AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

A SELECTIVE SURVEY OF LITERATURE ON WATER TUNNELS TO PROVIDE A BASIS FOR THE DESIGN OF THE LUCAS HEIGHTS WATER TUNNEL

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ABSTRACT

With the decision to construct a water tunnel at Lucas Heights, a survey of literature on water tunnels was undertaken to provide a basis for the design of the tunnel and to keep abreast of the latest information on modern techniques in water tunnel operation.

All types of water tunnels are discussed but particular emphasis is placed on the closed loop, closed jet tunnel design since this type gives maximum experimental flexibility.

Individual tunnel components and ancillary equipment are discussed in detail. The bibliography gives references relating to tunnel design, performance and operation.

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1. INTRODUCTION

During the A.A.E.C.'s research programme on high temperature gas-cooled reactors it was decided to construct a small water tunnel at Lucas Heights. Its immediate use was to be for analogue studies of coolant flows through reactor cores of the packed bed type. However, maximum flexibility of application was required to permit the study of a wide range of flow problems.

Since many of the problems of designing such a tunnel rarely occur in conventional engineering practice, the authors undertook an extensive survey of all locally available literature dealing with tunnel design and operation. The Lucas Heights tunnel was then designed on the basis of this survey, since the available experimental facilities and time did not allow the construction of a small pilot tunnel or even testing of components.

The three Australian research water tunnels at the Universities of Adelaide, Queensland and Sydney were visited. These tunnels are in various stages of development, and tunnel design and operational problems were discussed with the staff.

This survey deals with the various water tunnel types and uses, circuit arrangements, component design, and ancillary services, but is biased towards the closed loop, closed jet working section tunnels since only these provide the maximum flexibility required at Lucas Heights. Appendix 3 lists those tunnels throughout the world about which some information was available. However, this list has some omissions because other tunnels, about which no information was available, are known to exist.

The bibliography details both general and specific references dealing with all types of tunnel and component design and tunnel operation. Not all of the listed works have been directly referred to in the text and some of the overseas publications listed were not available for perusal at the time of writing.

The tunnel design eventually evolved for Lucas Heights and the results of commissioning tests will be reported separately. At the time this report was submitted the tunnel was in the final stages of erection.

2. TYPES OF WATER TUNNELS

Water tunnels, like wind tunnels, are test facilities for the production of relative motion between an object and a body of fluid. Generally there is controlled motion of fluid past a model mounted in the working section in order to simulate the motion of the prototype through water under actual operating conditions.

The term 'water tunnel' is often used rather loosely, and for this survey it is defined as a research facility which has the following features:

(a) A uniform fluid velocity distribution is produced in the working section space occupied by the model.

(b) Steady flow, or controlled accelerating/decelerating flow can be maintained in the working section. Most water tunnels have been used to produce only steady flow conditions, the exceptions being the two small tunnels at the Massachusetts and California Institutes of Technology.

(c) The flow velocity and the pressure in the working section can be varied independently. If the tunnels are not used for cavitation studies independent variation is not as necessary.

In addition, many tunnels feature controlled variation of water temperature and air content.

2.1 Flow Circuit

As with wind tunnels, both open and closed flow circuits are possible, the latter often being called the return flow type. Open circuit water tunnels are rare, since they are practicable only where large volumes of water can be run to waste. The main disadvantage of the closed circuit tunnel is that the noise generated by the pump is transmitted by the water and the tunnel shell to the working section where it could interfere with acoustic measurements. However, in modern closed tunnels this background noise level is low enough to permit most acoustic measurements. On the other hand in open circuit tunnels independent control of velocity and pressure is difficult.

The literature indicates that only two large open circuit tunnels are in operation. These are the 10-inch free jet tunnel at the St. Anthony Falls Hydraulic Laboratory (SAF)* University of Minnesota, U.S.A. and the ONERA tunnel at Chatillon, France. In addition the 20-inch water turbine testing tunnel at the National Engineering Laboratory (NEL), Glasgow, Scotland, may be operated optionally on open circuit for extreme accuracy during flow calibrations.

* For abbreviations used throughout the text refer to Appendix 1.

The majority of water tunnels are thus of the closed circuit type, where pumps are used to circulate water through a closed loop. Only these will be considered in the remainder of this report.

2.2 Working Section

Depending on the working section design, water tunnels may be classified as open jet, free jet, closed jet, slotted wall, and free surface types.

2.2.1 Open jet tunnels

In the open jet tunnel the water issues from a contraction and flows unconfined through a larger chamber containing water at rest. After a certain distance it enters a collector, alternatively called a gathering nozzle or pick-up cone, and is returned through a recirculating duct. Figure 1 depicts schematically the typical open jet circuit of the MIT 20-inch tunnel. The pressure in the surrounding water chamber usually may be varied to suit the experimental requirements and, depending on the method used to vary this pressure, there may or may not be a free surface.

As the jet is surrounded by static fluid one might expect the longitudinal distribution of the static pressure to be constant over the whole length of the working section. However, friction between the jet and the static water produces a rapidly growing mixing zone and shrinking jet core. Thus the open jets have rather large longitudinal pressure gradients, which in turn limit the usable working section length. Further limitation on the working section length is imposed by the difficulty of collecting the jet smoothly, the resulting pressure-velocity pulses being propagated back to the working section. Ripken (1951) quotes the maximum length of the working section as being about equal to its diameter and a maximum velocity of about 50 ft/sec. Model mounting and access to the working section are easy for this type.

Most open jet tunnels are in the United States, and are used particularly for propeller studies. Some (for example, the DTMB 36-inch diameter tunnel) have the open jet working section as an alternative to the closed jet one.

A major advantage of open jet working sections is that wall interference effects are small. For example, in the open jet configuration of the 36-inch DTMB tunnel propellers as large as 27 in. dia. may be tested with negligible wall interference effects, whereas for the closed jet configuration the maximum propeller diameter is only 18 inches.

2.2.2 Free jet tunnels

Here the jet issues from the contraction and flows through a chamber containing a gas. Horizontal jets are subject to gravitational forces and assume a parabolic trajectory. This limits the working section length particularly at low velocities. Vertical jets, owing to gravity effects, experience a reduction in jet size.

Free jet tunnels are rare, being used only for extreme cavitation studies. They were first constructed by Reichardt in Germany during World War II (Robertson 1956). The SAF 10-inch tunnel, (see Section 2.1) has a vertical downward flow free jet with provision for both two-dimensional and three-dimensional studies. Another tunnel, having a horizontal working section (9 x 7 in.) is at the Armament Research and Development Establishment, Kent, England.

2.2.3 Closed jet tunnels

An example of this circuit type is shown in Figure 2. Water simply flows through a duct of appropriate cross section, and the developing boundary layer along the walls produces a longitudinally falling pressure gradient, acceleration of the jet core, and the destruction of the jet uniformity. Nevertheless it is possible to obtain a much more stable flow than in the open jet type. The frictional losses are due to small scale eddying in the boundary layer and the required tunnel pumping power is only one half to two thirds that of the open jet tunnel. Model mounting is not as easy as in the open jet tunnel and wall interference effects place a limit on the maximum model size.

Most general purpose tunnels are of the closed jet type. To compensate for the growing thickness of the boundary layer and the falling longitudinal pressure gradient a slightly diverging working section was provided on some of the early tunnels, the divergence being matched to the speed of most frequent testing; however, this technique is seldom employed with water tunnels of more recent design.

2.2.4 Slotted wall tunnels

To overcome the wall interference effects associated with the closed jet type working sections, slotted wall working section tunnels were developed and are increasing in importance in both Europe and the U.S.A. They originated in England (Lever et al. 1957) and were adapted from transonic wind tunnel designs. The choking and interference effects associated with a closed working section severely restrict the size of model which can be tested at transonic speeds. (A tunnel is said to be 'choked' when further increase of the pressure ratio of the tunnel produces no increase of the Mach number in the working section ahead of the model; in practice this occurs when the region of sonic speed extends uniformly from the model to the tunnel walls). On the other hand, open jet tunnels do not experience the choking phenomenon but are unsteady and the jet breaks down. The slotted wall section is used as a compromise, the solid part of the boundary steadying the flow and the open part of the boundary preventing choking and reducing interference effects. It has been found that the advantages of slotted wall sections are still valid for very low subsonic flows.

The slotted wall tunnel consists of a closed jet working section with a series of longitudinal slots running the entire length of the boundary wall. The number of slots is arranged to give about 20 per cent perforation of the wall boundary. This inner section is encased in a larger chamber containing water essentially at rest. The restrained communication between the jet fluid and the chamber fluid in this hybrid working section produces a performance characterised by small wall interference effects, improved longitudinal pressure gradients (compared with the open jet sections), substantial working section length and high jet velocities.

In England slotted wall working sections are known to have been provided on the NPL No. 1 (Lithgow) tunnel and the Admiralty Research Laboratory (ARL) 30-inch tunnel. Other European tunnels incorporating slotted wall sections are the Netherlands Ship Model Basin (NSMB) No. 1 tunnel and the 8-inch tunnel at Trondheim, Norway. In the U.S.A. slotted wall sections have been included in the tunnels at the SAF and at the University of Iowa.

Both circular and rectangular working sections can be used and the maximum acceptable ratio of model to working section size for a cylindrical body in a circular working section is quoted as 1:3 (King et al. 1958); the corresponding ratio for a closed jet working section is 1:6.

In Figure 3 are shown longitudinal pressure distributions for the following working sections:

(a) open jet (1.6 diameters long),

(b) parallel cylindrical closed jet (2.18 diameters long),

(c) diverging cylindrical closed jet (2.18 diameters long), and

(d) cylindrical slotted wall (2.4 diameters long).

This information was obtained in the SAF 6-inch experimental closed circuit water tunnel (Straub et al. 1955). The curves were obtained for a velocity of 50 ft/sec and the pressure distributions are velocity sensitive. Note that at 50 ft/sec the usable portion of the open jet working section of 1.6 diameters is limited to about 0.5 diameters.

2.2.5 Free surface tunnels

To study flow around bodies when they are on or near a free surface and when cavitation is involved, free surface water tunnels are sometimes used. Here the water stream is confined by solid boundaries only at the bottom and sides; the top surface is an air-water interface. Since there is a free surface, the modelling is governed by both the Reynolds and the Froude numbers, the latter being expressed as the ratio of flow velocity to the wave velocity.

Although there are a number of open flumes the literature lists only a few facilities which may be classified as water tunnels (the criterion being the mechanism for pressure variation). All of these are in the U.S.A. An exceptionally advanced variable pressure tunnel (called a 'channel') at Hydronautics Inc., Maryland, has a working section 12 ft long, and 2 ft wide, the maximum water depth being 2 ft and the minimum pressure 3 ft water (absolute). It is used to study high speed hydrofoil craft, supercavitating propellers and high speed underwater missiles. Other free surface tunnels are located at the CIT (the Hydraulic Laboratory of the Newport News Shipbuilding and Dry Dock Company) and at the U.S. Naval Ordnance Test Section at China Lake, California.

3. USES OF WATER TUNNELS

The early water tunnels were built for marine propeller studies, but now other investigations, particularly those involving cavitation, are increasing in importance. Many general purpose water tunnels have been constructed since the war and these, as well as some highly specialised installations, have greatly widened the range of problems. Water tunnels have even been built to study chemical reactions (Kiser et al. 1957). The main uses of water tunnels may be classified in the following manner.

3.1 Studies Involving Cavitation

3.1.1 Marine propeller research

Practically all the larger tunnels have been used for research into marine propeller design and performance; lately emphasis has been on such aspects as partly and fully cavitating propellers, propeller vibration and singing, ducted propellers, and propeller performance in the non-uniform velocity fields which

occur in the wakes formed by ship hulls.

3.1.2 Cavitation fundamentals

With a view to improving the performance of propellers, turbines, pumps, hydrofoils and so on, the study of cavitation fundamentals has been undertaken in many tunnels. Those constructed especially for this purpose include the tiny $1\frac{1}{2}$-inch ultra high speed tunnel at the PSU, the SAF 10-inch tunnel, and a special two-dimensional 30 x 6 inch working section for the CIT 14-inch high speed tunnel.

3.1.3 Cavitation associated with submerged bodies

These studies are concerned with fully and partly cavitating hydrofoils (both isolated and in cascades) and with other submerged bodies such as ship appendages, sonar domes and torpedo noses. Problems investigated have included the determination of cavitation inception conditions, life in a cavitation-erosion environment, drag under cavitating conditions, and development of suitable contours for prescribed cavitation indices.

3.1.4 Cavitation in hydraulic machinery

At least three large water tunnels have been constructed for experimental investigations of cavitation in pumps and turbines. These are the Lewis water tunnel at Cleveland, Ohio, the NEL tunnel, and the Escher Wyss tunnel at Zurich, Switzerland.

3.1.5 Cavitation analogy

The cavitation analogy is based on the phenomenological similarity in the occurrence of cavitation and shock waves. Both these effects first occur on the surface of a submerged body at the point where fluid velocity is highest. The similarity was utilised during the second World War by Reichardt in Germany to develop shapes for high velocity aerodynamic parts. Other applications of this analogy involve water tunnel tests to determine where shock waves first occur on high speed bodies or combinations of bodies.

3.1.6 Internal flow studies

Internal flow studies constitute a mixed group in the sense that cavitation is not always present. They include flow through water tunnel components, through models of whole water tunnel circuits, through venturis, and through cryogenic fuel system components.

3.2 Studies Without Cavitation

3.2.1 External flow studies

To this category belong those studies relating to flow around hydraulic structure components, such as bridge piers and piles, where the components may be fully or partly submerged. In Australia the University of Queensland water tunnel is applied to this type of research.

3.2.2 Analogue studies and the Lucas Heights water tunnel

In some instances water tunnels have been used for analogue studies of gas flow around various aerodynamic shapes. Some recent work has been done in the Chatillon water tunnel in France (Werlé 1960, 1962, 1963, and Werlé and Fiant 1964), and in the Oceanics tunnel (Lehman and Kaplan 1965). The new water/wind tunnel now in service in the hydraulic laboratory of the School of Civil Engineering, University of Sydney, when used as a water tunnel, will provide an analogue research tool to study the dynamic behaviour of structures in natural winds.

The initial programme for the Lucas Heights tunnel will be the analogue study of gas coolant flow through a reactor model core of the packed bed type, that is, one composed of a large number of spherical fuel elements. The fundamentals of this analogy will now be discussed in more detail.

Only completely enclosed subsonic coolant flow is of interest and therefore the water analogy work is governed only by the Reynolds modelling, that is, the equivalence of model and prototype Reynolds numbers. In geometrically identical systems the basic advantages of using water to simulate gas flow are:

(a) At 20°C a water velocity of only $^1/_{15}$ that of air and a specific pumping power of only $\frac{1}{4}$ that of air are required to produce identical Reynolds numbers.

(b) Water viscosity decreases with increasing temperature. For example, the Reynolds number is doubled as the water temperature is increased from 20°C to 60°C.

(c) Because of the lower velocity and higher density of water, relatively simple flow visualisation techniques (such as the use of neutral density tracers) may be employed to determine flow patterns quickly and economically.

However, since the water flow is a model only with respect to the viscous and inertial forces, it cannot supply any information about the effects of surface tension, gravity, and elasticity (compressibility). If any of these become significant then the Reynolds modelling breaks down. Further, the analogy is limited to gas flows with negligible density gradients; in practice this imposes restrictions on gas velocity, so that the effect of gas acceleration due to intense heating within the pebble bed cannot be included. Also problems involving the mixing of two gases at different densities cannot be investigated.

4. CLOSED CIRCUIT COMPONENTS AND ARRANGEMENT

In Section 2, water tunnels were defined as research facilities which produce and maintain steady and uniform flow in the working section and have means for independent variation of flow velocity and pressure. It is now proposed to review the circuit components and the arrangement commonly used to achieve the desired working section flow.

4.1 Components

To obtain uniform velocity in the working section the flow is almost invariably accelerated through a contraction or nozzle immediately upstream from the working section. This both increases the flow uniformity and decreases the turbulence level. Flow pulsations and swirl are accentuated, but these may be eliminated by other methods. Although suitably shaped screens (several in series if required) or special flow distributors (Atkinson et al. 1967) may also be used to obtain a uniform velocity profile, they are suitable for small ducts only and have not been employed in water tunnels.

An entirely different method has been tried by Atkins (1965) in a small experimental water tunnel having a 6-inch square working section. Upstream from the working section the flow passes through a section of the tunnel in which the walls move forward at precisely the bulk average water velocity. The effective Reynolds number in this section is zero; thus the initial flow disturbances are rapidly damped out and a nearly flat velocity profile is established in about 12 inches.

The use of a contraction, especially a large one, to obtain a uniform velocity distribution in the working section requires that one or several diffusers of an area ratio equivalent to that of the contraction be provided between the working section and the contraction. Since the total included angle of a diffuser is limited in practice to about 7 degrees, the diffusion process occupies a large part of the tunnel circuit (at least one half of the total circuit length). This means that the velocity through the major part of the tunnel is low and hence the frictional losses are much less than if some other means, such as a series of screens, had been used to produce the uniform velocity profile.

Invariably all closed circuit tunnels have a number of turns; the most common number is four, although quite a few tunnels, particularly those incorporating resorbers, have more. All tunnels incorporate a settling section upstream from the contraction to damp out the smaller scale disturbances generated by the last turn and possibly other upstream components. Often honeycomb flow straighteners and less often turbulence reducing screens are inserted in the settling section.

On some tunnels a gradual transition section is provided between the working section and the first diffuser to reduce the cavitation susceptibility of that region.

To obtain steady flow in the working section it is necessary that steady conditions exist in the whole circuit, including the pump. This means that all possible causes of unsteady conditions such as large scale eddies in turns, diffusers (usually due to separation) and contractions, must be eliminated by careful hydrodynamic design of the circuit components.

4.2 Circuit Arrangements

Although the methods used to obtain the desired working section flow are essentially the same for all tunnels, the circuit arrangements vary greatly. However, two features common to most water tunnels are arrangement of the circuits in vertical planes and placement of the working section in the upper horizontal limb. This ensures that the working section is in the minimum pressure region, because it is essential that if cavitation occurs at all, it occurs first at the model, that is, in the working section, rather than in some other part of the tunnel. Two exceptions to this arrangement are the University of Queensland tunnel in which the working section is placed in the lower horizontal limb, and the NPL tunnel at Teddington which has the working section in one of the vertical limbs.

On most tunnels pumps are placed in the lower limb, where the pressure is highest, in order to reduce the risk of pump cavitation. However, for various practical reasons, the pumps are sometimes placed in other parts of the circuit, usually in one of the vertical limbs.

Tunnel design philosophy has changed over the years and the modern general purpose water tunnel looks quite different from the early water tunnels which were designed exclusively for propeller testing. Typical of the early American tunnels is the 24-inch open jet tunnel at the DTMB, which was installed in 1941 and is shown in Figure 4.

The design of these tunnels is characterised by large radius turns, with and without splitter plates, the first turn being positioned very close to the working section. This enables the model propeller shaft, which is brought out through this turn, to be as short as possible and thus to allow the shaft critical speed to be raised above the operating speed. Since at best only a short diffuser may be placed between the working section and the first turn; the latter is in the maximum or near-maximum velocity region consequently flow turning losses and cavitation susceptibility of the first turn are high.

To overcome this problem a different approach has been used by the European designers, and is shown in the circuit of the No. 1 Cavitation Tunnel at the NSMB illustrated in Figure 5. This tunnel is one of a number built to the design of the Hamburgische Schiffsbau Versuchsanstalt. The first turn is bifurcated, and the model propeller shaft leaves the tunnel at the breeching piece. This enables an effective diffuser to be placed after the working section whilst still keeping the propeller shaft length a minimum. Other tunnels employing bifurcated sections include the AEW No. 2 tunnel and the Kings College cavitation tunnel in London. There is, however, a penalty for the use of such sections, in that the bifurcation and the two-legged brackets supporting the model shaft cause velocity disturbances in the working section, for example, see Newton (1962).

The water tunnels designed and built after 1938, a typical example of which is the PSU 48-inch tunnel (Figure 6), no longer have large radius turns; these are replaced by mitred turns fitted with turning vanes. This not only leads to a more compact tunnel arrangement, requiring a smaller building, but also to improved tunnel performance. However, the compactness reduces the pressure in the lower horizontal limb to a level where pump cavitation occasionally limits the working section cavitation index.

Research on model propeller shafts running in several short, water-lubricated bearings has indicated that they can be operated safely at a super-critical speed that is, running above their lowest whirl frequency. Consequently, tunnels which are basically propeller tunnels, such as the NPL No. 2 tunnel shown in Figure 7, now incorporate rather long diffusers between the working section and the first turn. This particular tunnel has a downstream model propeller shaft 28 ft long. On this, as on some other propeller tunnels, upstream propeller shafts can also be used.

The tunnel circuit shown in Figure 7 incorporates a resorber system which forces back into solution any air that may come out of the water during cavitation tests and thus maintains the total air content undisturbed. For this the return circuit is arranged in a simple U-shape extending deep below the pump level. More complicated resorber systems are found on other tunnels and resorbers are further discussed in Section 6.

5. HYDRODYNAMIC DESIGN OF CIRCUIT COMPONENTS

Most tunnel components may be either of circular or rectangular section. Rectangular sections were used on some of the early American tunnels, but now almost all new tunnels of American and British design use circular sections throughout the loop. Some European designers still prefer rectangular sections.

5.1 Working Section

The various types of working sections have already been briefly discussed in Section 2. The present more detailed discussion is limited to the closed jet working section, since only this type was of interest in the Lucas Heights tunnel design.

5.1.1 Size

Working sections (and thus tunnels) vary in size from the very large 47 x 97 in. rounded rectangle working section of the AEW No. 2, and the 48-inch diameter circular working section at the PSU tunnel, down to the tiny $1\frac{1}{2}$-inch diameter circular section of the ultra-high-speed (332 ft/sec) cavitation tunnel, at the PSU. (In general the working section diameter is used to designate the tunnel).

The working section size limits the maximum model size which may be tested under free stream conditions before wall interference effects become appreciable. This is further discussed in Section 5.1.3.

5.1.2 Shape

Both circular and rectangular working sections are now widely used. The current American and British practice is to use circular working sections for both propeller and general purpose tunnels whilst the European designers favour the rectangular (square or slightly oblong) working sections. Where two-dimensional

flows are essential, as in hydrofoil studies, the standard working sections are often replaced by rectangular sections of large height to width ratios, or inserts used in the standard working sections to provide two-dimensional flow.

Inserts have been used in the tunnels at the DTMB and CIT. At the CIT the working section of the 14-inch tunnel was converted to a quasi-rectangular section (14 x 3 in) by a pair of curved inserts. However, the arrangement suffered from operational difficulties, such as flow unsteadiness at low cavitation numbers and appreciable longitudinal pressure gradients quite apart from limitations caused by the reduced size of the section, so an interchangeable section (30 x 6 in.) was constructed.

Interchangeable working sections are provided on the PSU 12-inch tunnel (20 x $4\frac{1}{2}$ in) and the NSMB No. 1 tunnel (about 48 x 12 in). Interchangeability is achieved by replacing the contraction, working section, and diffuser sections forming the upper horizontal limb. A special tunnel for testing hydrofoils in cascades has been constructed at the Tōhoku University, Sendai, Japan (Numachi 1953, 1961). This tunnel has a movable-wall working section 10.2 x 3.9 in; the longitudinal boundary of the section has been arranged to simulate flow discharge in a constant pressure chamber (such as the atmosphere).

Flow visualisation techniques are simpler for two-dimensional flows and it is possible to employ the schlieren method (see Bland and Pellick 1962). However, powerful and expensive light sources are required for the schlieren technique, because of the very small density changes caused by variations in water (compared with the density changes in gases); for successful application it appears that gas laser sources are necessary (Brackenridge and Gilbert 1965).

5.1.3 Relation between model and working section sizes

As in subsonic wind tunnels, the flow around models in water tunnels is different from that around prototypes moving through an infinite body of water. The main factors producing the discrepancies in wind tunnels, called tunnel interference effects, are solid blockage, wake blockage, lift effect, interference due to the static pressure gradient and, when the model spans a closed tunnel, wall boundary layer interference. In water tunnels, further interference effects are caused by partly and fully cavitating flows, in particular hydrofoils in two-dimensional flows. Full discussion of tunnel interference effects is beyond the scope of this survey. For negligible interference effects the largest recommended model size for axially symmetric bodies in circular working sections is quoted by Ross et al. (1948) and Ripken (1951) as $^{1}/_{8}$ of the working section diameter.

For this ratio Ross quotes the wall interference effects on drag as being 5 per cent. Maximum model sizes and interference effects for other model and working shapes may be estimated using the available methods of wind tunnel practice. If cavitation occurs then the tunnel wall interference effects are known to be greater than those for non-cavitating flows. This is particularly true for super-cavitating flows. Ōba (1964) has suggested that the wall effects in super-cavitating flows may be greatly reduced by sucking small amounts of water through slots in the top and bottom tunnel walls.

5.1.4 Flow quality and pressure distribution

At the exit from the contraction, in a well-designed circular section tunnel, a longitudinal velocity uniformity of about 1 per cent is obtainable up to within 5 per cent of the diameter from either boundary; in some cases values of about 0.5 per cent have been obtained. For rectangular sections vortex filaments occur in the corner regions and these affect the flow quality, although uniformity of about 2 to 3 per cent has been obtained. Figure 8 shows typical velocity profiles taken along the horizontal and vertical diameters at upstream and downstream working section ends in the SAF 6-inch experimental tunnel. Figure 9 shows the velocity distribution (in terms of percentage of the nominal 25 ft/sec velocity) at a cross section 12 ft downstream from the contraction in the rectangular working section of the AEW No. 2 tunnel. Referring again to Figure 8, as the jet length increases, the practically uniform flow at the beginning of the section is gradually reshaped to the turbulent velocity profile characteristic of fully developed turbulent flow in conduits. The reshaping takes place gradually with thickening of the wall boundary layer and with a corresponding increase in the mean kinetic energy of flow. This leads to a reduction of pressure in the direction of flow at a rate greater than that due to wall friction alone. A typical longitudinal pressure gradient has already been illustrated in Figure 3.

Very little information is available about the levels of turbulence in the reviewed tunnels, apparently because:

(i) relatively little water tunnel work so far has concerned the effects of small scale turbulence, and

(ii) suitable instruments such as hot film and hot thermistor anemometers have only recently been perfected enough to allow the measurement of turbulence in water.

Measurements in the PSU 48-inch tunnel, using turbulence spheres, have

indicated a turbulence level less than 1 per cent. The turbulence level in the Queensland University 13.5-inch has been estimated at about 0.5 per cent (Appelt private communication). It is claimed that in the tunnel developed by Atkins (1965) a turbulence level of 0.008 per cent may be achieved for Reynolds numbers up to 10,000. This level is of the order achieved in low turbulence wind tunnels.

5.2 Transition Section

5.2.1 Need for a transition section

To avoid the pressure drop associated with too sudden a change in flow direction at entry to a diffuser, a gradual transition section between the working section and the first diffuser is provided on some modern tunnels such as the PSU 48-inch, NPL No. 2, and SAF 6-inch. Since the pressure is the lowest and the velocity the highest at the exit from the working section, any further reduction in pressure may cause cavitation to occur. By providing a gradual transition, not only is the cavitation susceptibility of this region reduced (and thus the minimum tunnel cavitation parameter reduced, see Section 7.2) but the diffuser inlet velocity distribution is improved and the danger of separation decreased.

5.2.2 Transition shapes

A number of suitable shapes, all derived assuming potential flow, have been proposed for the transition section. A suitable shape is one having continuous first and second derivatives (velocity and acceleration). The continuity of the first derivative is required to avoid separation, and that of the second to avoid pressure jumps. Brazell (Ross et al. 1948) has suggested that the true transition curve is a clothoid, or logarithmic spiral, but that in practice lemniscates and cubic parabolas should also give good results. The cavitation susceptibility of a transition curve decreases with increase in length, but frictional losses limit the practicable length.

For the PSU 48-inch tunnel the transition shape has been determined by the following modified cubic equation:

$$\frac{d}{D} = 1 + \frac{\theta}{2}\,\frac{L}{D}\left(\frac{x}{L}\right)^3 \exp\left[\tfrac{1}{2}\left(1 - \left(\tfrac{x}{L}\right)^2\right)\right] , \qquad \ldots\ldots(1)$$

where d is the diameter at x, D is the initial (working section) diameter, L is the length of the transition, and θ is the total angle of the diffuser. A length of one and a half diameters was used and no allowance was made for the boundary layer thickness.

Ripken (1951) suggests that, in view of the inadequacies of the various theories, there is little justification for trying to approximate any transition curve on the basis of rates of change (velocity and acceleration) and that the transition should simply be made parabolic in form between points of tangency to the working section and the diffuser.

5.3 Turns

The several turns necessary in a closed circuit must be designed to deflect the water stream though the required angle without cavitation, with a minimum loss of energy and with a minimum disturbance to velocity uniformity. As already mentioned, the modern practice is to use mitred turns with suitably designed turning vanes, rather than the large radius turns favoured on the early tunnels. Ripken (1951) lists the following main advantages of vaned turns over the large radius turns:

(a) Less distortion of the velocity distribution.

(b) Smaller energy losses (as low as 0.1 $V^2/2g$, compared with approximately 0.2 $V^2/2g$ for a large radius turn of turn radius to pipe radius ratio $R/_r$ = 3.6, 0.3 $V^2/2g$ for $R/_r$ = 2, and 1.0 $V^2/2g$ for $R/_r$ = 1).

(c) Minimum strength and scale of such turbulence as is created.

(d) Minimum external physical dimensions.

(e) Sensitive control of the velocity distribution by making the vanes adjustable.

Although quite a number of works on the design of vane turns have been published, extensive experiments were undertaken for the larger tunnels to select the optimum vane profile, pitch/chord ratio, vane angle of incidence, and so on (see for example, Robertson and Turchetti 1947, and Ripken 1951). Both thick and thin vanes have been used, the former being favoured on the larger high speed tunnels, where the vane strength and vibratory characteristics also become important. Although thick vanes can have lower energy losses than thin ones, they are fairly expensive, their streamlined contours of fairly large thickness/chord ratio being difficult to machine. They also show appreciable scale effects, thus requiring extensive experimentation to extrapolate model tests to the full-size tunnel components.

Thin vanes, although giving slightly higher energy losses, are used on some of the smaller tunnels, for example on the 20-inch MIT tunnel, designed according to the method of Kroeber (1932), and on the Queensland University 13.5-inch tunnel, designed according to the method of Salter (1946). The shape of thin vanes varies from simple arcs of circles, with or without straight extensions, to special curves, but they are easily manufactured. According to Salter, the optimum pitch/chord ratio for thin vanes is about 0.2, the minimum number of vanes between 15 and 20, and the optimum angle of incidence about 5 degrees to the upstream axis of the tunnel. The higher losses associated with thin vanes are largely caused by the uneven gap width, but values as low as 0.12 $V^2/2g$ for a 90 degree turn have been obtained, the corresponding minimum value for thick vanes being 0.05 $V^2/2g$. The energy loss depends on the inflow conditions and in practice the minimum figures are not achieved. Experiments performed in the SAF 6-inch experimental tunnel (Ripken 1951) gave losses for thick vane turns as 0.1 $V^2/2g$ ± 2 per cent, but indications were that these could be much greater for unfavourable inflow conditions. A value of 0.16 $V^2/2g$ has been quoted for the thin vane corners in the MIT 20-inch tunnel.

5.4 Diffusers

Although diffusers do not directly affect the flow in the working section, they are critical components, since their function is to decelerate the high velocity flow without causing poor flow elsewhere in the circuit. As already mentioned the diffusion process occupies a significant part of the total tunnel circuit. Therefore there is every incentive to design water tunnel diffusers having minimum length and maximum divergence angle consistent with good pressure recovery and separation-free flow. In spite of the fact that there is an immense amount of literature dealing with diffuser design and performance, accurate estimation of diffuser performance using published correlations is not very reliable, since it depends not only on the geometrical parameters, such as the total angle of divergence, the diffuser length, the ratios of exit to inlet areas, and surface roughness, but also on the quality of flow at inlet, the outlet conditions, the flow Reynolds number, and the flow turbulence as well. Therefore most tunnel diffuser geometries have been selected and performance figures predicted from model tests.

The presence of the model body in the working section affects diffuser performance and efficiency, but it is almost impossible to evaluate this influence, particularly for general purpose tunnels. Hence it is necessary to provide two or more diffusers to give more conservative angles of divergence and shorter lengths than are possible with fixed operating conditions. Ripken (1951) quotes reduction in efficiency from 0.93 to 0.88 for some diffuser model studies in which a model was installed in the working section. The conservative diffuser design is well illustrated in Figure 10, taken from McDonald and Fox (1966). Here conical diffuser pressure recovery coefficients were plotted as functions of the diffuser geometry $\emptyset$ and L/r_1, where $\emptyset$ is the total diffuser angle, L is the diffuser length along the centre line and r_1 is the diffuser radius at inlet. The line A-A represents the maximum pressure recovery for a constant L/R_1, and the line B-B the first appreciable stall or separation (geometries below B-B are stall-free). These performance figures have been obtained using water flow under idealised operating conditions, that is, low turbulence flow, thin inlet boundary layer and free jet exit conditions. Geometries of several water tunnel diffusers have been superimposed on this figure and lie well below limits of the geometries which give maximum pressure recovery and stall-free operation. The University of Queensland water tunnel diffuser is an exception in that its geometry lies on the line B-B, but it is operating satisfactorily (Appelt private communication). However, since the water tunnel diffusers do not operate under the conditions applying to Figure 10, their performance figures may be different, and, in particular, the line B-B may be lower. Therefore the diffusers may be operating closer to the 'danger' line B-B than Figure 10 would indicate. For two-dimensional diffusers the line of first appreciable stall lies below the line for maximum pressure recovery (Kline et al. 1959).

There appears to have been no actual attempt to shorten diffuser lengths by methods such as boundary layer removal, boundary layer acceleration, flow rotation and expansion by deflectors or vanes. Some of these methods require large and complicated auxiliary pumping machinery, and all of them are sensitive to inflow conditions. The presence of models in the working section causes inflow conditions to vary, so such techniques have been considered impracticable for large water tunnels.

5.5 Settling Sections, Honeycombs and Screens

5.5.1 Settling sections

Although careful design of tunnel components between the working section and the contraction reduces major turbulence, it is found necessary in practice to provide a settling section immediately upstream from the contraction to reduce further the level of residual eddies, vortices and also spatial flow non-uniformities

that could be caused by presence of the model in the working section. Experience has indicated a straight length of 2 to 3 diameters to be the minimum required, the cross section being determined by the tunnel contraction ratio. Usually, artificial flow correction devices in the form of honeycombs and screens are installed in the settling section to reduce the flow disturbances to an acceptable level.

5.5.2 Honeycombs

The prime purpose of honeycombs is to reduce spatial flow non-uniformities and swirl. The former are reduced by frictional losses, the latter by elimination of the larger cross flow components in the honeycomb cells. Typical honeycombs have been used in the ARL 30-inch tunnel, (hexagonal tubes 1 ft long by $2\frac{1}{4}$ in. across flats), and in the PSU 48-inch tunnel (4 x 4 in. square cells 2 ft long). Other than for experimental investigations honeycombs do not appear to have been used for turbulence control. Although in water tunnel practice the cell length to size ratios are usually about 5 or 6. Lumley (1964) has performed some experiments in the PSU 12-inch tunnel on honeycombs with cell length to size ratios of 32 and has found that they can be used effectively as turbulence reducers. He says that a honeycomb can produce the same turbulence reduction as 4 screens of blockage coefficient 0.45 at the expense of only one velocity head (compared with four velocity heads for the screens).

Usually honeycombs are located immediately before the contraction, although on some tunnels (for example the PSU 48-inch) they are placed some distance upstream to allow for the decay of the honeycomb-generated (fine scale) turbulence before the flow enters the contraction.

Sometimes honeycombs are placed immediately downstream from the pump (DTMB 12-inch tunnel) to eliminate undesirable flow rotation.

5.5.3 Screens

Screens are used for two main purposes:

(i) to reduce turbulence, and

(ii) to alter the longitudinal velocity distribution.

As turbulence reducers screens are not used in water tunnels nearly as much as they are used in wind tunnels. The reason appears to be that water tunnel research work so far has been relatively little concerned with small scale turbulence effects. Screens also suffer from hydroelastic interaction effects and hence particularly in large water tunnels, are not very suitable for turbulence reduction.

However, screens are used quite extensively to produce desired longitudinal velocity distributions in the working section. Thus particular flow fields, for example wakes produced by ship hulls, can be simulated. A different tecnnique for producing such non-homogeneous velocity fields is used in the Delft University of Technology tunnel. Here a velocity regulator containing 146 individually adjustable check valves has been installed in the settling section.

5.6 Contractions

As mentioned in Section 4.1 the rapid contraction of the water stream before it enters the working section ensures an approximately uniform velocity distribution and reduces the stream turbulence level. The ideal contraction should also have everywhere along its walls monotonically increasing flow velocity and for practical reasons should be of reasonably short length.

5.6.1 Velocity distribution

Tunnel specifications usually stipulate that the velocity variations in the working section jet core shall be less than one per cent. Velocity variations obtained in practice have already been discussed in Section 5.1.4. The attainable velocity uniformity is a function of the contraction ratio. Elementary analysis shows that for one per cent departure from uniformity the area contraction ratio must be at least 7 to 1 (Ripken 1951). The literature survey has shown that in practice the contraction ratios actually adopted vary between 3.029 and 27 to 1. The most favoured contraction ratio appears to be about 9 to 1. The lower ratios are found on the older European tunnels with rectangular cross sections.

5.6.2 Changes in turbulence

Although very little information is available, it is thought that the process of turbulence change in contractions is essentially the same for air and water. Theoretical considerations and experimental verifications indicate that in wind tunnel contractions (see Corrsin 1963) the following changes in turbulence occur:

(a) The contraction exerts a selective effect on the turbulence components; the r.m.s. (root mean square) value of the longitudinal velocity fluctuations, u', is decreased, but the two lateral component r.m.s. values, v' and w', are increased. The increases are such that the total turbulence $q' = (u'^2 + v'^2 + w'^2)^{\frac{1}{2}}$ is increased.

(b) However, owing to the velocity increase through the contraction, the turbulence level $q'/\bar{V}$ is considerably reduced by the contraction. The degree of reduction increases with increasing contraction ratio, and the maximum reduction occurs when the initial turbulence is isotropic. The longitudinal component, $u'/\bar{V}$ always decreases, but $w'/\bar{V}$ may increase or decrease depending on the contraction ratio and the characteristics of initial turbulence.

(c) Contraction distorts the initial turbulence; turbulence initially isotropic in character becomes nearly axisymmetric.

The reduction in turbulence level obtainable in wind tunnel contractions is illustrated by Dryden and Schrauber (1947). They quote a reduction in $q'/\bar{V}$ of 3.77 for a 7.1 to 1 contraction. This indicates that q' actually increased about 1.9 times (3.77/7.1).

5.6.3 Geometric shapes of contractions

Many different methods are available for the design of suitable contraction shapes. They are all based either on intuitive reasoning or on the simplifying assumption of (non-friction) potential flow through the contraction. Hence their ultimate performance characteristics must be determined by experiment. Ideally a contraction should produce a uniform velocity distribution at exit, should have everywhere along its walls monotonically increasing velocity and should be of reasonably short length. Goldstein (1945) has shown theoretically that, with a uniform velocity distribution at exit, the requirement of monotonically increasing velocity along the surface is incompatible with finite length of contraction. All contractions of finite length, designed to give uniform flow at exit, have therefore regions where the wall velocity gradient becomes negative, although the mean velocity gradient is always positive. Negative wall velocity gradients usually occur in entrance and exit regions. The more severe negative gradients occur in the exit region, where overspeeding of the wall velocity occurs, that is, it exceeds the mean flow velocity at exit. This overspeeding is associated with a pressure 'dip'. At the entrance to the contraction a corresponding pressure rise occurs at the wall.

Experience has shown that an appreciable increase in stream uniformity may be achieved with any sufficiently smooth shape (but local regions of adverse gradients still exist). Prandtl has suggested that this occurs because all streamlines receive approximately the same (large) increment of kinetic energy from the available pressure energy. In the past, when the solution of the problem of potential flow through a contraction of a given shape was almost impossible, the standard method of design concentrated on regularity of the boundary, and defined it algebraically in the hope that the velocity, too, would possess this regularity.

With the advent of high speed computers, the potential flow equations may now be solved to almost any degree of accuracy; this identifies regions in which the velocity gradient changes sign (and which in real flow could cause separation and/or cavitation). The contraction shape may then be adjusted to reduce the severity of the velocity pressure changes. For real fluids the shape of the contractions should be modified by a slight displacement of the wall outward to allow for the boundary layer thickness. However this requires a prior knowledge of the start of the boundary layer in the settling section and is applicable for one tunnel speed only. Among the many papers that deal with the design of contractions are: Batchelor et al. (1944), Cheers (1945), Stanitz (1952a, 1952b), Lin (1954), Whitehead et al. (1954), Gibbings et al. (1957) and Jordinson (1961). Lin proposed a two-dimensional design giving a rapid change of cross section, with no pressure discontinuity or adverse pressure gradient, but essentially uniform flow at the exit. He also suggested that satisfactory two-dimensional shapes have some extra margin of safety when used for tunnels of circular cross section.

5.6.4 Contraction shapes of existing water tunnels

Very little information was available about the basis of contraction designs for the water tunnels reviewed. The PSU 48-inch tunnel contraction design is made up of two transition curves defined by Equation 1 (Section 5.2.2) but no allowance has been made for boundary layer development. It is a typical example of the contractions designed on the basis of intuitive reasoning. The University of Adelaide 18-inch tunnel contraction used the design of Batchelor et al. (1944) with an allowance for boundary layer growth. The NEL 20-inch tunnel contraction was designed from data published by Rouse and Hassan (1949) on electrolytic tank investigations. The contraction for the CIT 14-inch tunnel was designed according to the method of Tsien (1943).

All the above tunnels, and even the University of Queensland 13.5-inch tunnel, which operates with a temporary contraction consisting of 3 straight segments, are known to perform satisfactorily. The departure from velocity uniformity, except for the wall boundary region, has been found to be in the region

of ± 1 per cent. It would therefore appear that for all usual water tunnel applications almost any recognised contraction design method could be selected.

Axisymmetrical contractions are known to perform better than non-circular contractions, in which unequal boundary layer growth and boundary layer interaction at sharp corners are likely causes of flow irregularities. A novel method for the design of the new two-dimensional contraction for the CIT 14-inch tunnel has been described by Kiceniuk (1964).

6. ANCILLARY SERVICES

Various ancillary services have been included depending on the intended use of the tunnels reviewed. Typical of the more complex type of modern tunnel is the ARL 30-inch tunnel in (Figure 11). It incorporates the following facilities:

(a) water filtration plant to provide clear water to fill and top up,

(b) resorber in the main loop to redissolve bubbles formed at the model,

(c) deaerator to reduce total air content,

(d) cooling system to extract the heat input from the pump (making use of a refrigerator plant operating in a by-pass loop),

(e) tunnel pressure control by means of a pressure loading cylinder,

(f) variable speed, variable pitch, impeller pump to control water velocity accurately, and

(g) drain-down tanks of sufficient capacity to contain water drained from the working section limb of the tunnel when access is required to change or adjust models.

These and other features employed in various tunnels are now discussed in more detail.

6.1 Temperature Control

Variation of the water temperature gives rise to variation in both the Reynolds number and the cavitation parameter, so control of water temperature has been considered necessary in some of the tunnels reviewed.

Most of the energy supplied to the pump is imparted to the water, producing an increase in temperature. The rate of temperature increase depends on the capacity of the water tunnel and, to a lesser extent, on the ambient temperature. The rise in temperature caused by the pump in the large 48-inch PSU tunnel is

3°F/hour at 60°F and this results in a variation of approximately 3 per cent/hour in the Reynolds number.

To maintain a constant loop temperature, many water tunnels incorporate a heat exchanger in a by-pass circuit. Examples are to be found at PSU (48-inch), CIT, ARL, DTMB (36-inch) and NEL.

It is interesting to note that at NEL, the heat exchanger is unnecessary even under the most arduous conditions. It has been found that adequate corrections are readily made to the water density and vapour pressure to compensate for the small temperature rise which occurs.

When flow tests at higher water temperatures are performed, a heater is sometimes incorporated in the tunnel or by-pass circuits to increase the rate of water heating beyond that achieved by the pump alone. In the two PSU tunnels, water temperatures may be varied between 40°F and 120°F providing a threefold increase in the Reynolds number. The larger of the tunnels, the 48-inch, is conventional in that a heat exchanger is placed in a by-pass circuit. The smaller (12-inch) is unusual in that the heat exchanger, used for both setting the required temperature level and subsequently regulating it, is an integral part of the main tunnel loop, and takes the full water flow.

A simple jacket cooler on the main loop is provided on the 20-inch MIT tunnel.

6.2 Velocity Measurement and Control

Working section water velocity is usually varied by adjusting the pump rotational speed or, where incorporated, the pump blade pitch; rotational speeds commonly can be set at any one of a large number of incremental steps. Examples are the AEW No. 2 tunnel, where the axial pump is driven by a 400 h.p. variable speed motor capable of being set and maintained in steps of 1 r.p.m. up to the maximum of 1000 r.p.m., and on the CIT 14-inch high speed tunnel where the speed of the 48-inch propeller pump is varied to give velocity settings in the working section from 0 to 99.9 ft/sec in steps of 0.1 ft/sec.

High accuracy speed control is achieved in the ARL 30-inch tunnel (± 0.1 per cent of full-scale reading down to 15 per cent of the top speed), in the AEW No. 1 tunnel (± 0.25 per cent of full scale reading), and in the NPL No. 1 tunnel by means of a Ward-Leonard variable speed electric motor system. At ARL this system is equipped with an electronic speed-holding servo. In the NPL No. 2 tunnel, where the speed of the 850 h p d.c. drive is adjusted by varying either the blade

pitch or the rate of rotation, an electronic control maintains the speed of the impeller motor to within ± 0.1 per cent of the set value. Automatic control of water speed using a sensing device in the working section is impracticable because the tunnel circuit responds only slowly to changes in the pump r.p.m. The same degree of control as at ARL is provided in the 36-inch tunnel at DTMB (± 0.1 per cent of the maximum speed).

Velocity in the working section is usually obtained by measuring the pressure drop across the contraction. For example, the Kings College (London) tunnel employs a water 'U' tube and the AEW No. 2 tunnel has a Boulton and Paul differential manometer with an accuracy of 0.01 inches of mercury.

A pitot tube fixed in the working section is sometimes used for velocity measurement. At the DTMB 36-inch it provides an alternative to pressure drop measurements across the contraction. The 18-inch tunnel at the University of Adelaide also uses a fixed pitot tube. This tunnel appears to be unique in that two centrifugal pumps in parallel are incorporated. One pump is used for working section velocities up to 20.5 ft/sec, and both are run to achieve the maximum velocity of 31 ft/sec. The fine speed is controlled by a manually operated motorised gate valve.

6.3 Water Treatment

6.3.1 Air content

When performing cavitation tests on propellers and models in water tunnels, control of the content of dissolved gases is essential. In model testing, free air bubbles may reduce the water clarity to an extent that flow visualisation and photography of tracers may become very difficult and sometimes impossible.

Air content control is achieved by two methods: resorption and vacuum deaeration. Air produced in the form of bubbles during cavitation or introduced as a tracer may be redissolved in a resorber. The gases formed at each pass of the water over the model or other feature are not removed from the loop water but merely redissolved before the water re-enters the working section. It is usual, therefore, to incorporate a vacuum deaerator in a by-pass system to reduce the air content of the tunnel water and make-up to a desired level. Silverleaf and Berry (1962) report that air content of the water influences propeller cavitation.

Resorbers commonly take the form of a deep well through which the main loop flow is made to pass several times (usually four) at low velocity before re-entering the working section. In the resorber, the water is subjected to comparatively high pressures for an appreciable time to give sufficient opportunity for the air to redissolve. This design originated on the CIT 14-inch tunnel where it is 11 ft 6 inches in diameter and its lowest point is 85 ft below the working section. Other 4-pass resorbers are used on the NEL 20-inch tunnel, the ARL 30-inch tunnel (both in England), the 36-inch tunnel at DTMB and the experimental tunnels at SAF.

Little information on the performance of resorbers is available but it is estimated that bubbles entering the resorber at DTMB with diameters of up to 0.015 inch will be re-absorbed into the solution. The resorber at NPL, having very long side limbs (not a 4-pass resorber) with the bottom limb 180 ft below the working section, will redissolve into solution all bubbles up to 0.012 in. for all working section velocities up to 45 ft/sec with a loop water air content of 30 p.p.m. by weight.

Vacuum deaeration involves subjecting the loop water to low pressures when both free air bubbles and some dissolved air is extracted. Commonly a portion of the by-pass flow is deaerated. To increase the surface area of the water exposed to the low pressure, the water may be either sprayed into a vessel connected to a vacuum pump (ARL 30-inch tunnel) or passed through a bed of raschig rings or similar packings (PSU 48-inch tunnel). The vacuum vessel at PSU is 6 ft in diameter and 25 ft high. Approximately 1 per cent of the total capacity of the loop is passed through the deaerator every minute.

Deaerator performance achieved may be gauged from the following examples. Water in the PSU 48-inch tunnel may be deaerated down to an air content of 3 p.p.m. (The solubility of air in water at 20°C and 760 m.m mercury total pressure is approximately 23 p.p.m.). At NEL, the air content may be reduced from saturation down to approximately 4 p.p.m. within a few hours.

The 19.7-inch square tunnel at Oceanics Inc., New York, has an unusual method of deaeration. When filling the loop, the level of water in the tunnel is maintained so that a free water/air surface exists along the upper horizontal limb. A vacuum pump is then started and the ambient pressure inside the tunnel reduced. The water in the tunnel is kept circulating slowly with a faster circulation undertaken every 15 minutes or so to agitate it. The water added to fill the tunnel is not previously degassed but since it is a small proportion of the total loop water, this is considered unimportant.

6.3.2 Particulate matter and algae growth

Most natural water supplies are discoloured and somewhat corrosive when in contact with mild steel. Surface treatments and/or corrosion inhibitors added to the water minimise this trouble, but algae and accidentally introduced impurities remain.

At NEL, an automatic system is installed to flocculate, filter and dose the water to inhibit corrosion. At Kings College, London, a high degree of clarity is obtained by continuously filtering the loop water and adding a corrosion inhibitor; this has removed the serious problem of having to change the water several times a year. At AEW and NPL a filtration plant is fitted in the by-pass or secondary circuit. In the AEW No. 2 tunnel, the continuously operating by-pass filter removes impurities down to four microns, giving a good clarity for photography.

At ARL, the filtration and water treatment plant is common to both the water tunnel and the rotating beam channel. Water clarity is measured by means of a hydrophotometer, developed at ARL, and a clarity of 90 per cent per metre has been obtained. The floc on the surface of the sand filters is formed by dosing with aluminium sulphate and further dosing with sodium carbonate maintains the pH value at 7.4. A standard automatic vacuum chlorinating unit serves to prevent organic growth.

The comments by Burt in the discussion of the paper by Lever et al. (1957) are of interest here. He reported that a change of 25 per cent in the critical Reynolds number from 3.2 to 2.4 x 10^5 occurred when the water clarity was allowed to decrease from 85 to 75 per cent per metre. Silverleaf, later on in the same discussion, disagreed with Burt's findings; however this indicates that high clarity water could be necessary for other reasons besides visualisation or photography.

6.3.3 Corrosion and surface treatment

To avoid having to drain and refill the tunnel too often, most laboratories resort to water treatment and/or surface treatment. The larger tunnels are, for economic reasons, usually fabricated in mild steel so that some type of surface coating on the walls is essential. Mumma (1941) reported that there was a considerable loss of testing time in changing water containing accumulated rust and dirt. At an opportune time, both the 12-inch and 27-inch tunnels at DTMB were surface-treated to keep them as free from corrosion as possible. The interior surface of the 12-inch tunnel was cadmium plated and coated with sprayed hard rubber. The same process was used on the 27-inch tunnel except that zinc was sprayed onto the steel as a substitute for the cadmium plating.

A high quality bitumen was thought to be the most economic yet effective coating for the ARL 30-inch tunnel. A phenolic resin was used in the high velocity sections. A coating consisting basically of a metallic zinc pigment in a metal silicate vehicle has given satisfactory service in the University of Queensland water tunnel for about four years.

At NEL, the water is dosed with 0.3 per cent sodium nitrite to inhibit corrosion. One per cent of the same additive is used in the Kings College tunnel. The effect of the dosing at NEL has been investigated and, although no significant influence on cavitation could be ascribed to its use, it does react with some common engineering materials, such as zinc, and a better alternative is being sought.

6.4 Pressure Control

In tunnels which are used primarily for research into cavitation phenomena, pressure in the working section must be controllable over a wide range, preferably down to the vapour pressure of the water itself. To achieve this, pneumatic and hydraulic methods are used.

Typical of the hydraulic controlled tunnels are the NPL No. 2 and the DTMB 36-inch. Water is forced into or drawn out of the tunnel by a positive displacement pump. The respective pressure ranges achieved are 0.1 to 6 atm absolute and 0.136 to 4.08 atm abs.

The majority of the tunnels having pressure control employ a pneumatic system, as at the NEL (0.2 to 4 atm abs.) the AEW No. 2 (0 to approximately 1.37 atm abs.), the ARL 30-inch (0.1 to 3 atm abs.) and the NPL No. 1 (1 to 2 atm abs.).

With this method the free surface area is usually arranged to be small, or else a free float is provided at the air/water interface to limit the air absorbed into the water.

The free float technique is employed on the 30-inch tunnel at ARL, and the required accuracy of pressure control is within ± 0.01 p.s.i. This is achieved by measuring the water pressure in the working section using a precision deadweight manometer. This manometer gives an electric signal proportional to the error between the desired pressure and the actual tunnel pressure; the signal is amplified to govern the throttle and leak valves which regulate the pressure above the float.

At the SAF 6-inch tunnel, working section pressure is controlled by raising or lowering the free surface of a water leg, flexibly connected to the tunnel boundary at the contraction or working section. Working section pressures can thus be varied between + 1 p.s.i. and water vapour pressure.

7. TUNNEL PERFORMANCE COMPARISON

The tunnel performance parameters used for comparing the merits of different installations are the power factor (or energy ratio) and the cavitation parameter.

7.1 Power Factor

This parameter is used to express the performance economy of the tunnel circuit. It is usually defined as the ratio of the kinetic energy of the working section jet to the pump head or total circuit losses. Sometimes the reciprocal of this ratio, called the effectiveness ratio, is used. Typical values of modern closed jet tunnel power factors are:

PSU	48-inch	-	0.14
NPL	44-inch	-	0.2
CIT	14-inch	-	0.2

However, power factors may be quite poor if the tunnel design is hydrodynamically inefficient. Thus, for example, the power factor for the Kings College tunnel is 1.2. This tunnel has been constructed from parts salvaged from a wartime German acoustic testing tank. The NPL No. 1 tunnel illustrates how improvements to existing circuits of some of the older tunnels can improve the power factor; after certain modifications the power factor improved from 0.72 to 0.31. Tunnels fitted with slotted wall working sections have somewhat higher power factors, the power factor for the NPL No. 1 tunnel rising to 0.38 for a slotted wall configuration. Resorbers, when provided, increase tunnel losses, and as already mentioned, open jet working sections also give more undesirable power factors. From model tunnel experiments at the SAF, Straub et al. (1955) quote the following power factors:

Working section	Without resorber	With resorbers
Closed jet	0.17	0.215
Open jet	0.245	0.29
Slotted wall	0.275	0.32

The following table gives a breakdown of tunnel circuit losses. It has been computed from the experiments performed in the SAF 6-inch tunnel (Ripken 1951).

	Fraction of total performance loss (%)
Working section	26.4
Diffusers	34.0
Turns	21.0
Straight sections	1.7
Honeycomb	2.9
Contraction	14.0

7.2 Cavitation Parameter

The suitability of a tunnel for cavitation studies is expressed by the cavitation parameter. This is a relative and arbitrary evaluation of the tendency of a boundary geometry to produce local regions of low dynamic pressure when subjected to a liquid stream, and is given by

$$\sigma = \frac{P - P_c}{\frac{1}{2} \rho V^2} ,$$

where, in general,

P = absolute pressure of the undisturbed water,

P_c = cavitation (or vapour) pressure of the water,

ρ = density of the water,

V = relative free stream velocity between the model and water.

The numerator of the cavitation parameter is the net static head which acts to collapse the cavity. The denominator is the dynamic head of the water, and since pressure variations which take place on the surface of the model result from changes in the velocity, the dynamic head is a measure of the pressure reductions that may cause a cavity to form or expand. Thus the cavitation parameter may also be interpreted as the ratio of the pressure available for collapsing the cavity to the pressure available for inducing formation and growth of the cavity.

The aim of a good water tunnel design is to prevent cavitation from occurring elsewhere in the tunnel before the cavitation parameter of the model reaches a value necessary to simulate prototype conditions. Depending on the velocity and the specific design, cavitation may first occur either in the entrance to the

contraction, the exit from the contraction, the working section, the entrance to the first diffuser, the first turn vanes, or the pump blades. At high speeds the entrance to the diffuser is the area most susceptible to cavitation, at low speeds, the top part of the contraction entrance. Since the presence of a model in the working section may affect the cavitation susceptibility, the tunnel cavitation parameter is usually determined for an empty working section. In most tunnels the pressure and velocity in the working section are changing and therefore for the purposes of comparison it is usual to evaluate the parameter on the tunnel axis at the working section upstream end conditions, even though cavitation is likely to occur elsewhere (usually at entrance to the first diffuser). An indication of the variation of the cavitation parameter along the working section and its dependence on the tunnel velocity may be obtained from the experiments performed in the 3 ft long working section of the SAF 6-inch experimental tunnel (Ripken 1951).

Velocity	σ at w.s. upstream conditions	σ at w.s. downstream conditions
18 ft/sec	0.636	0.571
84.5 ft/sec	0.151	0.097

At both velocities cavitation first occurred at the diffuser transition.

Other experiments performed at the SAF (Straub et al. 1955) show how the cavitation parameter depends on the type of working section:

cylindrical closed jet	$\sigma = 0.07$
diverging closed jet	$\sigma = 0.023$
open jet	$\sigma = 0.4$
slotted wall	$\sigma = 0.6$ to 0.9

In each case the parameters were evaluated at the working section upstream conditions, the pressures being determined at the wall. For the two closed jet working sections cavitation occurred at the top of the working section-diffuser transition; for the open jet it occurred in the high shear region at the boundaries of the diffusing jet; and for the slotted wall section it occurred in the wakes of the guide bars.

Typical minimum cavitation parameters for some of the other closed jet tunnels are:

PSU 48-inch	0.3
AEW No. 2	0.5
NPL No. 2	0.1
Oceanics	0.1
Kings College	0.5

The SAF 10-inch free jet tunnel has a cavitation parameter of 0.01.

The survey has indicated that for most tunnels the contractions, guide vanes and pumps seldom limit the cavitation studies. One exception is the PSU 48-inch tunnel where pump cavitation sometimes occurs at working section cavitation parameters between 0.5 and 0.8 and interferes with acoustic tests in the working section.

Accurate comparison of tunnel performance in terms of the cavitation parameter is limited by factors which are not directly included in the cavitation parameter, such as the air content, cavitation hysteresis and the accuracy of the determination of the incipience and 'dessinence' (Dr. Holl PSU) of cavitation. Also the wall pressures may not be reliable guides for the evaluation of the cavitation parameter. Studies in the PSU 48-inch tunnel have indicated a true minimum $\sigma = 0.3$, while the value deduced from wall pressure measurement yields a value of $\sigma = 0.05$.

8. CONCLUSIONS

For guidance in the design of the Lucas Heights tunnel, the findings of the survey may be summarised as follows:

(a) The tunnel should be of the closed loop, closed jet design, as this is the most suitable for general purpose research.

(b) Provision should be made for alternative circular and two-dimensional working sections. Two-dimensional sections are required because considerable work on flow visualisation is anticipated.

(c) For general purposes working sections of constant cross sectional area are preferable. However, the tunnel design should allow for the incorporation of diverging and slotted wall working sections.

(d) Although high pressure recovery is desirable, the main aim of the diffuser design should be to ensure separation-free performance.

In the absence of model tests it appears that the design criteria given by McDonald and Fox (1965) can be used as a guide in the selection of diffuser geometry. However, since the presence of a model in the working section may adversely affect the diffuser performance, a shorter length and/or smaller angle should be selected to allow a margin of safety.

(e) Mitred vane turns are preferable to long radius turns, since they have lower losses, provide better velocity distribution downstream and require less installation space.

(f) The settling section should be as long as practicable to allow the decay of the smaller scale turbulent eddies and provision should be made for the installation of a honeycomb, mainly to improve velocity distribution.

(g) A contraction ratio of 9 to 1 appears adequate for achieving velocity uniformity of ± 1 per cent in the central core.

(h) Water temperature should be controllable; without cooling, the relatively small amount of water would be rather quickly heated by the pump energy and constant temperature work would not be possible. On the other hand, heaters are faster than pump energy alone for achieving the elevated water temperatures required to attain high Reynolds numbers.

(i) Because it is intended to run the tunnel at elevated temperatures, a deaerator should be incorporated to extract the released gases.

(j) Surface treatment is very important to prevent corrosion of all internal ferrous surfaces of the tunnel, particularly to avoid reduction of water transparency.

(k) Provision should be made for filtering of the mains water before filling the tunnel. This is especially important for flow visualisation studies. Since algae on viewing windows and in the water will greatly reduce visibility, its growth should be inhibited by an additive prepared commercially for this purpose.

9. ACKNOWLEDGEMENTS

The authors are grateful to Mr. G. W. K. Ford for helpful suggestions in the preparation of this literature survey.

Professor R. A. A. Bryant of the University of New South Wales, made available his personal (unpublished) 1957 survey of work on water tunnels, cavitation and allied topics studied in the United States since 1946.

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APPENDIX 1

NOTATION

d	diameter
g	gravitational acceleration
r	radius of pipe
σ_1	radius at diffuser inlet
q'	total r.m.s. turbulent velocity
u'	longitudinal r.m.s. turbulent velocity
v', w'	lateral r.m.s. turbulent velocities
x	length
D	diameter
L	length
P	absolute pressure
P_c	cavitation (vapour) pressure
P_o	pressure at working section upstream end
R	turn radius
V	velocity
$\bar{V}$	mean velocity
σ	$\frac{P - P_c}{\frac{1}{2}\rho V^2}$ cavitation parameter
θ	total angle (diffuser or transition)
ρ	fluid density

APPENDIX 2

ABBREVIATIONS OF ESTABLISHMENT NAMES

AEW	Admiralty Experiment Works
ARL	Admiralty Research Laboratory
CIT	California Institute of Technology
MIT	Massachusetts Institute of Technology
NEL	National Engineering Laboratory
NPL	National Physical Laboratory
NSMB	Netherlands Ship Model Basin
ONERA	Office National d'Etude et de Recherches Aeronautiques
PSU	Pennsylvania State University (Ordnance Research Laboratory)
SAF	University of Minnesota (St. Anthony Falls Hydraulic Laboratory)

APPENDIX 3

DETAILS OF TUNNELS REVIEWED

Where possible all relevant information on each tunnel is noted. Any omission of details, or non-inclusion of certain features which may nevertheless exist, results from unavailability of information.

AUSTRALIA

University of Adelaide, Adelaide, S. A.

Research Water Tunnel

This tunnel was originally constructed as an open circuit tunnel in 1955. In 1963 it was converted to the present closed circuit configuration.

Working section	:	closed jet, 18 in. dia, 8 ft long.
Contraction	:	16 to 1.
Maximum velocity	:	20.5 ft/sec with one pump in operation, 31.0 ft/sec with two pumps.
Pressure	:	controlled by varying the air pressure in the stilling chamber air space.
Pumps	:	two double inlet centrifugal pumps.
Drive	:	two 125 hp a.c. motors, tunnel speed variation by motorised gate valves fitted downstream from the pump.
Uses	:	propeller vibration research.

University of Queensland, School of Civil Engineering, St. Lucia. Qld.

13.5 inch Tunnel

Working section	:	closed jet, 13.5 in. dia, 5 ft 6 in. long.
Contraction	:	9 to 1.
Maximum velocity	:	22 ft/sec.
Pump	:	turbine pump 16 in. dia.
Drive	:	30 hp a.c. motor, driving pump through hydraulic pump-motor combination.
Uses	:	study of flow around submerged bodies.

Continued...

APPENDIX 3 (Continued)

University of Sydney, School of Civil Engineering, Sydney, N.S.W.

Water/Wind Tunnel

In this tunnel, which was placed in service in 1965, both water and air may be used as the working fluid.

Working section	:	rectangular closed jet 36 x 24 in.
Contraction	:	very small at present, but can be increased to about 6:1 when higher quality flow is required.
Pump	:	48 in. dia. axial flow.
Drive	:	150 hp a.c. motor through a hydraulic pump-motor combination and gear-box.
Uses	:	to study the dynamic behaviour of structures in natural winds.

BRAZIL

At least one tunnel to the design of Kempf and Remmers of Hamburg, Germany.

CANADA

National Research Laboratory

A 10 x 13 in. water tunnel.

FRANCE

Although France has several water tunnels very little information was available.

Paris Cavitation Tunnel

Working section	:	closed jet about 36 in. dia.
Maximum velocity	:	48 ft/sec.

ONERA Water Tunnel at Chatillon

This is a large open circuit water tunnel of the blowdown type but no details were available.

Continued...

APPENDIX 3 (Continued)

GREAT BRITAIN

Admiralty Experiment Works, Haslar

No. 1 Tunnel

Construction of this tunnel commenced in 1937 and was completed 4 years later.

Working section	:	closed jet, 2 ft square with rounded corners.
Pump	:	axial flow.
Drive	:	150 hp d.c. motor, speed control governed within ± $\frac{1}{4}$ per cent by Ward-Leonard system.
Ancillary systems	:	deaerator now in common with No. 2 tunnel.

No. 2 Tunnel

This is the largest tunnel in the world. It was originally built by Blohm and Voss of Hamburg for the H.S.V.A. This tunnel was completed in 1943 and damaged in a bombing raid later in the same year. After the war it was shipped to England; the re-erection, with some improvements, was completed at Haslar in January 1958. This tunnel is characterised by a bifurcated diffuser and large radius bends.

Working section	:	closed jet 7.8 ft x 3.9 ft with rounded corners 17 ft $6\frac{1}{2}$ in. long.
Contraction	:	3.029 to 1.
Maximum velocity	:	26.3 ft/sec.
Cavitation parameter	:	0.5.
Pressure	:	variable pneumatically between zero and 25 lb/in^2 abs.
Pump	:	cast iron impeller 6 ft 9 in. dia.
Drive	:	variable speed 400 hp d.c. motor driving the impeller through flexible couplings and 4:1 reduction gear box. Speed control in steps of 1 r.p.m. to the maximum of 1,000 r.p.m.
Ancillary systems	:	600,000 lb/h deaerator, continuously operating by-pass filters.
Overall size	:	63 ft long x 40 ft high.
Uses	:	propeller tests.

Continued...

APPENDIX 3 (Continued)

Admiralty Research Laboratory, Teddington

30-inch Tunnel (completed in 1956)

Working section	:	slotted wall, 30 in.dia, 15 ft long.
Maximum velocity	:	60 ft/sec.
Contraction	:	9 to 1.
Power factor	:	0.41.
Pressure	:	variable pneumatically between 0.1 and 3 atm. abs.
Pump	:	variable pitch axial flow pump.
Drive	:	850 hp d.c. motor, speed control by Ward-Leonard system to an accuracy of 0.1 per cent of the maximum speed.
Ancillary systems	:	1,000 gal/min deaerator, 1,000 gal/min refrigeration plant, 4-pass resorber of 19,000 ft^3 capacity, water filtration plant (common with the rotating beam channel).
Overall size	:	upper limb 71 ft long, overall height including resorber 75 ft.
Uses	:	testing of underwater weapons.

12-inch Tunnel

This was originally built as a prototype for the 30-inch tunnel, and is a scaled-down version of it in all important respects, except that it has no resorber.

Armament Research and Development Establishment, Fort Halstead, Kent

ARDE Tunnel

Working section	:	free jet, 9 x 7 in, fixed vertical side walls and free top and bottom surfaces.
Maximum velocity	:	40 ft/sec.
Cavitation parameter	:	0.01.
Pressure	:	variable.
Uses	:	cavity flow research.

Continued...

APPENDIX 3 (Continued)

Kings College, Naval Architecture Department, London

Cavitation Tunnel

This tunnel has been constructed from parts of a horizontal closed circuit flow tank built in Germany for acoustic tests on underwater weapons and scheduled for destruction in 1945. The parts were taken to England, rebuilt and placed in operation in December 1949.

Working section	:	40 in x 32in x 12 ft long with rounded corners.
Contraction	:	5 to 1.
Maximum velocity	:	24 ft/sec in the forward direction and 17 ft/sec in the reverse direction.
Power factor	:	1.25.
Cavitation parameter	:	0.5.
Pressure	:	variable pneumatically
Pump	:	axial flow.
Drive	:	300 hp motor.
Ancillary systems	:	continuously operating filters.
Uses	:	propeller testing.

National Engineering Laboratory, Glasgow, Scotland

Water Turbine Cavitation Tunnel

Working section	:	suitable for testing Francis and Kaplan turbines having a maximum runner diameter of 20 in.
Contraction	:	9 to 1.
Pump	:	350 hp speed controlled centrifugal pump (maximum discharge 30 ft^3/sec), alternatively 210 hp axial flow pump of variable pitch (maximum discharge 60 ft^3/sec).
Pressure	:	variable pneumatically between 0.2 and 4 atm.
Ancillary systems	:	deaerator, heat exchanger and vertical resorber.
Uses	:	water turbine testing.

Continued...

APPENDIX 3 (Continued)

National Physical Laboratory, Ship Division, Feltham

No. 1 Tunnel (Lithgow)

This tunnel was originally designed and constructed in 1932 at Teddington; in order to improve its performance it was extensively modified in 1954-57. In 1962 it was transferred to Feltham.

Working section	:	slotted wall, 18 in. square with rounded corners, 40 in. long; it can be converted to closed jet configuration by replacing the slotted wall boundary bars with close fitting plastic sheets.
Contraction	:	6 to 1.
Maximum velocity	:	closed jet - 41 ft/sec, slotted wall - 38 ft/sec.
Power factor	:	0.31 for closed jet, 0.38 for slotted wall.
Pressure	:	variable pneumatically between zero and 1 atm. gauge.
Pump	:	fixed-pitch axial pump.
Drive	:	80 hp d.c. motor, fitted with Ward-Leonard control system.
Ancillary systems	:	deaeration plant common with No. 2 tunnel. No provision for heating or cooling of tunnel water.
Overall size	:	24 ft long x 17 ft high between centre lines.
Uses	:	propeller testing and forces on submerged bodies.

No. 2 Tunnel

Construction of this tunnel began in 1956 and it was first used in 1959.

Working section	:	closed jet, 44 in. dia, 88 in. long.
Maximum velocity	:	55 ft/sec.
Contraction	:	7.4 to 1.
Power factor	:	0.20.
Cavitation parameter	:	0.1.
Pressure	:	variable between 0.1 and 6 atm abs. by using water as the pressurising medium.
Pump	:	variable pitch axial flow pump.
Drive	:	850 hp d.c. motor fitted with electronic speed control which maintains the speed constant within ± 0.1 per cent of the set value.

APPENDIX 3 (Continued)

Ancillary systems	:	deaerator, heat exchanger and about 150 ft deep resorber.
Overall size	:	87 ft 3 in. long x 180 ft deep between centre lines including the resorber.
Uses	:	propeller studies, cavitation studies on hydrofoils and other fixed bodies either alone or simultaneously with propellers.

National Physical Laboratory, Teddington

A small water tunnel having a closed rectangular working section with the flow vertically upwards.

Vospers Limited, Portsmouth

Cavitation tunnel with a 20-inch square working section.

Uses:	:	research on high speed propellers, rudders and stabilising fins.

JAPAN

Tōhoku University, Sendai

Cavitation Tunnel

Working section	:	closed jet, 26 cm high x 10 cm wide, movable walls.
Contraction	:	27 to 1.
Maximum velocity	:	11.7 m/sec.
Pump	:	centrifugal pump.
Drive	:	variable speed shunt-commutator motor.
Overall size	:	7.3 m long x 5 m high between centre lines.
Uses	:	cavitation tests on hydrofoils in cascades.

Continued...

APPENDIX 3 (Continued)

THE NETHERLANDS

Netherlands Ship Model Basin, Wageningen

NSMB Cavitation Tunnel No. 1

This tunnel is of the H.S.V.A. design and has a bifurcated diffuser.

Working section	:	closed jet 36 in. square, alternatively two-dimensional section 4 x 1 ft.
Pump	:	axial flow.
Overall size	:	35 ft long and 23 ft high between centre lines.

Delft University of Technology, Shipbuilding Laboratory

Delft Cavitation Tunnel

This tunnel has facilities to produce a non-homogeneous velocity field by means of a velocity regulator in the settling section. The regulator consists of 146 individually adjustable check valves.

Working section	:	closed jet 30 cm square.
Maximum velocity	:	9m/sec.
Cavitation parameter	:	0.25.
Pump	:	axial flow.
Drive	:	20 hp motor, speed control adjusted by means of a hydraulic variator.
Overall size	:	5.03 m long x 1.70 m high between centre lines.
Uses	:	propeller and cavitation studies.

NORWAY

Trondheim Ship Model Basin

This tunnel has been constructed to gain experience for a larger tunnel.

Working section	:	closed jet, 8 in. dia, provision for two alternate slotted wall working sections.
Maximum velocity	:	32 ft/sec.

Continued...

APPENDIX 3 (Continued)

SPAIN

Cavitation Tunnel at El Pardo

Erected 1951; same design as NSMB No. 1 Tunnel.

Working section	:	36 in. square.
Motor	:	300 hp.

SWEDEN

Swedish State Shipbuilding Tank, Goteborg

A variable pressure tunnel to the design of Kempf and Remmers of Hamburg, Germany.

Karlstads Mekaniska Werkstad

The Kristinehamn Tunnel

SWITZERLAND

Escher Wyss, Zurich

Constructed in 1955, a variable pressure testing tunnel for measuring characteristics and observing cavitation phenomena in water turbines and pumps. Two motors 400 hp each, maximum head 330 ft.

U.S.A

David Taylor Model Basin, Hydromechanics Laboratory, Washington D.C.

12-inch Tunnel

This tunnel, which was completed in 1929, was originally located in the old U.S. Experimental Model Basin; it was moved to DTMB in 1940.

Continued...

APPENDIX 3 (Continued)

Working section	:	open jet, 12 in. dia.
Contraction	:	6.25 to 1.
Maximum velocity	:	24 ft/sec.
Pressure	:	variable pneumatically between 1 lb/in^2 abs. and atmospheric.
Pump	:	axial flow.
Drive	:	15 hp motor.
Ancillary systems	:	vacuum pumps for water deaeration and water filters.
Overall size	:	15 ft 6 in. long x 13 ft 6 in. high between centre lines.
Uses	:	propeller testing.

24-inch Tunnel

Placed in operation in 1941.

Working section	:	open jet 24 in. dia.
Contraction	:	9 to 1.
Maximum velocity	:	59 ft/sec.
Pressure	:	variable pneumatically between 2 lb/in^2 and 30 lb/in^2 abs.
Ancillary systems	:	vacuum pumps for water deaeration and water filters.
Pump	:	axial flow.
Drive	:	400 hp.
Overall size	:	41 ft 4$\frac{3}{8}$ in. long x 19 ft $\frac{1}{8}$ in. between centre lines.
Uses	:	propeller and hydrofoil testing.

36-inch Tunnel

Tunnel was placed in operation in 1962.

Working section	:	interchangeable open and closed jet sections, 36 in. dia.
Contraction	:	9 to 1.

Continued...

APPENDIX 3 (Continued)

Maximum velocity	:	84.5 ft/sec.
Pressure	:	variable between 2 p.s.i.a. and 60 p.s.i.a. by means of a constant flow, positive displacement pump system.
Pump	:	78 in. dia. adjustable four blade propeller pump.
Drive	:	3,500 hp synchronous motor driving 2,887 hp water cooled eddy current coupling. Electronic speed regulator provides a speed control accuracy ± 0.1 per cent of maximum speed.
Ancillary systems	:	2,000 gal/min water filtering system, 2,000 gal/min vacuum type deaerator, 95 ton refrigeration system, 4-pass 70 ft deep resorber.
Overall size	:	68 ft 2-inch long x approx. 30 ft high between centre lines (excluding resorber).
Tunnel shell	:	stainless and stainless-clad steel.
Uses	:	testing of propellers and submerged bodies such as hydrofoils, ship appendages, sonar domes etc.

The Pennsylvania State University, Ordnance Research Laboratory, University Park, Pa.

48-inch Tunnel

The largest tunnel in the U.S.A.; operational since 1949.

Working section	:	closed jet, 48 in. dia.
Contraction	:	9 to 1.
Maximum velocity	:	80 ft/sec.
Power factor	:	not given.
Cavitation parameter	:	0.3.
Pressure	:	variable pneumatically between 3 and 60 lb/in^2 abs.
Temperature	:	variable between 40 and 120 deg F.
Pump	:	variable pitch axial flow.
Drive	:	2,000 hp variable speed induction motor.
Ancillary services	:	deaerator, heaters, refrigeration plant and water filters.

Continued...

APPENDIX 3 (Continued)

Overall size	:	97 ft 2 in. long x 31 ft high.
Uses	:	torpedo testing, basic and applied cavitation research.

12-inch Tunnel

Working section	:	closed jet, 12 in. dia ; alternate section 20 x 4½ in.
Pressure	:	variable pneumatically.
Drive	:	150 hp induction motor through a fluid coupling.
Ancillary systems	:	vacuum system for water deaeration, heat exchanger in the main circuit.
	:	general cavitation studies.

The Ultra-high-speed Cavitation Tunnel

Working section	:	closed jet, 1½ in.dia.
Velocity	:	5 discrete velocities: 45, 76, 132, 234 and 332 ft/sec.
Pressure	:	variable up to 1,200 lb in^2 abs.
Pump	:	centrifugal.
Drive	:	150 hp induction motor through a 5-speed gear box.
Ancillary systems	:	filters and heat exchanger; deaerator common with other tunnels.
Overall size	:	87.75 in. long x 25.6 in. high between centre lines.
Uses	:	study of cavitation fundamentals.

California Institute of Technology, Hydrodynamics Laboratory, Pasadena, California

14-inch High-speed Tunnel

The 14-inch tunnel, which was first put into operation early in 1942, was the first to incorporate a resorber.

Working section	:	closed jet 14 in.dia, 6 ft long; an alternative hydrofoil testing section 14 x 3 in.

Continued...

APPENDIX 3 (Continued)

Maximum velocity	:	100 ft/sec.
Contraction	:	18 to 1.
Power factor	:	0.2
Pressure	:	variable pneumatically between vapour pressure and 100 lb/in^2.
Pump	:	48 inch dia. propeller pump.
Drive	:	350 hp d.c. motor, speed variation in 1,000 steps of 0.1 ft/sec.
Ancillary services	:	58 ft deep, 4-pass resorber of 45,000 gal. capacity, refrigeration system, 1,100 gal. storage tank, air content control system.
Uses	:	cavitation research.

Unsteady Flow Cavitation Tunnel

Blow-down type, operated by compressed air.

Working section	:	2¾ in.square, 14 in.long.
Contraction	:	6.5 to 1.
Maximum velocity	:	100 ft/sec.
Uses	:	cavitation research.

12-inch Square Low Speed Tunnel

Constructed in 1951.

Working section	:	closed-jet 12-inch square.
Maximum velocity	:	15 ft/sec.
Uses	:	turbulence diffusion studies.

Free Surface Water Tunnel

Constructed in 1946.

Working section	:	20 in. wide and 30 in. deep, the normal depth of flow is 21 in.
Maximum velocity	:	30 ft/sec.
Pressure	:	air pressure above the free surface variable from $^1/_{15}$ atm. to atmospheric.
Pump	:	42 in. dia. propeller pump.
Motor	:	75 hp d.c. motor.
Uses	:	to determine hydrodynamic characteristics of bodies when near a free surface.

Continued...

University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis

10-inch Free Jet Tunnel

This is the only large open circuit tunnel. It draws water from a river supply and returns it to the river at a lower level (height difference 44 ft 10 in.).

Working section	:	free jet 10 in. dia, alternatively 7 x 5 in. two-dimensional.
Maximum velocity	:	50 ft/sec.
Cavitation parameter	:	0.01.
Pressure	:	variable between vapour and atmospheric pressure.
Uses	:	cavitation studies.

6-inch Experimental Tunnel

This tunnel has had three different arrangements and has been used as a model for the following three water tunnel design studies:

(i) The first arrangement was a 1/10th scale model of a 60-inch closed jet tunnel; the plans to build the prototype at the DTMB did not materialise.

(ii) The second arrangement was a model of a 24-inch open and closed jet tunnel.

(iii) The third arrangement simulated a 36-inch tunnel equipped with a resorber. It has alternative cylindrical and diverging closed jet working sections, an open jet working section and a slotted wall working section.

Massachusetts Institute of Technology, Cambridge, Mass.

20-inch Tunnel

Constructed in 1938.

Working section	:	open jet 20 in. dia.
Contraction	:	9 to 1.
Maximum velocity	:	34 ft/sec.
Pump	:	axial flow

Continued...

Drive	:	75 hp motor.
Ancillary systems	:	external jacket heat exchanger.
Overall size	:	21 ft long x 19 ft high between centre lines.
Uses	:	propeller testing.

Unsteady Flow Tunnel

Blow-down type, using compressed air.

Working section	:	closed jet 1 in. dia.
Maximum velocity	:	100 ft/sec.
Acceleration	:	Up to 5 ft/sec^2 for 20 sec.
Pressure	:	variable from 4 lb/in^2 abs. upwards.
Uses	:	friction and cavitation studies under transient conditions.

Oceanics, Inc., Water Tunnel Division, Plainview, New York

The Oceanics tunnel was placed in operation in June 1963. It is of a typical European design, having been designed and erected by Kempf and Remmers of Hamburg, Germany.

Working section	:	closed jet, 19.7 in. square with rounded corners, 7 ft long.
Contraction	:	6 to 1.
Maximum velocity	:	40 ft/sec.
Cavitation parameter	:	0.1
Pressure	:	variable pneumatically between 0.05 and 2 atm abs.
Ancillary systems	:	vacuum pump for water deaeration.
Overall size	:	33 ft long x 30 ft high.
Uses	:	general cavitation studies and simulation of aircraft landing conditions on aircraft carriers heaving, rolling and pitching in heavy seas.

Continued...

APPENDIX 3 (Continued)

Hydronautics, Inc., Laurel, Maryland

Free Surface, High Speed Channel

Operational since 1962.

Working section	:	2 ft wide x 12 ft long, maximum water depth 2 ft.
Maximum velocity	:	65 ft/sec at 0.5 ft depth and 33 ft/sec at 2 ft depth.
Cavitation parameter	:	0.25 at 20 in. depth and 0.06 at 12 in. depth.
Pressure	:	variable down to 3 ft water abs.
Drive	:	1,000 hp motor.
Ancillary systems	:	heat exchanger and filter.
Uses	:	to study high speed hydrofoil craft, super-cavitating propellers and high speed underwater missiles.

State University of Iowa

This establishment has had several water tunnels. The types of tunnels in use at present are not known.

Newport News Shipbuilding and Dry Dock Company, Newport News, Va.

Circulating Water Channel

Working section	:	free surface, 7 x 24 in.
Maximum velocity	:	21 ft/sec.
Pressure	:	variable above the free surface.
Motor	:	60 hp.
Uses	:	skin friction and similar studies.

Naval Ordnance Test Station, China Lake, California

A free surface water tunnel.

Continued...

APPENDIX 3 (Continued)

Lewis Research Center, Cleveland, Ohio

Lewis Water Tunnel

This is a closed loop test facility for studying cavitation in water pumps.

Maximum flow	:	10,000 gal/min.
Pressure	:	variable pneumatically between 5 and 200 ft water.
Ancillary systems	:	deaerator, heat exchanger and filters.

YUGOSLAVIA

Ship Hydrodynamics Institute, Zagreb

Tunnel with a working section about 40 in. square, to the design of Kempf and Remmers of Hamburg, Germany.

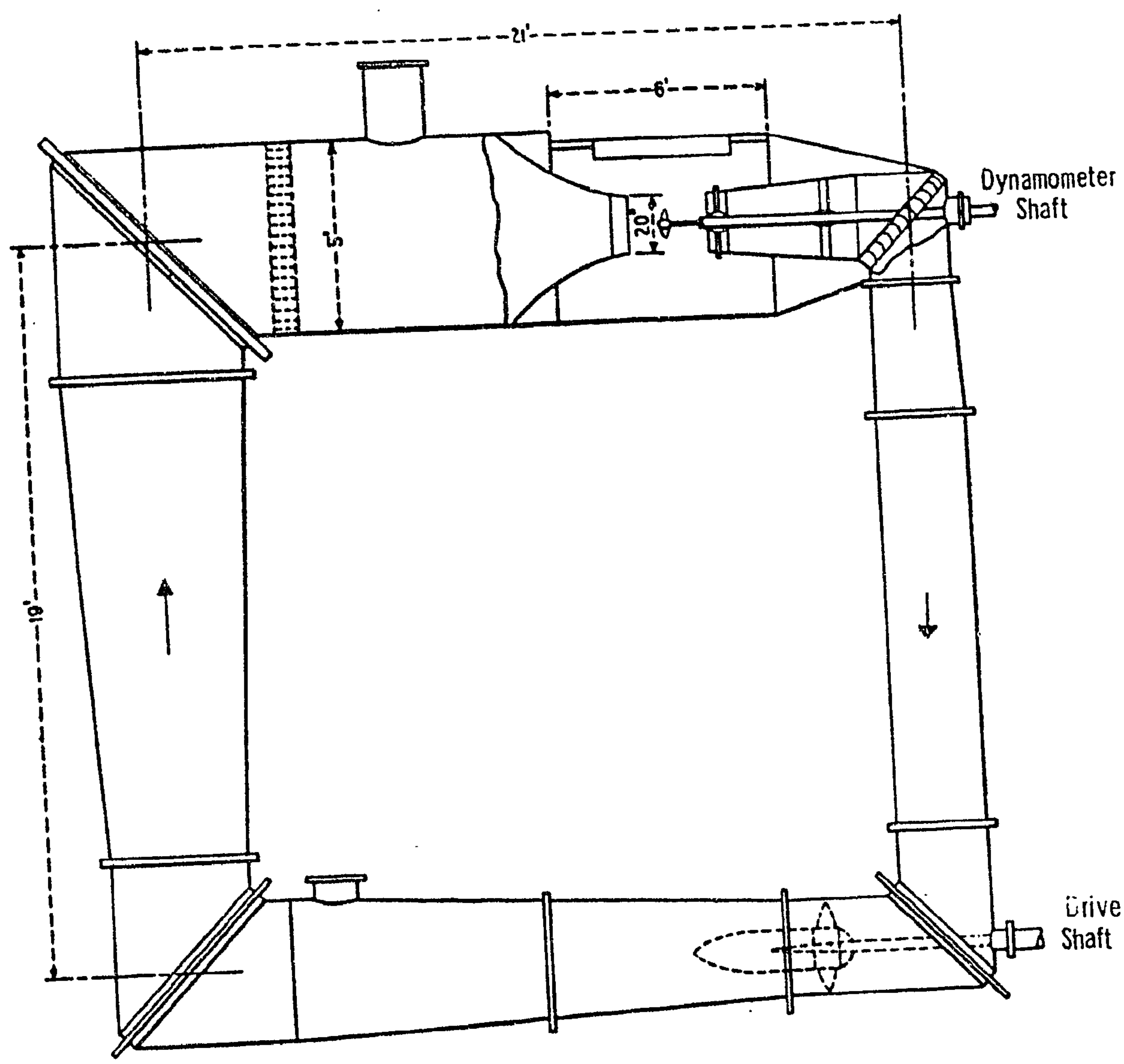

FIGURE 1. CIRCUIT ARRANGEMENT OF MIT 20-INCH TUNNEL

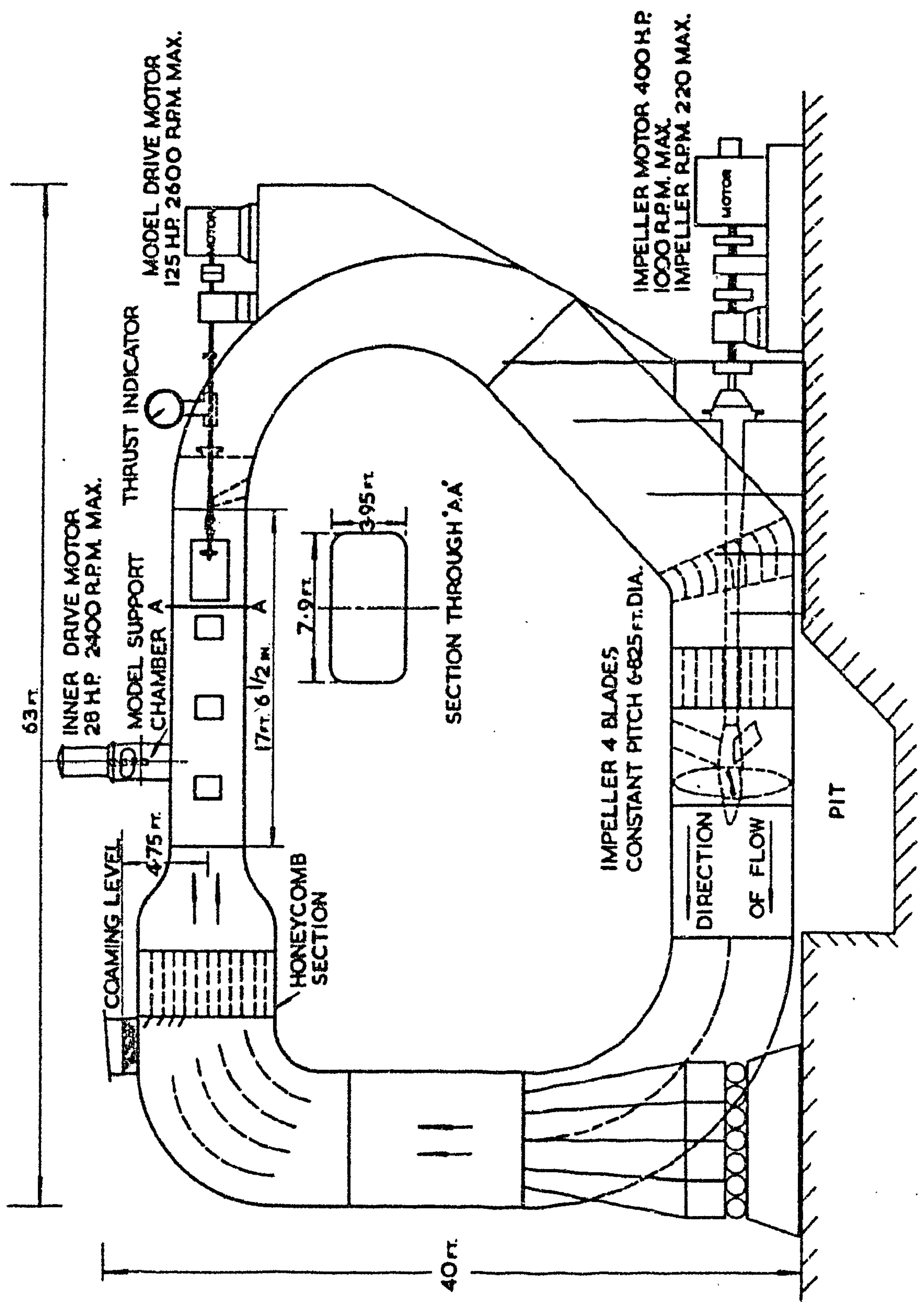

FIGURE 2. CIRCUIT ARRANGEMENT OF AEW NO. 2 TUNNEL

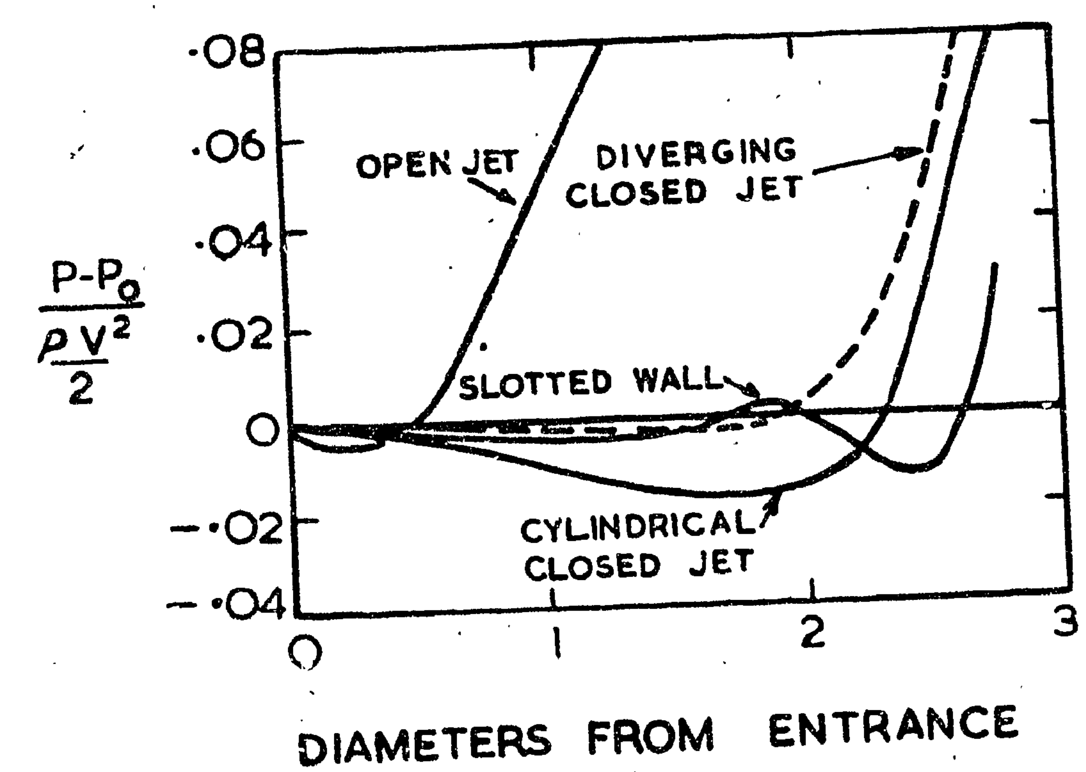

FIGURE 3. WORKING SECTION LONGITUDINAL PRESSURE DISTRIBUTIONS (Straub et al. 1955)

P1223

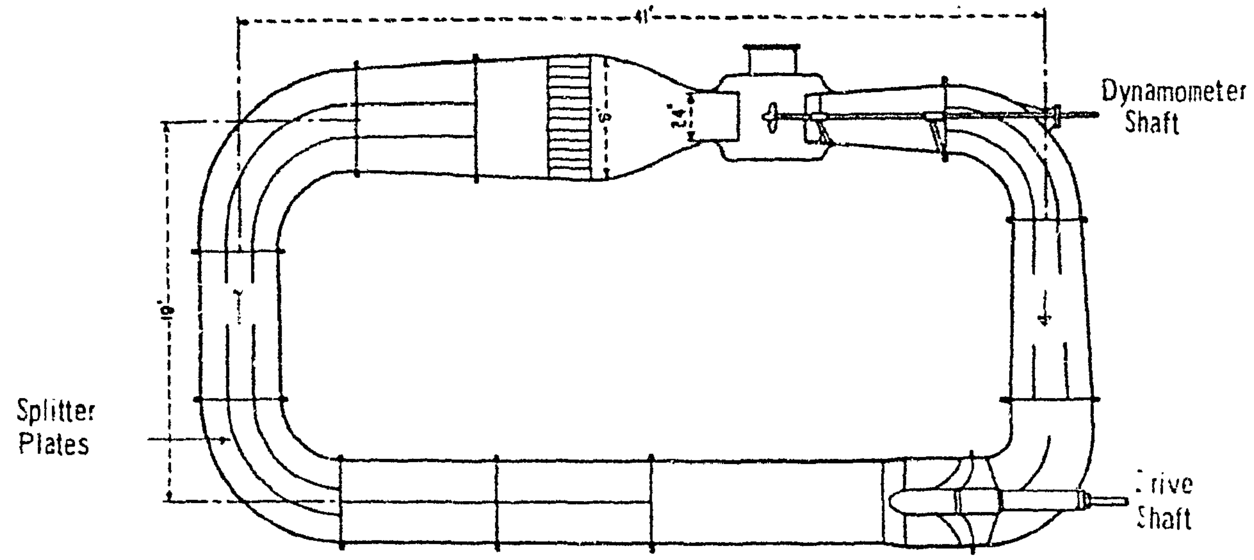

FIGURE 4. CIRCUIT ARRANGEMENT OF DTMB 24-INCH TUNNEL

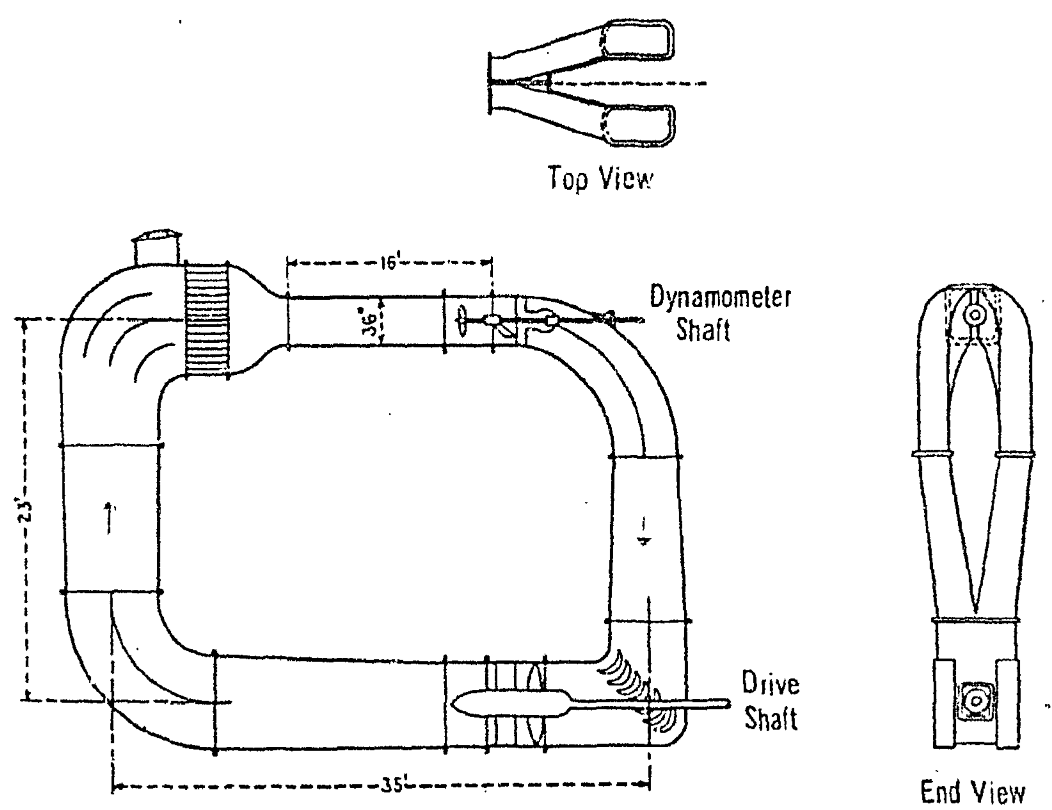

FIGURE 5. CIRCUIT ARRANGEMENT OF NSMB NO.1 TUNNEL

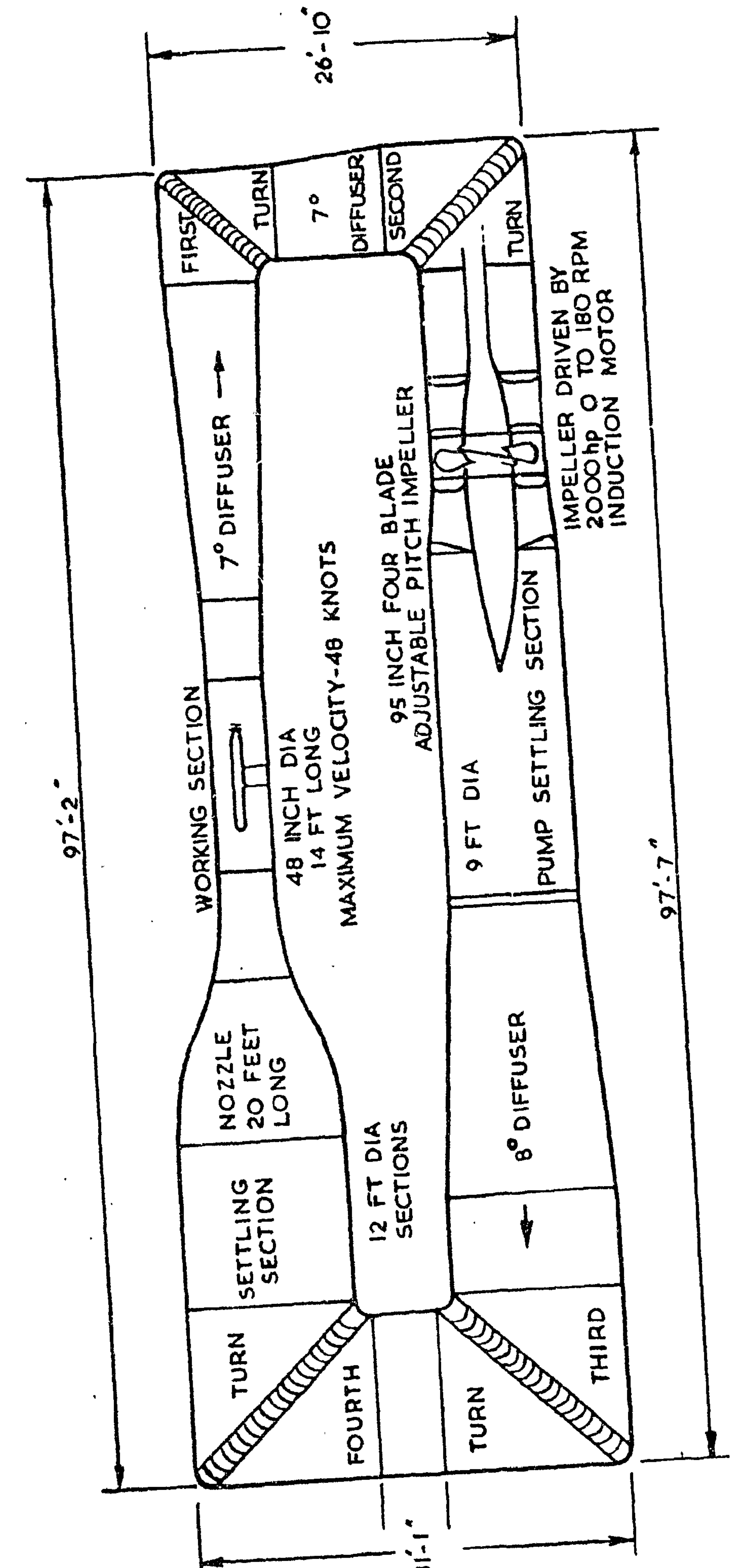

FIGURE 6. CIRCUIT ARRANGEMENT OF PSU 48-INCH TUNNEL

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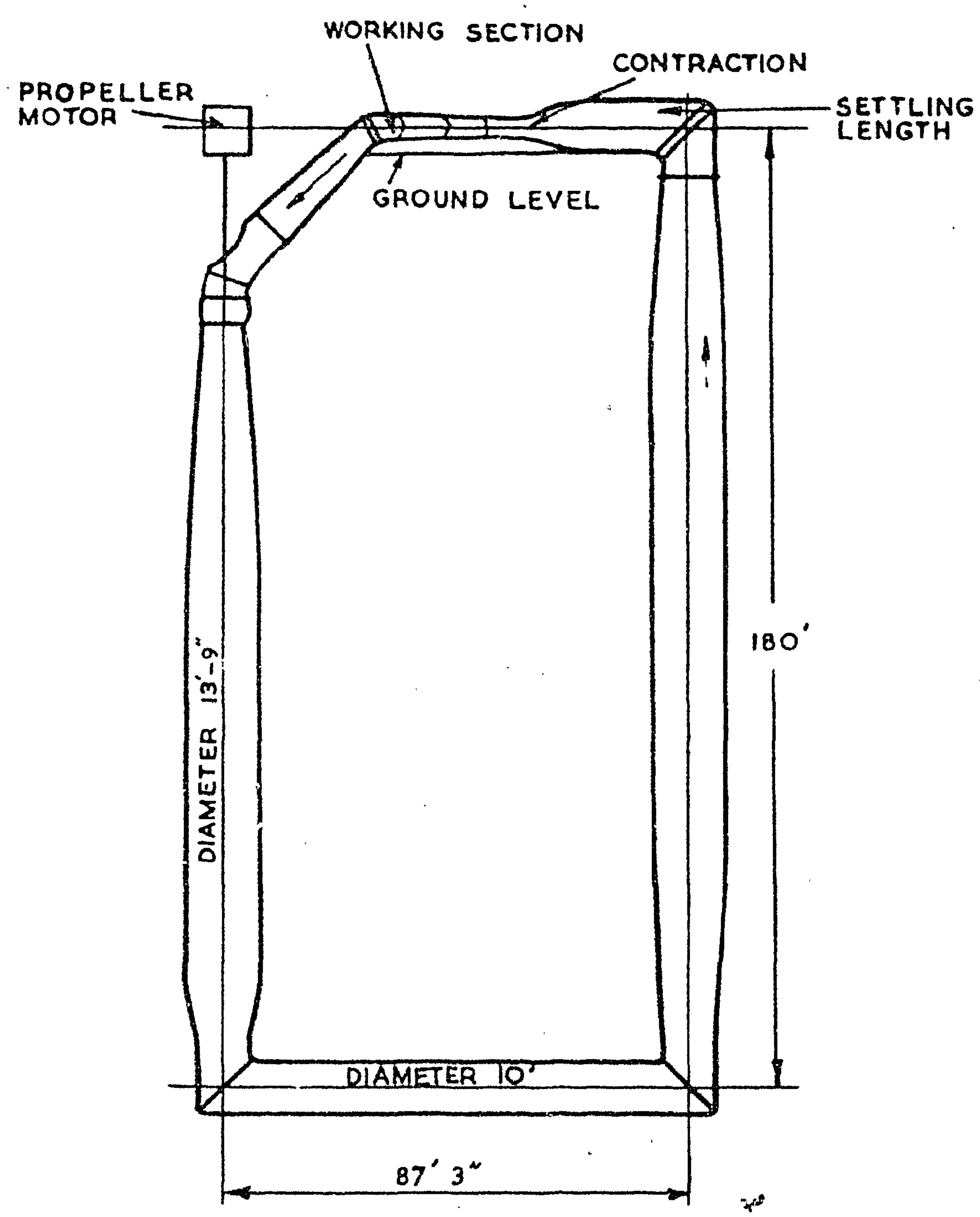

FIGURE 7. CIRCUIT ARRANGEMENT OF NPL No. 2 TUNNEL

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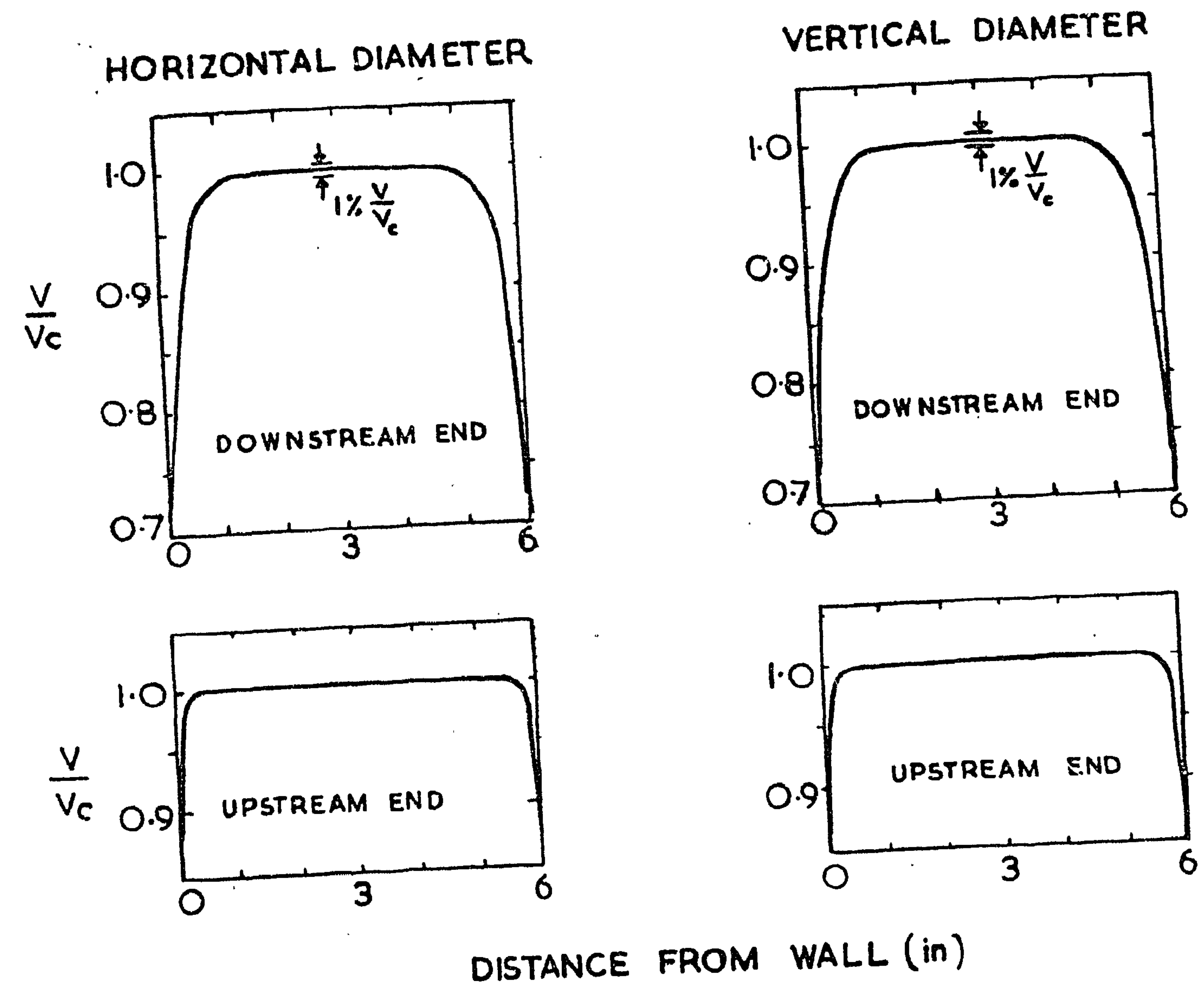

FIGURE 8. VELOCITY PROFILES IN THE WORKING SECTION OF SAF 6-INCH TUNNEL (Ripken 1951)

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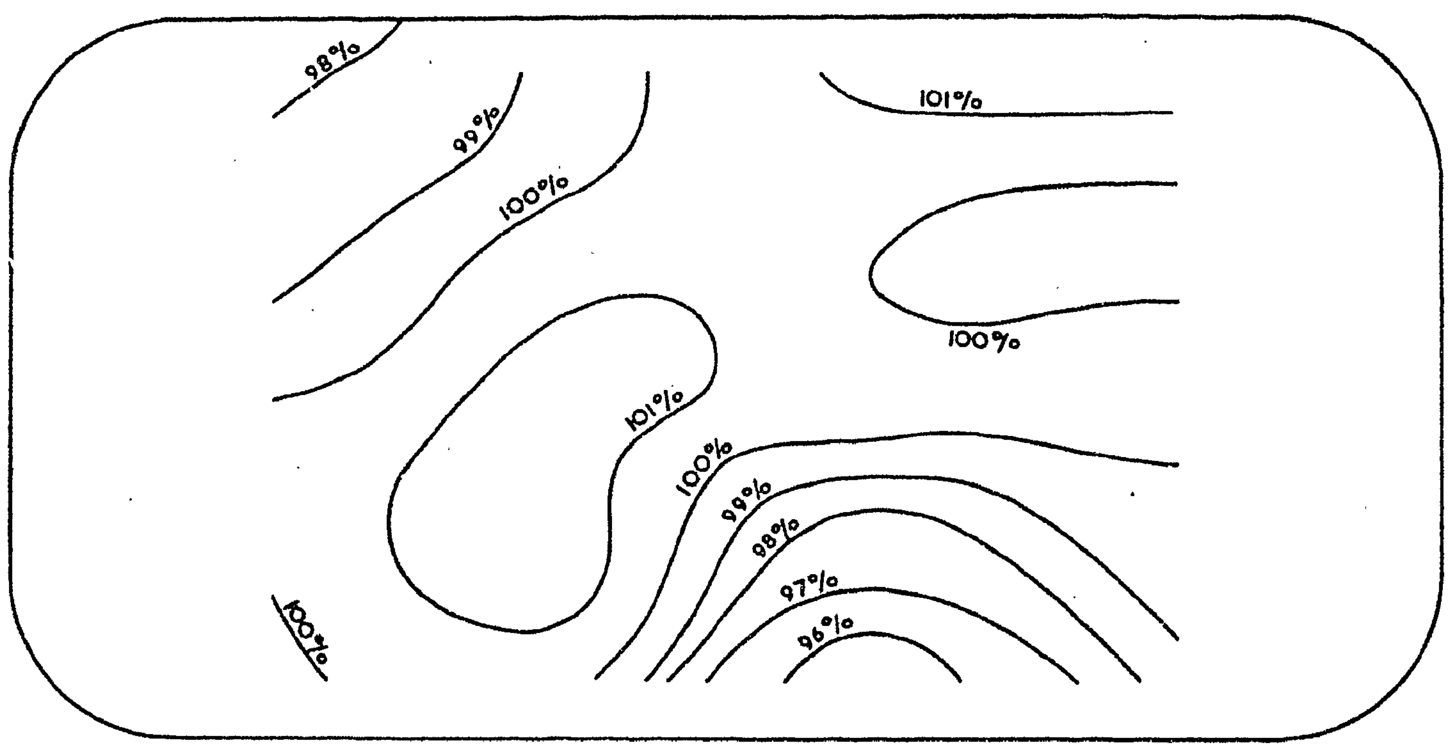
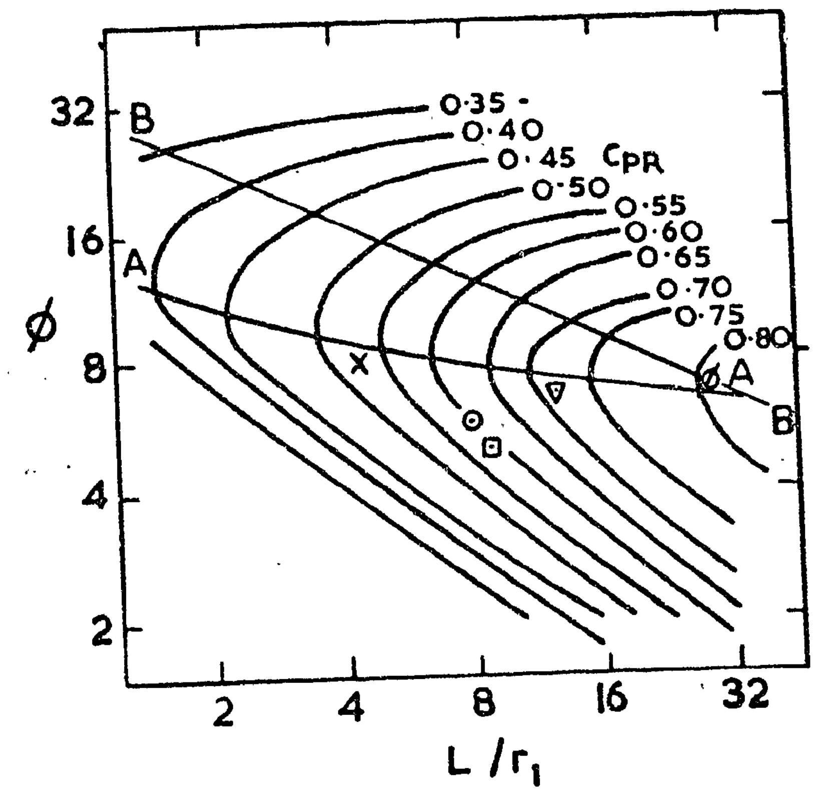


VELOCITY CONTOURS AS PERCENTAGES OF MEAN FLOW. 12 FT FROM CONTRACTION

FIGURE 9. VELOCITY DISTRIBUTION IN THE WORKING SECTION OF AEW NO. 2 TUNNEL



ϕ	DIFFUSER TOTAL ANGLE
L	DIFFUSER LENGTH ALONG CENTRE LINE
r_1	DIFFUSER RADIUS AT INLET
AA	LINE OF MAX PRESSURE RECOVERY C_{PR}
BB	LINE OF FIRST APPRECIABLE STALL

X	PSU 48-INCH (3rd DIFFUSER)
∇	PSU 48-INCH (1st DIFFUSER)
⊙	CIT 14-INCH
⊡	NPL No.2 (INCLINED DIFFUSER)
ϕ	UNIV. OF QUEENSLAND 13·5-INCH

FIGURE 10. CONICAL DIFFUSER PERFORMANCE (McDonald et al. 1966)

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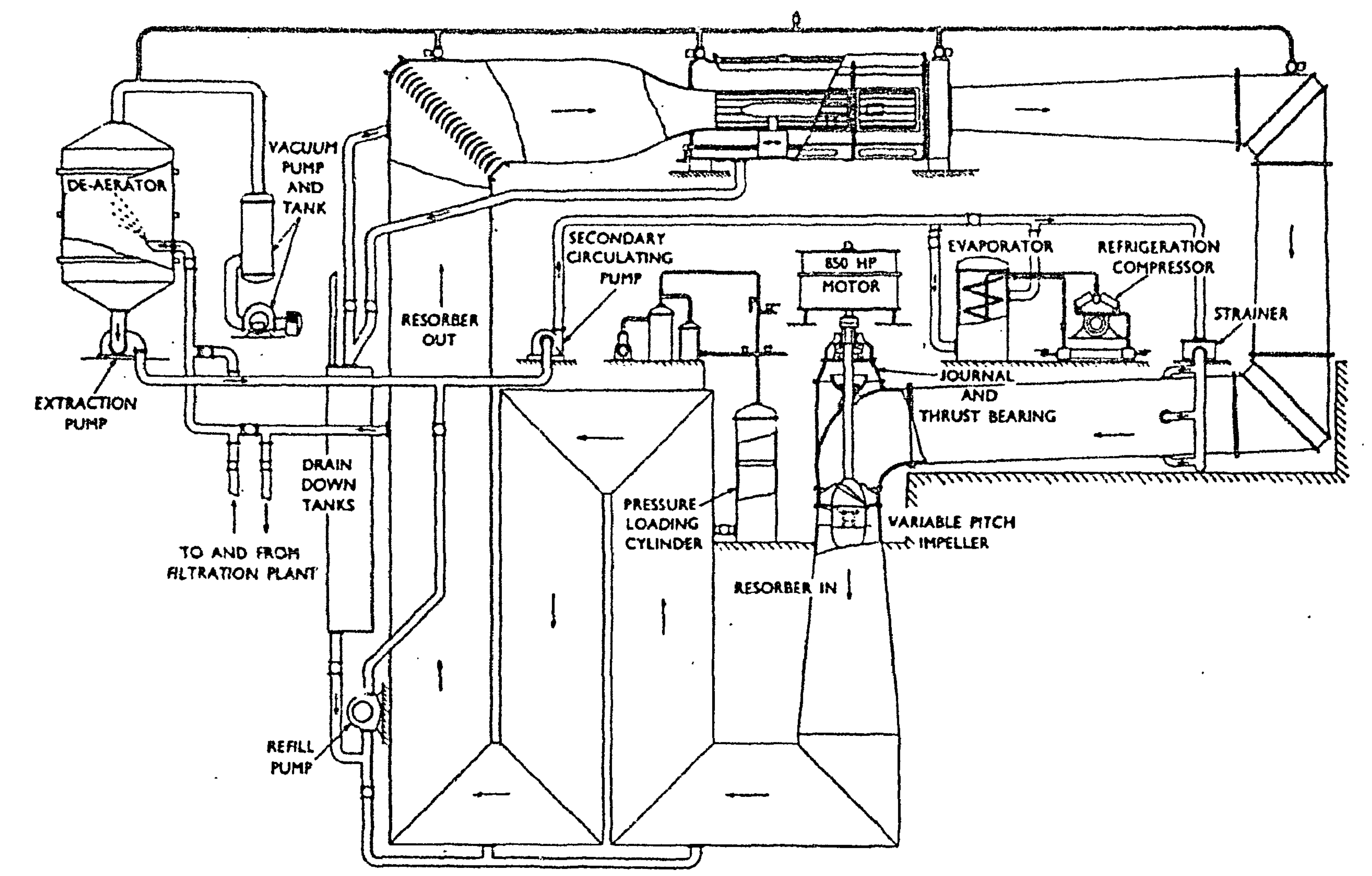

FIGURE 11. CIRCUIT ARRANGEMENT OF ARL 30-INCH TUNNEL AND ANCILLARY PLANT