy of the original and the here described model tests.

In fact, the discrepancy in the tail water depth of only 0.3 ft. (full size) can be partially explained by the estimate for the velocity of approach in the calculation. This was for the prototype and did not obtain in the model tests.

18.4.2. There is no reason why the flexible spillway sheet method should not be extended to much larger tests, either in a larger flume, or, with a wider sheet, in full models of a weir. Accuracy is necessary in making the sheet, and some slight clamping motion is necessary. This would have been very easily arranged in the box used for the Kincardine experiments, and had the idea been developed then, the spillway shape might have differed somewhat from that adopted. However, the shape adopted appears reasonably logical and economic in the light of the further tests and of Bradley's and Peterka's work. The total length from the crest of the weir to the edge of the spillway for the profile adopted is 29 ft. Up to about 6 ft. could have been saved on the slope and bottom curve. Thereafter the distances to the edge are 14 ft., 12 ft., and 16 ft., for the adopted shape, shape of test L7 (Fig. 18.16) and Bradley and Peterka's recommendation respectively. Of course, the first two of these shapes are slightly deeper at the deepest point. It was mainly in the weir slope that a saving could have been made, the actual length of the dissipation apron compares well with the recommendation.

18.4.3. For a similar investigation in the future it would seem best to carry out tests in a flume and also on a full width model, if possible with simulation of the banks and the cross flow. Were this done it would also be advisable to try density difference tests in the full width model as conditions might be quite different from that obtained in a flume.

18.5. References

18.1 Jack Allen, "Scale Models in Hydraulic Engineering", Longmans, London, 1947.

18.2 E. A. Elevatorski "Hydraulic Energy Dissipators". McGraw-Hill, N.Y., 1959.

18.3 H. W. King, "Handbook of Hydraulics" McGraw-Hill, N.Y., 1929

18.4 J. N. Bradley and A. J. Peterka, "The Hydraulic Design of Stilling Basins". A group of six papers, Proc. A.S.C.E., Jrn. Hy. Div., Vol. 83, No. HY5, October, 1957.

18.5 H. Rouse, T.T. Siao and S. Nagaratnam, "Turbulence Characteristics of the Hydraulic Jump". Proc. A.S.C.E., Jrn. Hy. Div., Vol. 84, No. HY1, February, 1958.

18.6 B.S. 12 : 1958 Portland cement (ordinary and rapid-hardening).

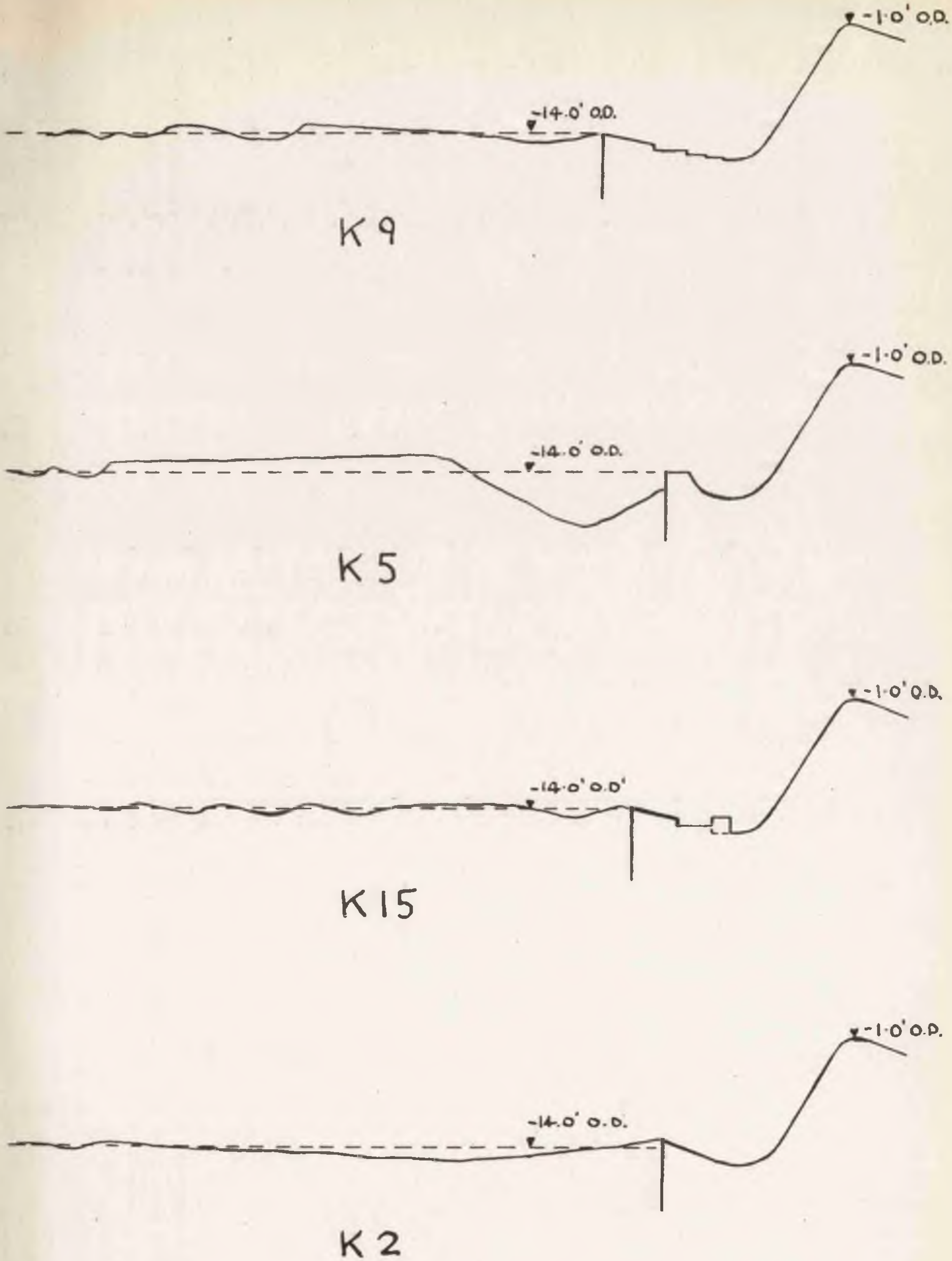


FIG. 18.1 COMPARISON OF KINCARDINE SCOUR MODEL TESTS; SPILLWAY AND ℄ SCOUR PROFILES.

FIG. 18.2 SCOUR FOR TEST K9

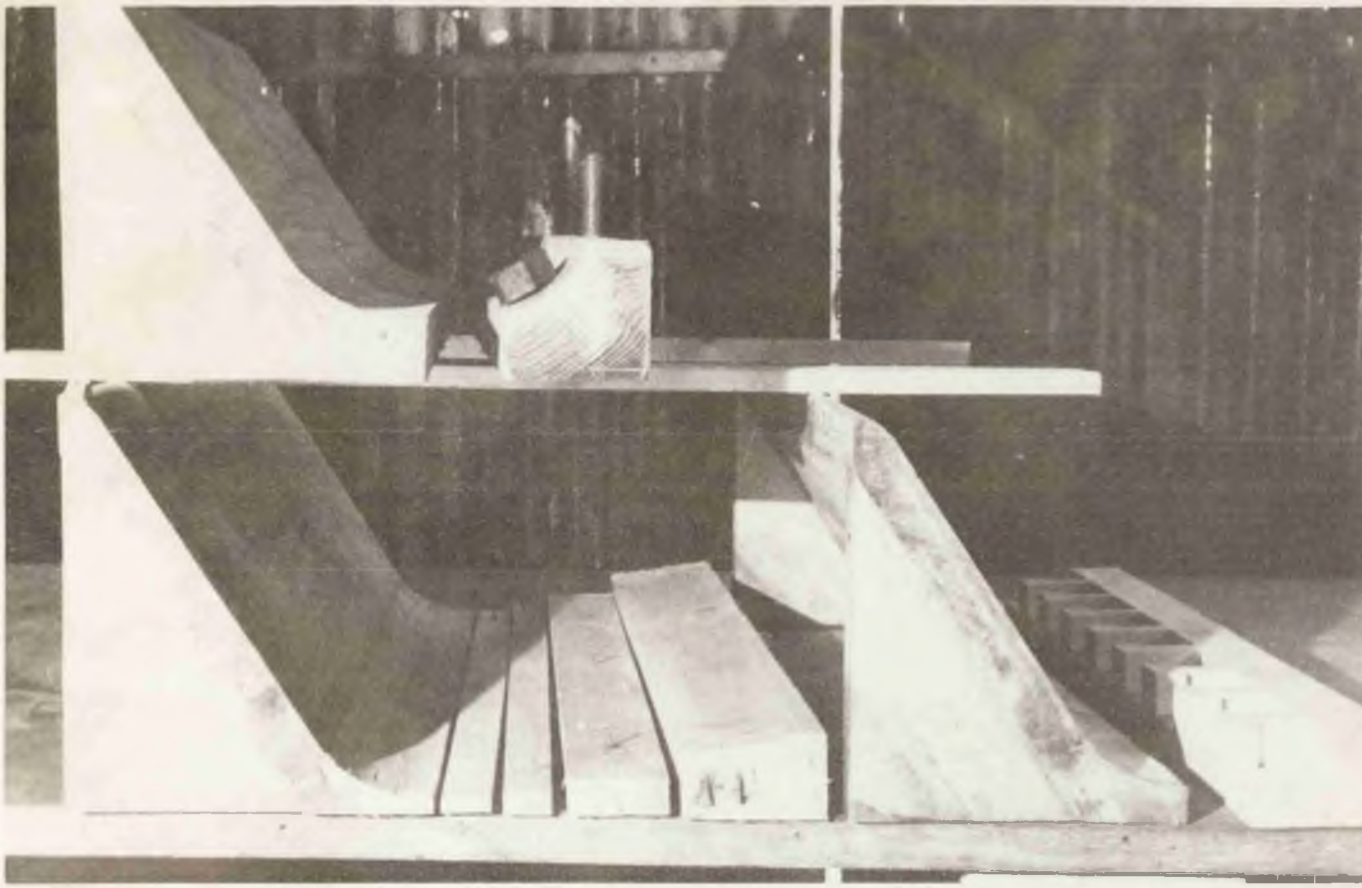
FIG. 18.3 SCOUR FOR TEST K5

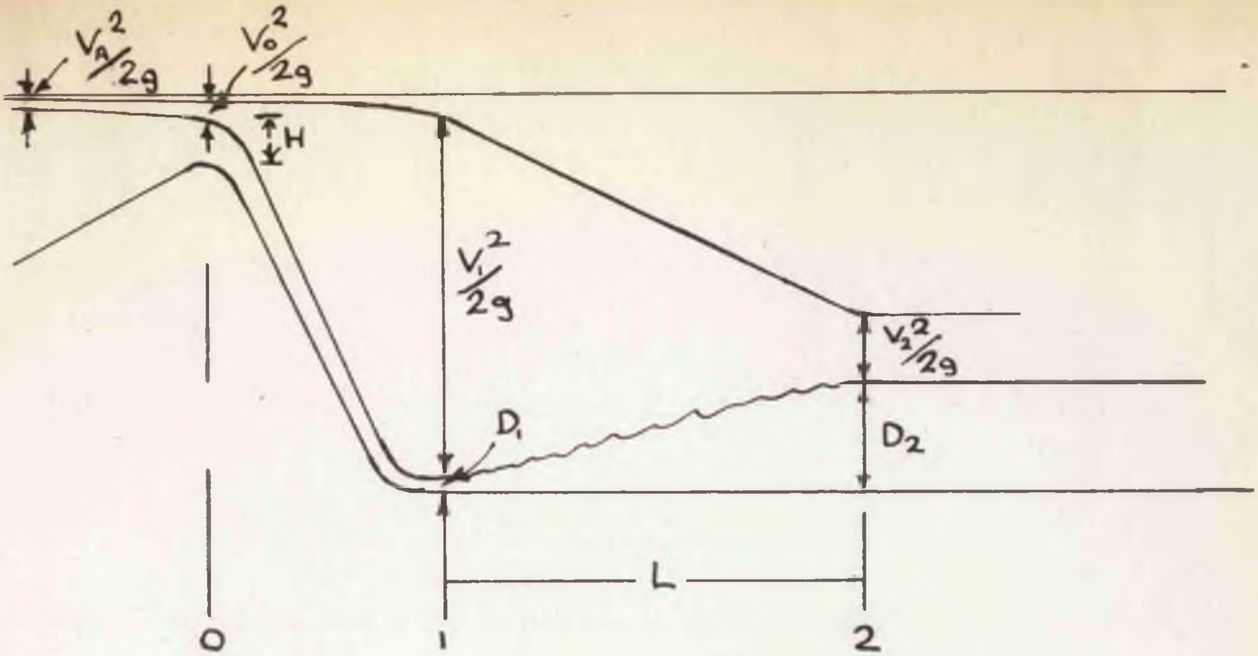

FIG. 18.4 SCOUR FOR TEST K15

FIG. 18.5 SCOUR FOR TEST K2

FIG. 18.6 KINCARDINE SCOUR MODEL;
SPILLWAY CONSTRUCTION 1.

FIG. 18.7 KINCARDINE SCOUR MODEL
SPILLWAY CONSTRUCTION 2.





$$Q = C \times L \times H^{3/2}$$

$$11.55 = 3.6 \times 1 \times H^{3/2} \quad \therefore \quad H = 2.17$$

$$V_1 = .92 \sqrt{[2g(13 + 1.085 + .5)]}$$

taking vel. of approach as 5.5 ft./sec. and .92 from Bradley and Peterka Fig. 15.

$$= 28.6 \text{ ft/sec.}$$

$$D_1 = 11.55/28.6 = 0.40 \text{ ft.}$$

$$F_1 = \frac{V_1}{\sqrt{g D_1}} = \frac{28.6}{\sqrt{32.2 \times .4}} = 7.95$$

∴ T.W. depth / D_1 = 10.7 (Bradley and Peterka Fig. 5)

∴ T.W. depth (D_2) = 4.3 ft.

Length of jump (Bradley & Peterka Fig 6) $0.4 \times 67 = 26$ ft.
(Elevatorski) $6.9/(D_2 - D_1) = 26.8$ ft.

FIG. 18.8 SCHEMATIC DIAGRAM AND CALCULATION FOR HYDRAULIC JUMP AT FOOT OF SPILLWAY.

FIG. 18.9 ARRANGEMENTS FOR SPILLWAY
SCOUR TESTS

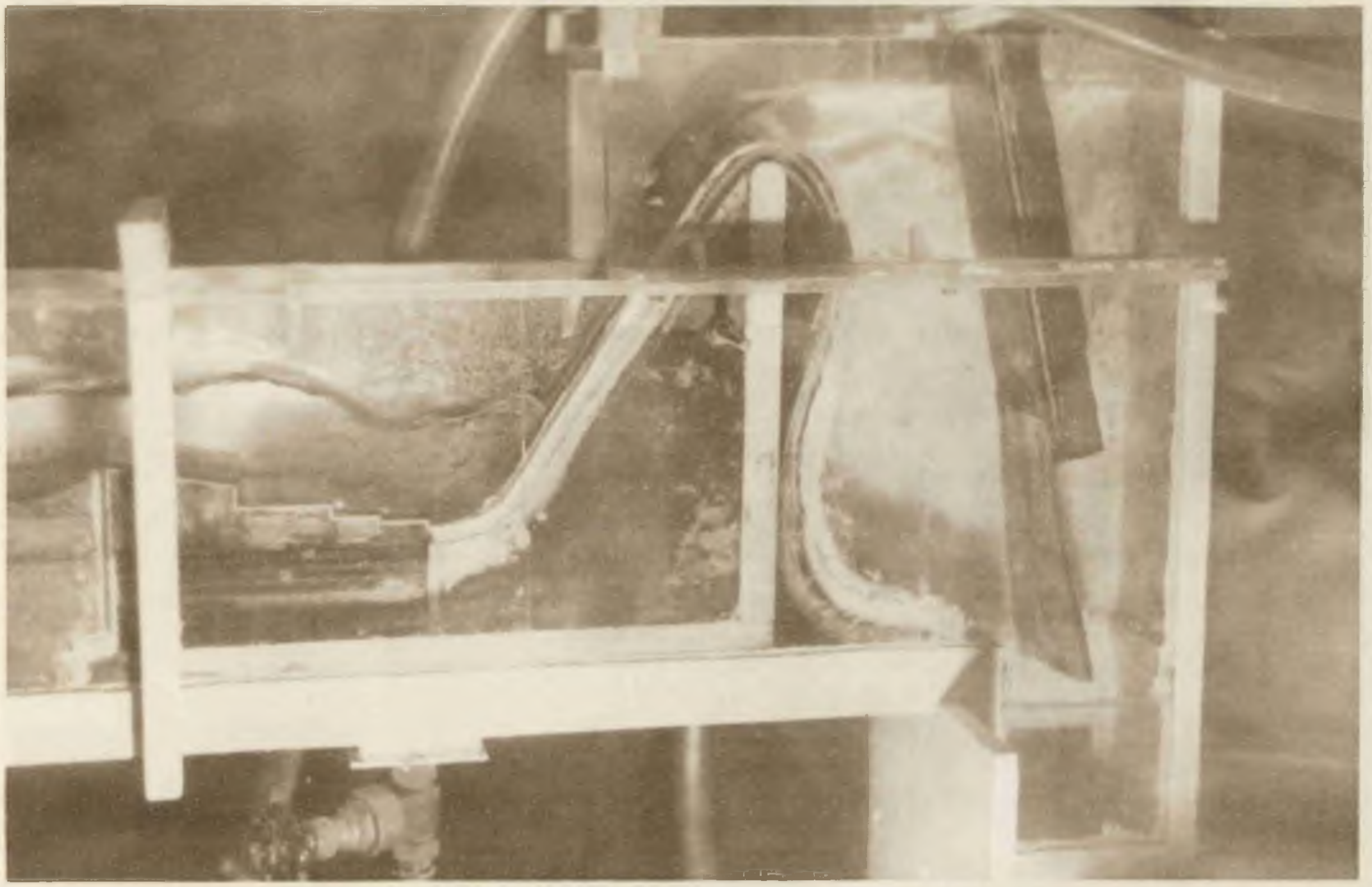
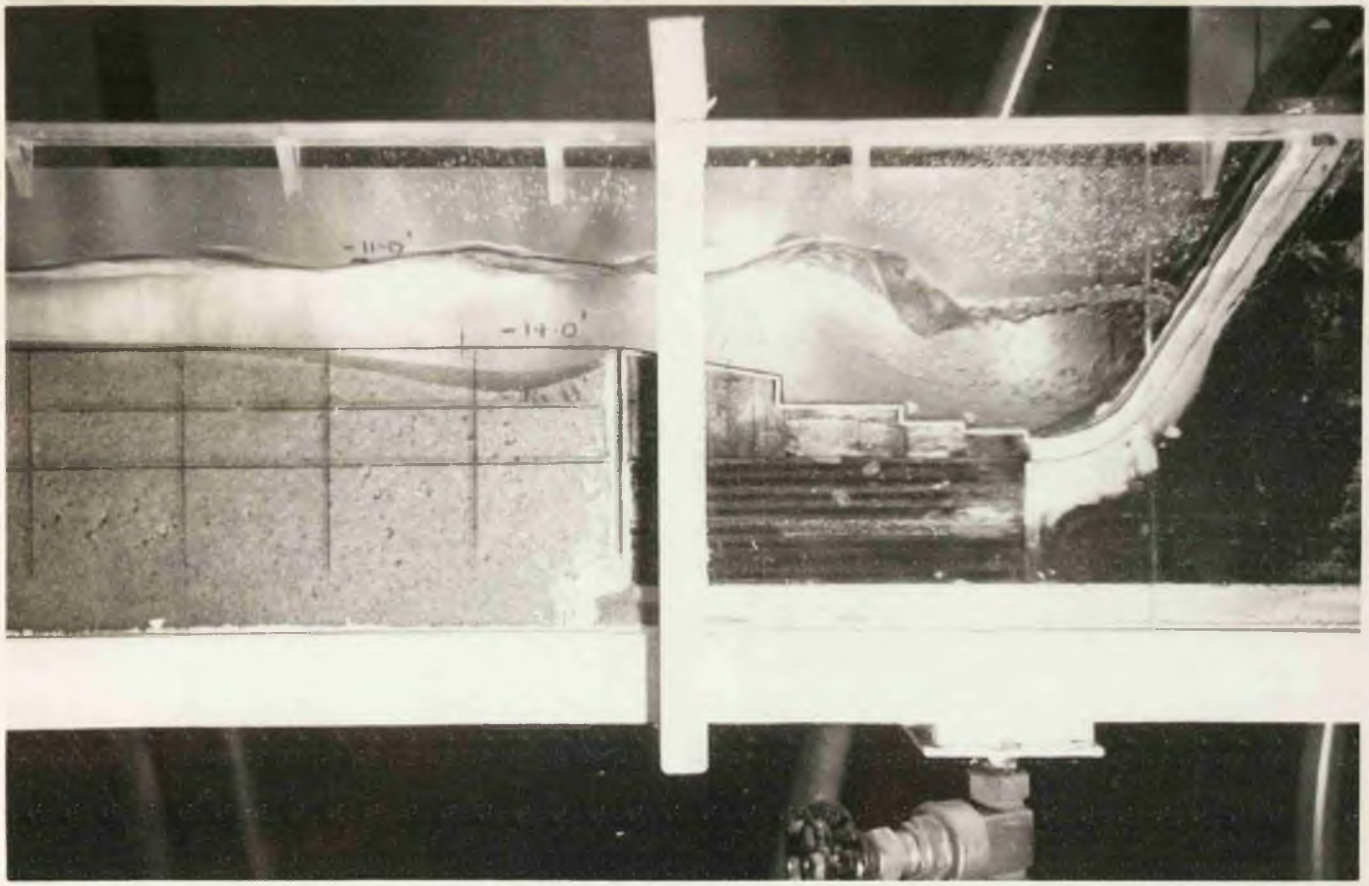


FIG. 18.10 TEST L1

FIG. 18.11 TEST L2


-11-0'
-14-0'

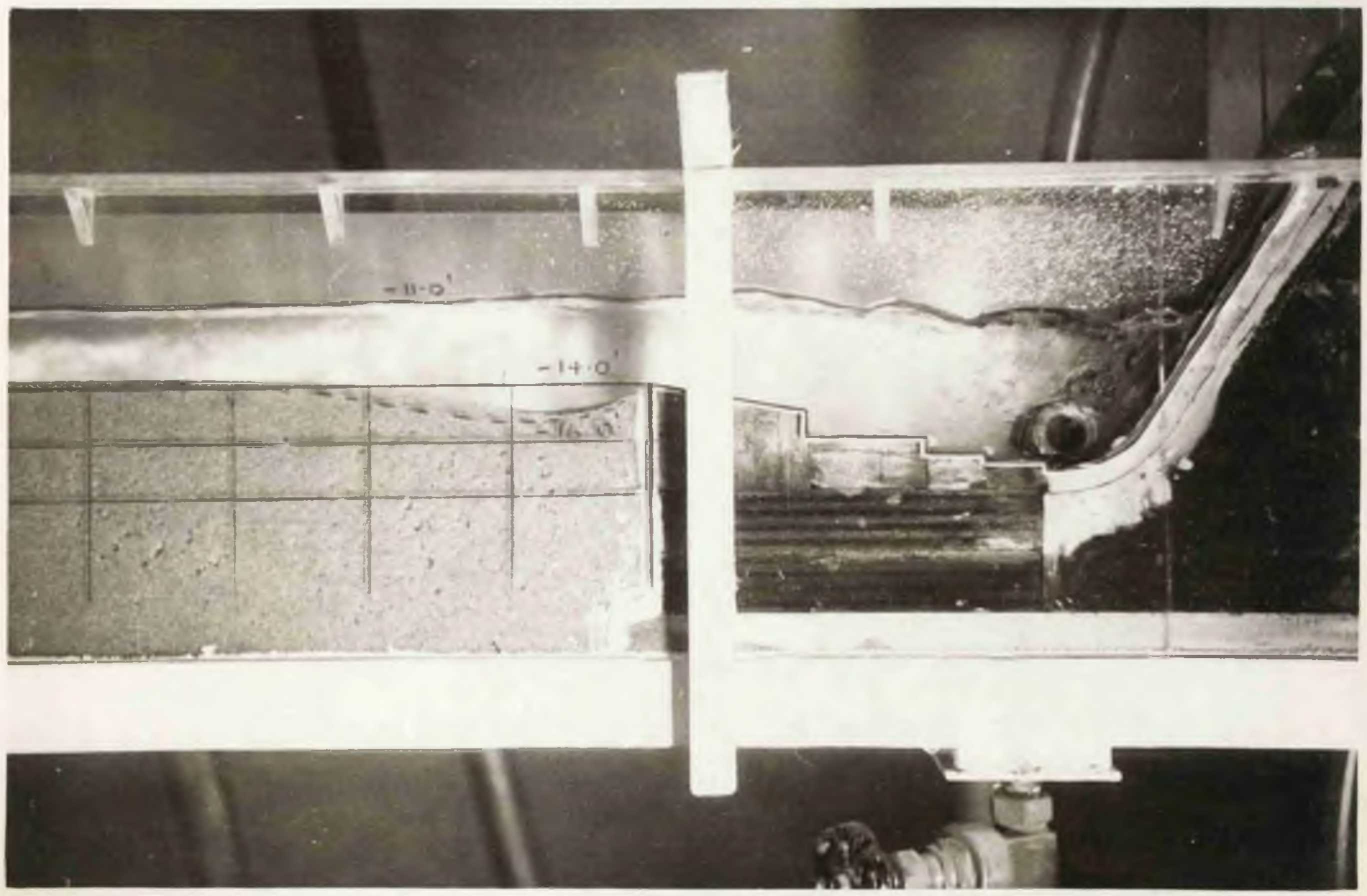
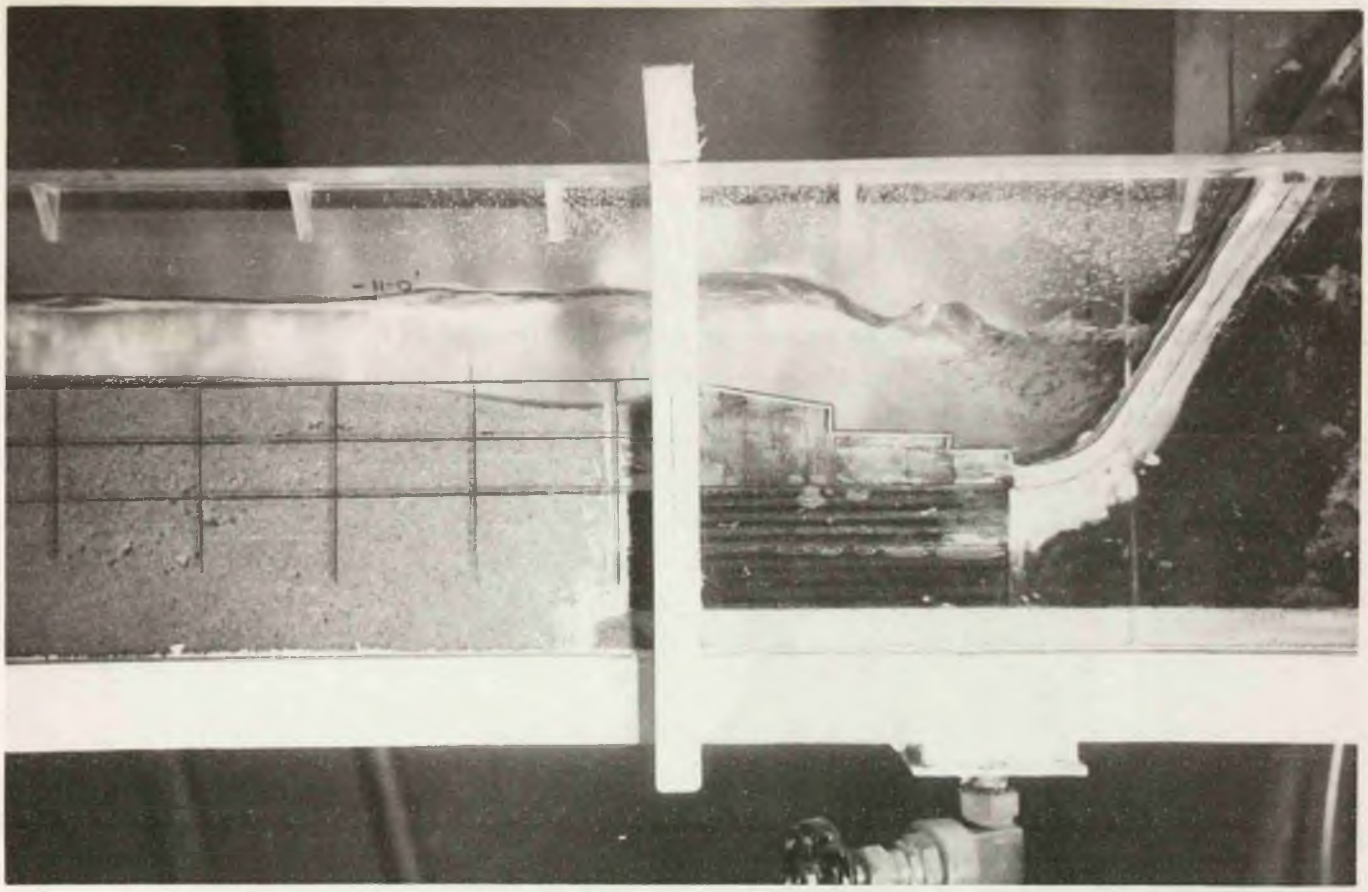

-11-0'
-14-0'

FIG. 18.12 TEST L3

FIG. 18.13 TEST L4


- 11-0'

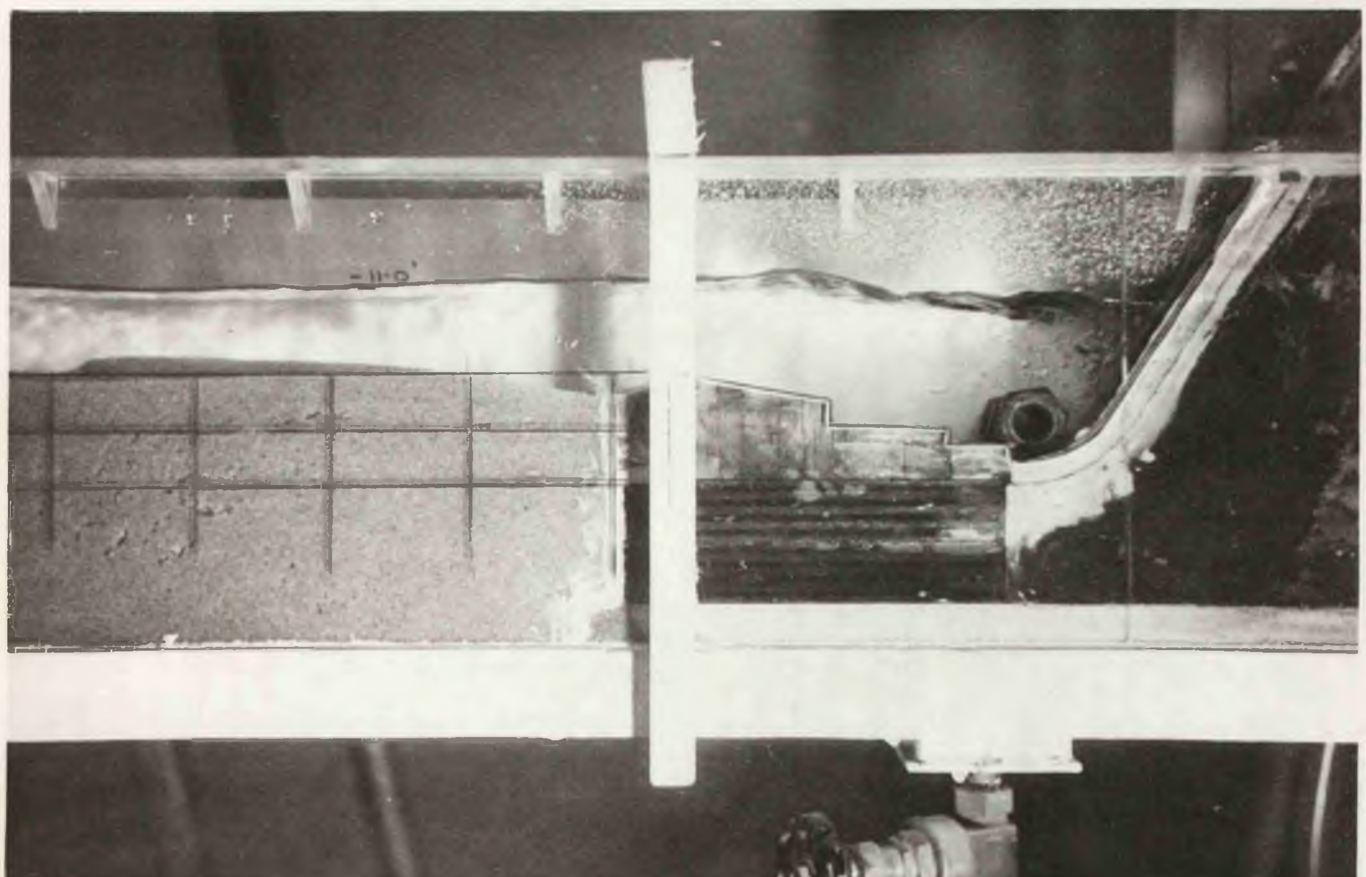
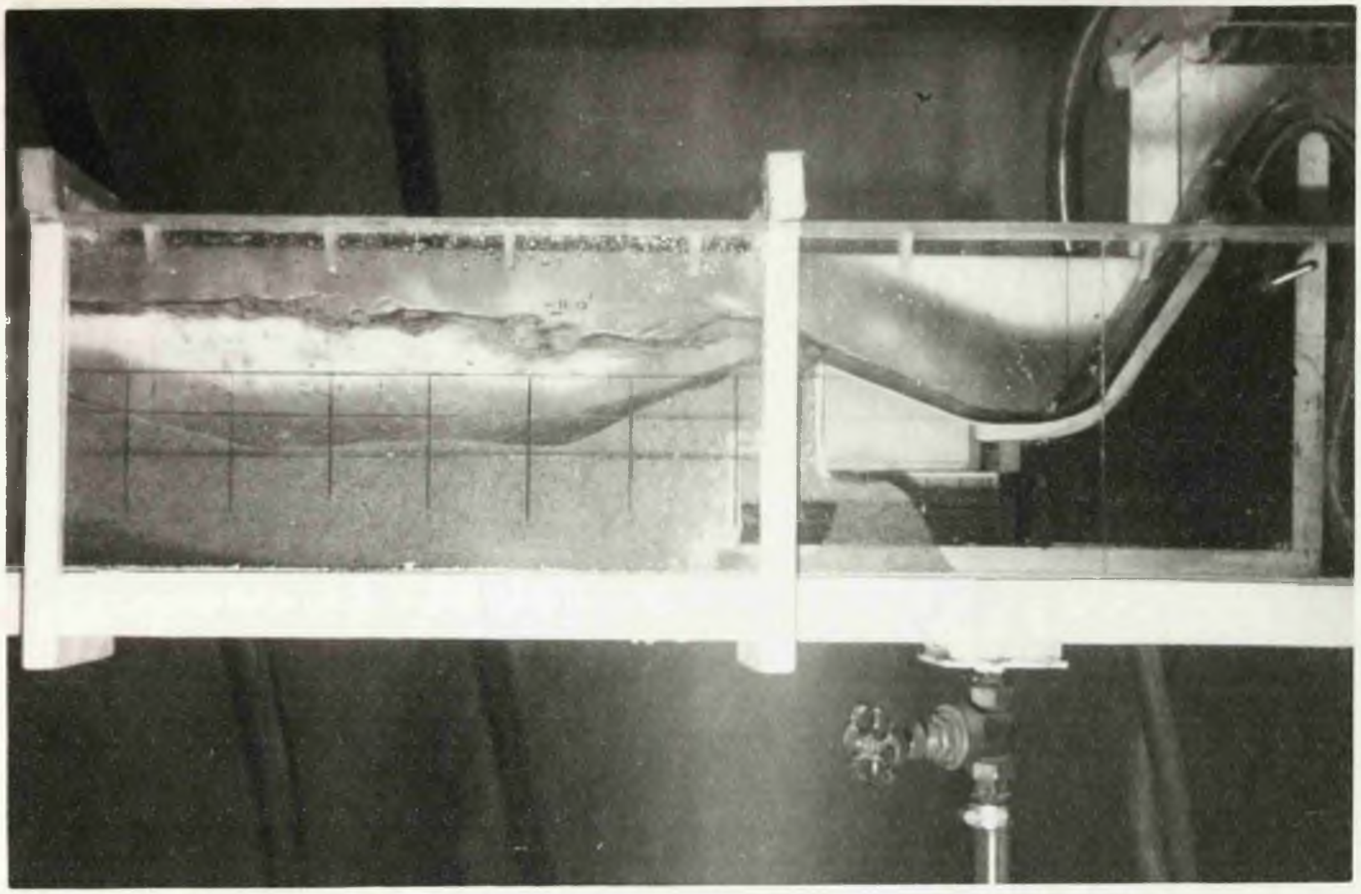

- 11-0'

FIG. 18.14 TEST L5

FIG. 18.15 TEST L6



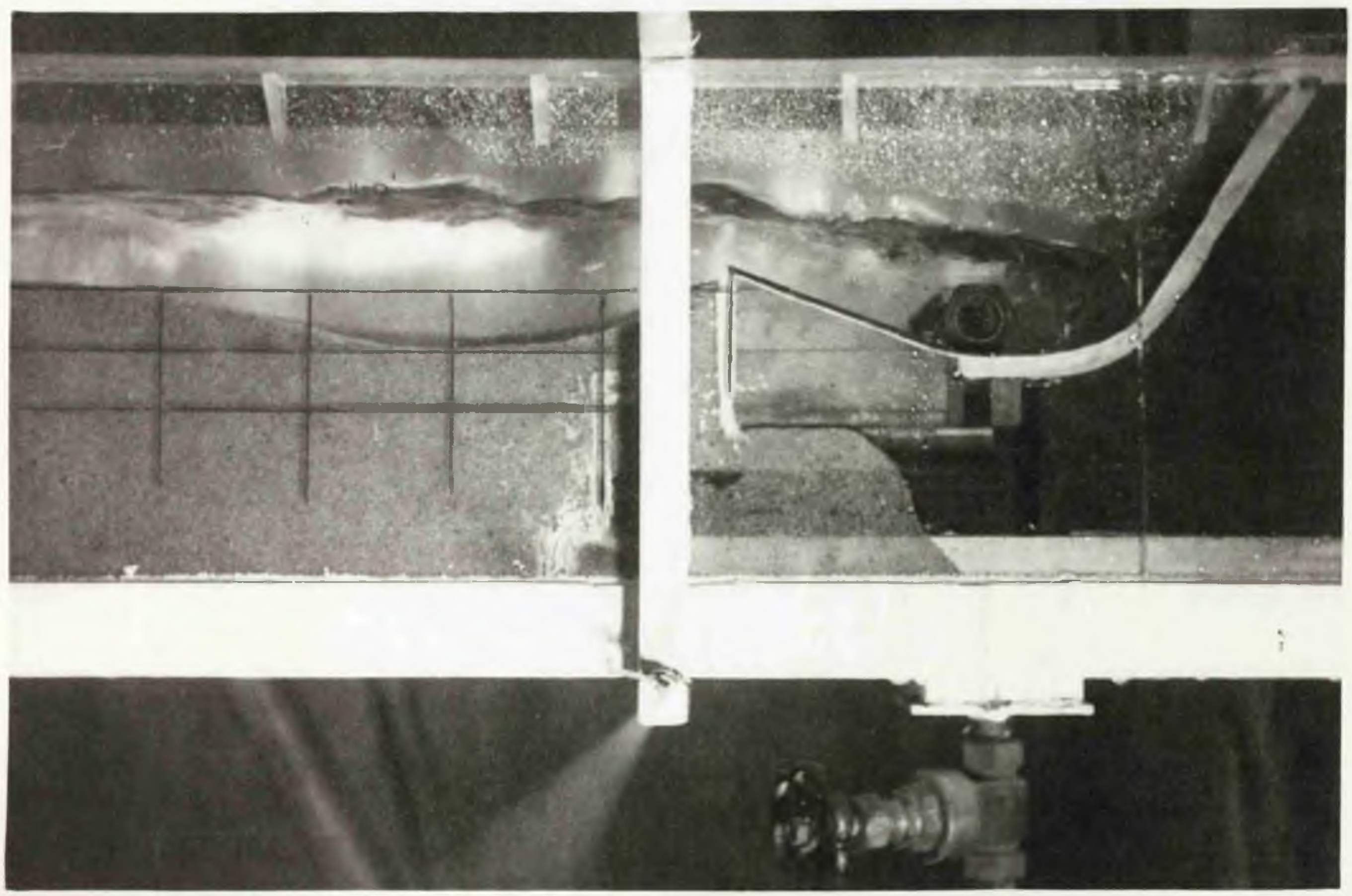


FIG. 18.16 TEST L7

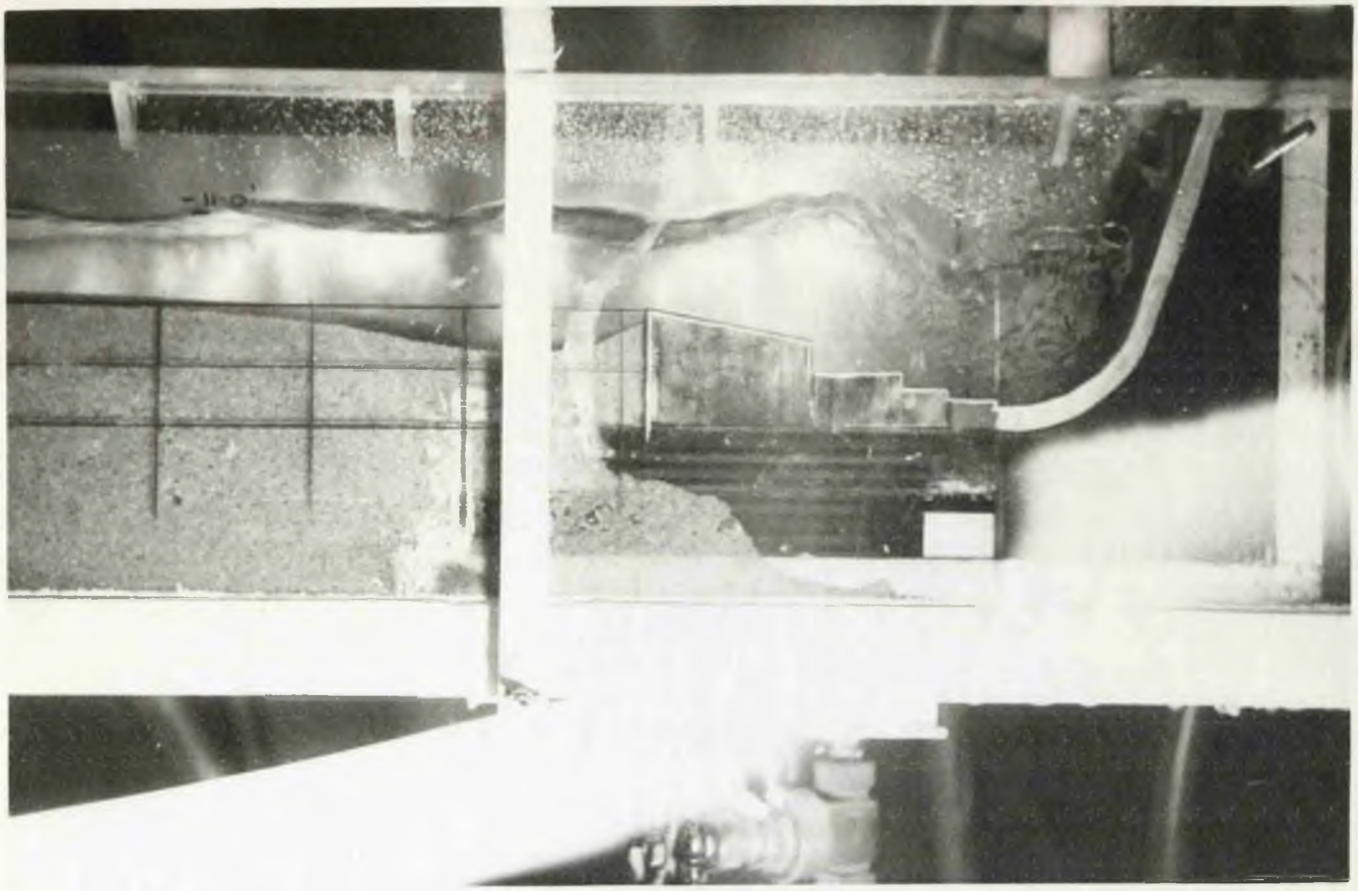


FIG. 18.17 TEST L10

FIG. 18.18 TEST L11

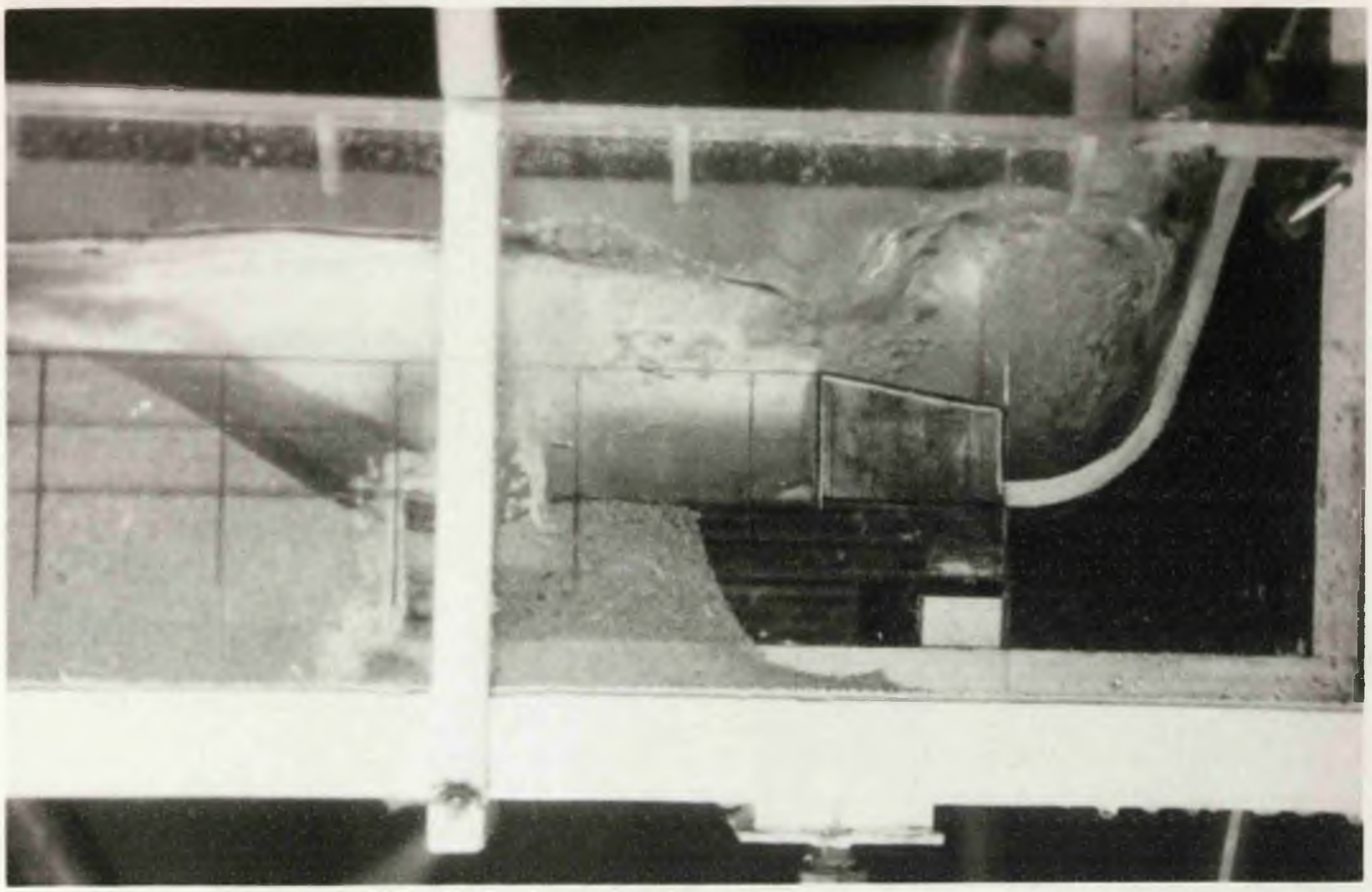
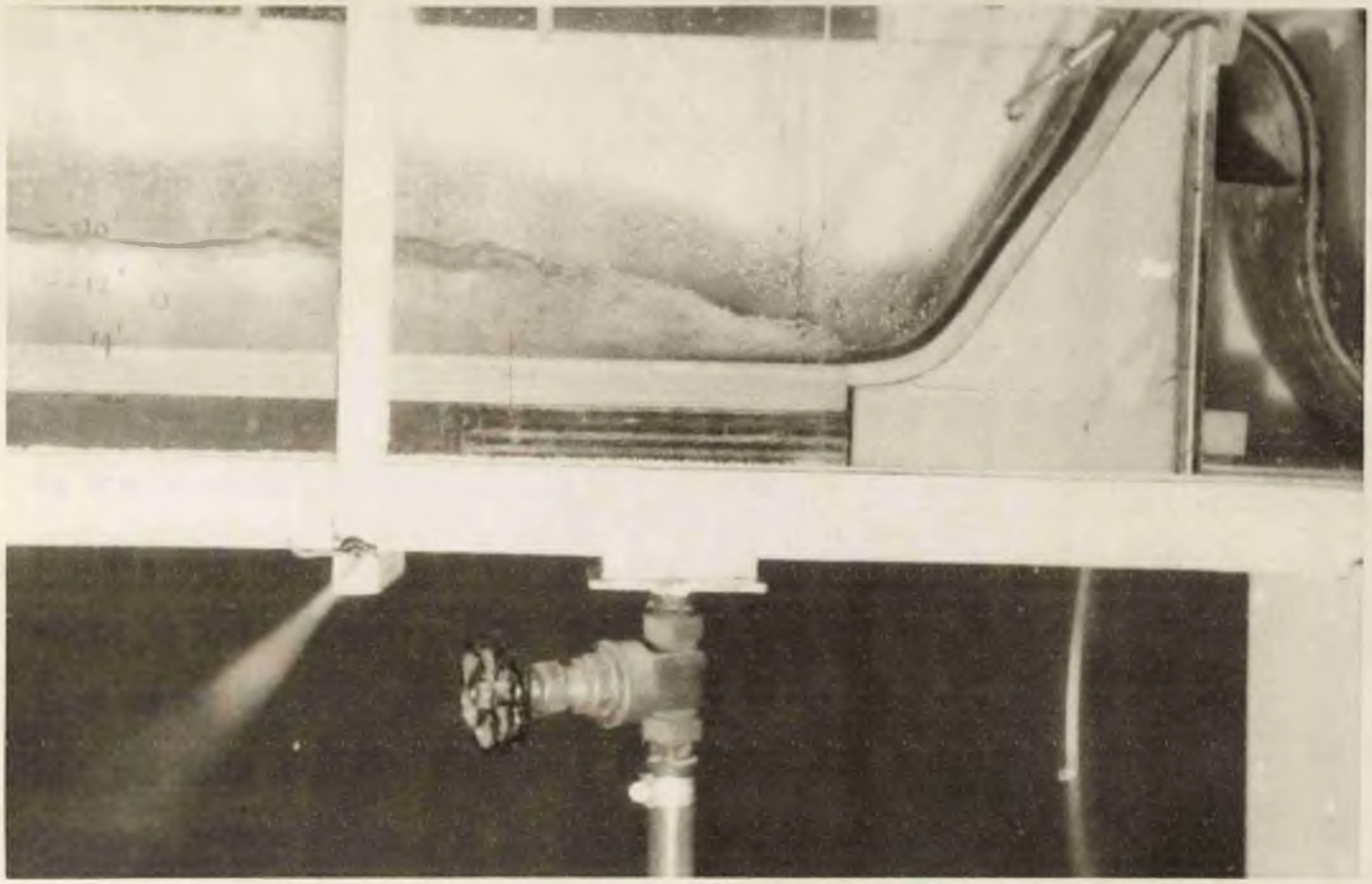
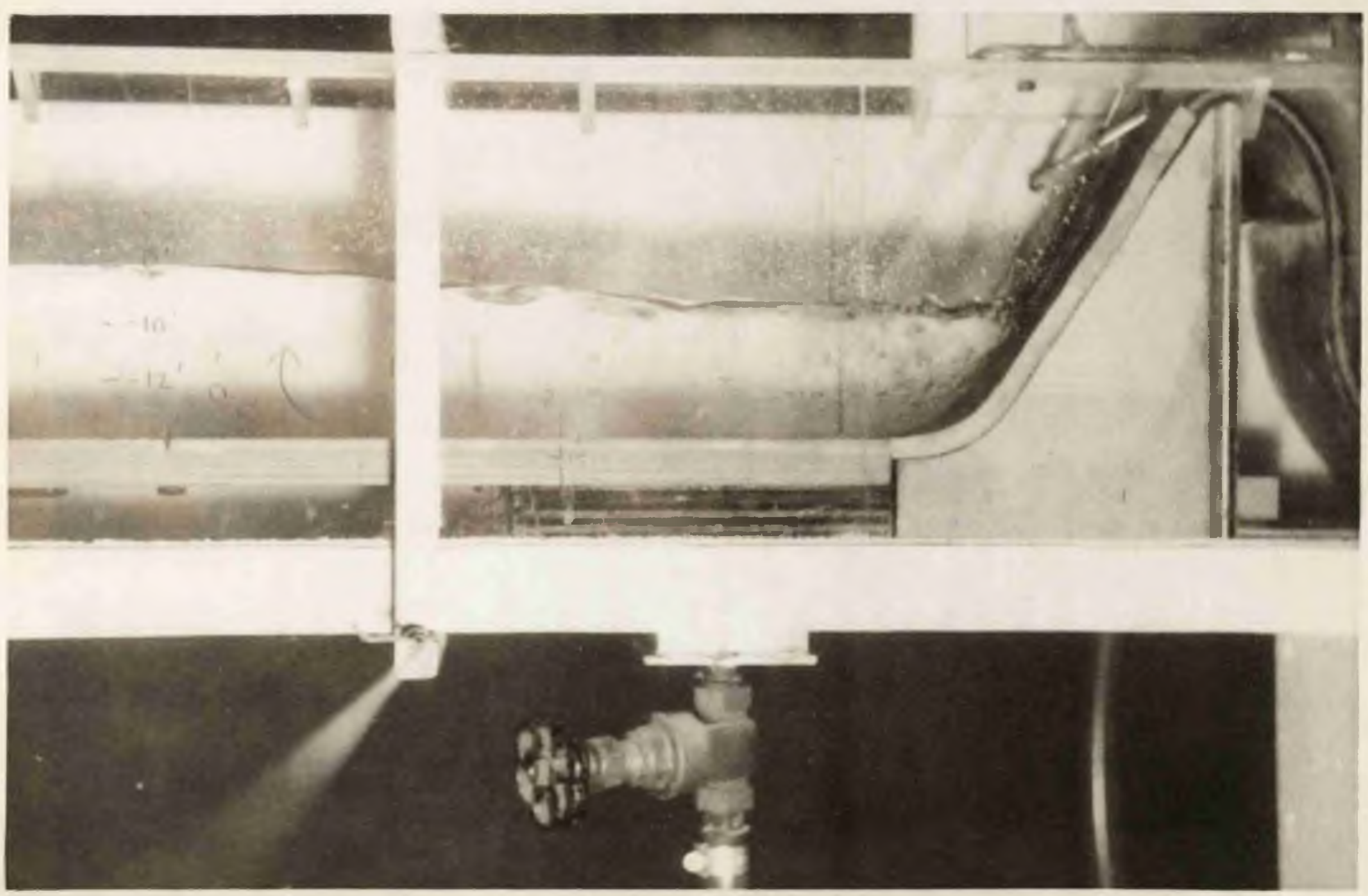


FIG. 18.19 TEST L12

FIG. 18.20 TEST L13





19. APPENDIX 4 - ADDENDUM TO KINCARDINE PAPER.

19.1. Introduction

19.1.1. This Appendix deals with some aspects of the Kincardine investigation which were not discussed in the paper, due to the restriction on its length. These points are thought to be of some interest with regard to the degree of simulation which may have been achieved in the model, or as guides to the approach which should be made to any similar investigation in the future, but are not of sufficient basic importance as to be dealt with elsewhere in this thesis. References and figures are numbered consecutively from those of the Paper and discussion (i.e. starting at 29 and 10 respectively) and for this section, follow at the end of the section.

19.2. Observations made in the river

19.2.1. Measurement of the flow of a large non-tidal river at a particular water level can be a fairly complex operation.[29,30] However, if a complete survey of a selected cross section is made while the river remains at some chosen level then a fairly accurate computation of the flow associated with that level can be made. One velocity meter is normally sufficient, being positioned at a selected grid of positions over a period of hours, or even days in the case of a large river overseas.

19.2.2. Where tidal flows are to be measured the problem is immensely greater since the level and flows alter continuously and since similar conditions may not be repeated during a fairly lengthy period of observation as a result of tidal irregularities and the cyclic variation between spring and neap tides. It has been observed[17] that to study fully the water movements in an estuary it may be better to build a model, calibrate and adjust it by comparison with flow measurements made at selected corresponding sections in the prototype, then use it to study flows in general, rather than to study these in the prototype. This can apply even where there is no question of the effect of proposed new works, dredging or the like being examined in the model. As an alternative to the mechanical approach of the model, total flow may be obtained by calculation. In this case the flow would be taken as the quantity required to provide the difference in volume upstream of a point between selected levels at that point. In common with the model method, accurate knowledge of the regime and of the tide wave shapes are required but the result obtained is unlikely to be accurate when small increments of level are concerned (i.e. to obtain the flow past a point at a particular level).

19.2.3. In the case of the Kincardine investigation the flow measurements available had not been made with the object of assessing the flow for a particular tidal curve, but merely to illustrate the general trends of flow in the river near the proposed power station site. Even for this purpose they were not, in the opinion of the Author, particularly well chosen. (Stations A to H, Fig. 2 of paper). Fig. 10 shows the spring tidal curves obtained at some of the stations. Curves thought to be typical of the extreme condition to be examined were obtained at stations E and F, and section DEF was chosen for flow assessment. Unfortunately, the recordings for station D were eratic, showing a reversal of flow at the height of the ebb tide and could not be used. At no time during the investigation was any explanation found for this irregularity and it was concluded that the marine surveyors had been in error in their recordings at station D.

19.2.4. Allowing for the sketchy nature of the information, the agreement (paragraph 7 of Paper) between the assessments of flow was reasonably good; about 5% discrepancy. Had it been possible to study the flows in a tidal model of the Forth (such as that actually being operated by the Hydraulics

Research Station[8] only four years or so prior to the decision to carry out the Kincardine investigation) many of the difficulties involved in reproducing flow directions, with the relatively short length of river actually modelled, might have been more easily overcome. For instance, due to acceptance of chance combination of tidal curve with arbitrarily selected stations, no indication of the local reversal of flow into the isolated arm (paragraphs 2 and 9 of Paper) was given by the marine surveyors' recordings. This reversal was later shown to be of considerable importance with regard to the movements of discharged condensing water.

19.3. Effect of salinity variations in the Forth

19.3.1. The Forth, in the vicinity of Kincardine, is an example of a well mixed estuary, there being little saline stratification at any time and particularly so at low water springs when the river is comparatively shallow and the water at Kincardine has come from the tortuous 'links of Forth'. The velocity measurements showed only the slightest trace of surface ebb flow continuing after bottom flood flow had started; and this only at neap tides. If nett bottom movement upstream exists in the Forth as observed in the Thames,[17] it probably ceases downstream of Kincardine. But longitudinal variation in salinity certainly exists and because of the distance between the intake and the outfall and the circulation time, there will probably be an increase in salinity in the discharged water compared with the surrounding water during the ebb. At the latter stages of a spring ebb, the situation becomes complex as the presumably fresher water from the south channel will affect the intake while slightly salter water persists at the outfall. A complete study of such variations in salinity would have been extremely time consuming if carried out in the prototype, extreme tides occurring perhaps twice yearly, and would have required the construction of a fairly large scale tidal model of a considerable portion of the estuary downstream and the whole tidal river upstream if approached by model studies.

19.3.2. Tests were carried out in the Kincardine model with the heated outfall water also salted to bring its density slightly below that of the basic water. Fig. 11 shows a typical recording (basic temperature 58°F) which should be compared with those of Fig. 6 of the Paper. The effect during the ebb is quite apparent although the temperature rise is no greater than with the normal low basic temperature case (paragraph 15 of Paper), suggesting that the outfall water was fairly well mixed with the river water by the time it was carried to the intake. During the first part of the low stand there was little change from the normal case but just later than the time corresponding to the longest period of low stand thought possible, the intake water was much affected by the spread of bottom water from across the river. This suggested that a lesser saline density variation would have again had little affect on the intake water temperature during the ebb and would have tended to prevent the spread of heated water towards the intake during a low stand. For these reasons, and because of lack of knowledge of the salinity variations likely to occur in the prototype, the matter was not pursued although the figures for probable temperature rises in the river as given in paragraph 39 of the paper allow a margin over those recorded in the model to cover lack of similarity which may have resulted from the approximation of not using saline variations in the model.

19.4. Long term effects in the river

19.4.1. The assessment of the general temperature rise in the river as a degree or two (paragraph 40 of Paper) was based on an estimate made by the Author which gave 4.5°F as the maximum rise likely after a series of neap tides with the station on full load throughout. The method was based on an assumed mixing rate between a series of blocks of water passing up and down the river with heat losses according to Throne's formula.[9] Here again the Forth tidal model which existed in 1949[8] could have been used most profitably to study the dispersion of water introduced at Kincardine. At present, a tidal model of comparable scale is being used to study possible long term effects in the River Severn once the various nuclear stations sited on this river are in operation.

19.5. Terms of reference of investigation

19.5.1. At the time of the investigation the Author had no knowledge of the economic effect of recirculation; the consulting civil engineers merely being instructed that it should be kept below 5°F at all times. The decision to use outfall position 2 instead of the original position 1 seems rather conservative, and position 3 appears equally suitable on the evidence available and would have cost about £50,000 less again.

19.6. References

29 W. P. Creagar and J. D. Justin, "Hydro-Electric Handbook" 2nd Edition, Wiley, N.Y., 1950.

230 Guthrie Brown, Ed., "Hydro-Electric Practice". Blackie, Glasgow, 1958.

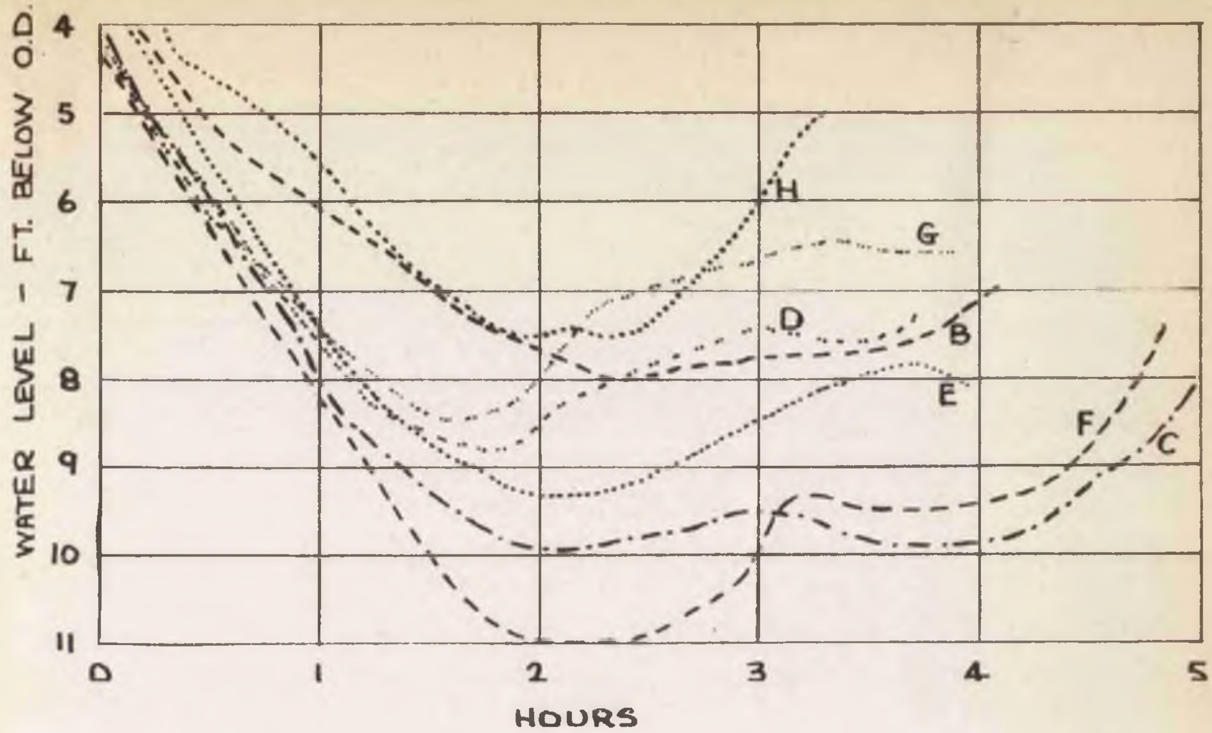


FIG. 10 - PART OF SPRING TIDAL CURVES OBSERVED AT STATIONS B, C, D, E, F, G + H.

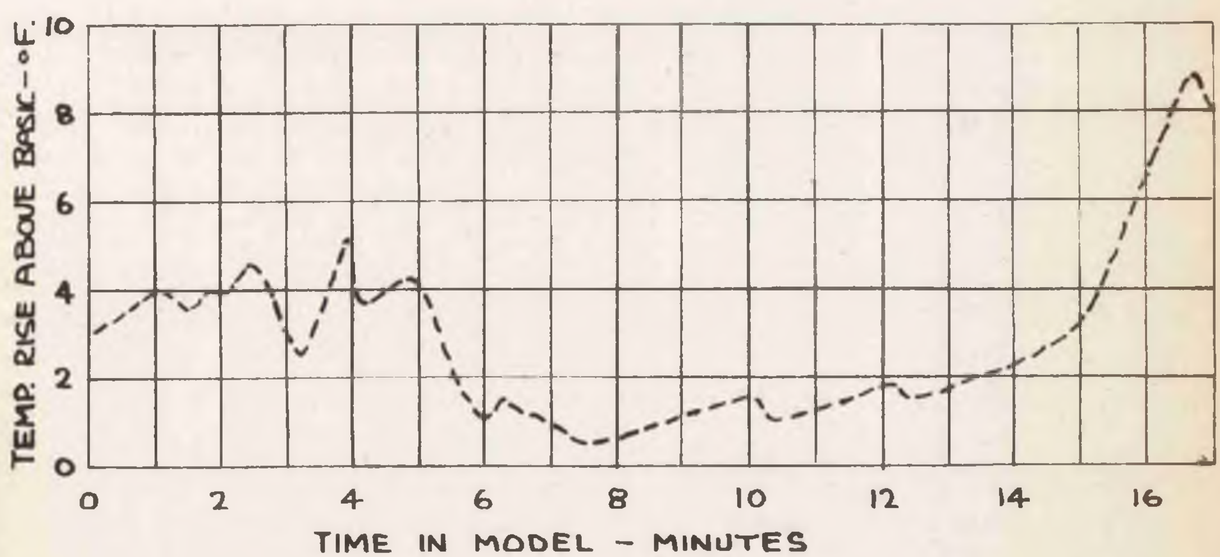


FIG. 11 - TEMPERATURE RISE OF INTAKE WATER USING OUTFALL N° 1 AND SALTED OUTFALL WATER.