ARE-TR88503

JULY 1990

COPY No 33

TRANSITION CONTROL VIA BOUNDARY LAYER HEATING

D J Atkins
S J Pearce

ADMIRALTY RESEARCH ESTABLISHMENT
Procurement Executive Ministry of Defence
Haslar GOSPORT Hants PO12 2AG

CONDITIONS OF RELEASE

0078682 BR-114792

**************************** DRIC U

**************************** DRIC Y

Reports quoted are not necessarily available to members of the public or to commercial organisations.

ARE TR88503

JULY 1990

TRANSITION CONTROL VIA BOUNDARY LAYER HEATING

by

D J ATKINS
S J PEARCE

Summary

This Report describes a theoretical method, based on linear stability theory, for predicting flow transition on axisymmetric heated underwater bodies, and a simple experiment using a four-to-one ellipsoidal nose in the 30-inch Water Tunnel. ~~at ARE (Teddington)~~. The experiment showed that filtering the tunnel water and vibration of the model have an effect on transition.

Agreement between theory and experiment is good without heating, but a more sophisticated experiment is needed to validate the theory for heated bodies. Although increases in transition Reynolds number of 40 per cent were observed experimentally, the theory suggests that much greater increases are possible for the same heat input by distributing it differently over the body surface.

(An earlier version of this Report was presented orally at Euromech 228 Colloquium on Boundary Layer Instability and Transition, Exeter, September 1987).

Admiralty Research Establishment
Haslar GOSPORT Hants PO12 2AG

90 238

Contents

Notation

D	Body diameter (m)
C_p	Specific heat of water (J kg^{-1} $°C^{-1}$)
g	Acceleration due to gravity (ms^{-2})
T	Temperature (°C)
u	Fluid velocity (ms^{-1})
x	Axial distance from nose (m)
β	Coefficient of thermal expansion of water ($°C^{-1}$)
ν	Kinematic viscosity (m^2s^{-1})

Subscripts

w	Denotes value at body surface
∞	Denotes ambient or freestream conditions

TRANSITION CONTROL VIA BOUNDARY LAYER HEATING

By D J Atkins
S J Pearce

1. INTRODUCTION

It is well-known that the transition Reynolds number on flat plates, and axisymmetric bodies with a favourable pressure gradient along most of their length, can be significantly increased by heating the surface. This phenomenon has implications for drag reduction and has been the subject of much published research, particularly in the USA. Wazzan et al (References 1, 2) showed theoretically, for a flat plate heated to a constant temperature above ambient, that the critical Reynolds number (based on displacement thickness) for neutral stability was increased from 520 to approximately 15000. The optimum overheat was about 40°C giving a transition Reynolds number of about 2×10^8 as compared with the unheated value of 3×10^6. These findings were confirmed for small overheats up to 8°C by Strazisar et al (Reference 3). Barker and Jennings (Reference 4) and Barker and Gile (Reference 5) investigated the stability of a heated laminar boundary layer developing inside a cylindrical tube. A number of different wall temperature distributions were tried and the optimum increase of a factor of 3-4 in transition Reynolds number was observed for a small (7-8°C) uniform overheat. Additional heating showed no further increases, in contradiction to the theory, which predicted increases up to an overheat of 35°C. Lauchle and Gurney (Reference 6) studied a "laminar-flow" body with a large region of favourable pressure gradient which was heated electrically. The maximum heating power available was 93 kW, which increased the transition Reynolds number from $4{\cdot}5 \times 10^6$ to $3{\cdot}6 \times 10^7$. The effect of increasing the total heating power from zero to the maximum value resulted in a linear increase in transition Reynolds number at first, followed by a levelling out at higher values. The theory however predicted a linear increase throughout the entire range of power inputs. The disparity between theory and experiment was attributed by the authors to surface roughness and the effects of free stream particles, and further research has been carried out on these effects (References 7, 8). This showed that heated boundary layers are more susceptible to external disturbances than unheated ones and that any improvements arising from surface heating can be nullified by such effects.

All the workers mentioned above used a theoretical approach based on two-dimensional linear stability theory. This involves solving a modified version of the well-known Orr-Sommerfeld equation, in which only the variation of viscosity (as a function of temperature) is taken into account. Lowell and Reshotko (Reference 9) derived the full disturbance equations in which fluctuations in all the fluid properties are taken into account, giving a more complex sixth-order system, and they showed that there is no major quantitative difference between the results obtained using the fourth- and sixth-order systems. However they neglected buoyancy effects in their linear stability model, and in common with previous workers assumed that buoyancy effects in the mean flow are negligible. Barker and Gile (Reference 5) and Lauchle & Gurney (Reference 6) commented, after some discussion, that the disagreement between their experiments and the theory cannot be attributed to flow asymmetries arising from buoyancy effects. Lauchle and Gurney had three hot-film probes at the same axial location, but at 120° intervals round the circumference of their test body, to measure any circumferential variations in stability. However two of the probes failed to operate and they were only able to use the results from the probe on top of the body. Asrar (Reference 10) showed theoretically by doing a full three-dimensional linear stability analysis (again neglecting buoyancy effects) that two-dimensional disturbances are the most critical for heated flat plate and axisymmetric flows. He also investigated the effects of different surface temperature distributions on a 6 to 1 prolate spheroid and concluded that a gradually increasing overheat with downstream position was better than a uniform or gradually reducing overheat.

The objectives of the present research are to develop a theoretical transition prediction method for underwater axisymmetric heated bodies and validate it experimentally. The prediction method was developed partly in-house and partly under contract with BMT Ltd under the direction of Dr M Gaster. Two computer programs known as HEATEDBL and FLTRANS were written and these are described in Reference 11. Brief details of the experiment are given in Section 3 and more detailed descriptions are given in Appendix A and Reference 12.

2. THEORY

The prediction method involves computing the laminar boundary layer and linear spatial stability. The boundary-layer calculation solves the coupled momentum and energy equations on a grid which expands with the boundary layer based on the usual similarity transform approach. The fourth-order Orr-Sommerfeld equation with variable viscosity is solved using a formulation of the compound matrix method developed at BMT Limited by Willis (Reference 13). Following Smith and Gamberoni (Reference 14), the onset of transition is assumed to occur where the most unstable frequency is amplified by a factor e^n, where n usually takes the value 9. Buoyancy effects have been neglected; a discussion in Appendix B suggests that for the present geometry and flow conditions they are not significant.

Numerical experiments on flat plates carried out by Atkins (Reference 15) have shown that the compound matrix method requires many data points (typically between 400 and 3200 depending on the overheat) to produce accurate eigenvalues, but is relatively insensitive to other physical and numerical parameters. Calculations for the temporal stability case using the full sixth-order equation, which takes buoyancy effects into account as well as fluctuations in all the other fluid properties, have been carried out by Thomas (Reference 16). These have shown non-trivial but small differences between fourth-order and sixth-order eigenvalues, confirming the results of Lowell and Reshotko (Reference 9).

3. EXPERIMENTAL INVESTIGATION

The 30-inch Water Tunnel at ARE (Teddington) was used for a simple heated body experiment. The test body was a four-to-one ellipsoidal nose attached to a long cylinder. Figure 1 shows a sketch of the model geometry and the pressure coefficient which was calculated using the method of Hess and Smith (Reference 17). Body offsets and pressure coefficients are tabulated in Reference 11. Unlike previous body shapes tested experimentally, the current body has a region of mildly adverse pressure gradient which is characteristic of typical underwater vehicle shapes. Heating was supplied by pumping hot water through a copper coil wound helically inside the nose. Intermittency measurements were made at a number of axial positions using glue-on hot-film probes. Body surface temperature was measured at the aft end of the heating coil using a thermocouple and at a few other locations by calibrating the hot-film probes as thermocouples. The temperature data from the hot-film probes turned out to be rather unreliable. The model surface was made smooth enough to avoid premature tripping due to roughness, and buoyancy effects were thought to be insignificant. However, the effects of model vibration and filtering the tunnel water were found to be significant.

The turbulence intensity was measured in the empty tunnel and the results are shown in Figure 2. There is a honeycomb arrangement in the settling section of the tunnel upstream of the contraction, and this results in low turbulence levels of 0·1 per cent at the start of the working section over a wide range of tunnel speeds (3-13 ms^{-1}). However the turbulence levels increase significantly further downstream, owing to the effect of the slotted wall section. As a result of this, the model was placed as far forward as possible, with the nose being 0·69 m from the tunnel throat. The range of tunnel speeds obtained during the transition experiments ranged from 2 to 14 ms^{-1}. At speeds above 10 ms^{-1} there was evidence of low-frequency model vibration which was clearly visible at 14 ms^{-1}.

Typical signals from the hot-film gauges are shown as Figure 3. As in previous work (Reference 18), four different flow regimes are identifiable, viz: laminar, wave-like, intermittent and fully turbulent. Figures 4(a) and 4(b) show the spectral density of the wave-like signals. The unheated spectrum has a single peak, which suggests that the disturbance may be a Tollmein-Schlichting wave (Reference 19). The heated spectrum is more complicated with a fundamental peak and first and second harmonics, which suggests that there may be non-linear effects.

Two separate series of transition experiments were carried out. The first series was without heating and the second mainly with heating. Halfway through the second series, the tunnel water was filtered for eight hours and this had an effect on the results (see Section 5). With heating, increases in transition Reynolds numbers of at least 40 per cent were observed, and intermittency values were generally lower than the corresponding unheated values. However the heated boundary layer was observed to be more susceptible to external effects such as model vibration, the presence of particles in the flow, and air or vapour bubbles.

Because of the unreliability of the hot-film temperature measurements, the variation of surface temperature (or surface heat flux) over the heated portion of the body surface was to a large extent unknown. The measurements (Reference 12) suggest that the temperature rises to a maximum and falls off near the tail end. The discussion in Appendix B suggests that three-dimensional effects are negligible on the present geometry. The total heating power supplied to the model was estimated from the water temperature at the coil inlet and outlet and found to vary between 4 and 12 kW over the range of flow speeds (4-14 ms^{-1}) and reservoir tank temperatures (48-68°C or 31-51°C above ambient).

4. NUMERICAL CALCULATIONS

Numerical calculations were carried out on the unheated body for a range of flow speeds from 4 to 14 ms^{-1} using computer programs HEATEDBL and FLTRANS

(Reference 11). Calculations were also carried out on the heated body (assuming axial symmetry) at flow speeds of 8, 10 and 12 ms^{-1} with a view to gaining some knowledge of the influence of surface heat-flux variation on transition to turbulence for the ellipsoidal nose. Heat was applied to the same region of the surface as used in the experiment. Various simple heat-flux profiles were tried, viz: constant, linearly increasing and linearly decreasing. A few computations were carried out using profiles of heat flux proportional to $\pm\sqrt{x}$ and $\pm x^2$, rather than $\pm x$, but the results obtained were not significantly different.

Figure 5 shows surface temperature profiles for a total heat input of 1·25 kW. In calculating these profiles, the effects of heat conduction along the surface were not taken into account. The temperature measurements estimated by calibrating the hot-film probes as thermocouples indicated that the temperature decreased downstream of x/D=2·0. This suggests that the theoretical case of linearly decreasing heat flux corresponds most closely to the experiment. Figure 6 shows the values of excess temperature at the end of the heating coil, i.e. at x/D=2·2, plotted against the total heating power.

Figure 7 shows predictions of flow transition based on e^9 obtained at a flow speed of 10 ms^{-1} with constant, linearly increasing and linearly decreasing heat-flux profiles. If the total heating power is less than 0·5 kW, there is little difference between the results using different profiles. Above 0·75 kW however, different heat-flux profiles give significant differences. The results indicate that gradually increasing heat flux has a more beneficial effect on transition than a constant heat flux which, in turn, has a more beneficial effect than a gradually decreasing heat flux. To illustrate the effect of flow speed, the results for 8 and 12 ms^{-1} are shown for the case of linearly decreasing heat flux. The trends in the present results are similar to those found by Asrar (Reference 10).

5. COMPARISON OF THEORY WITH EXPERIMENT

5.1. Unheated body

The unheated body experiment has resulted in a set of consistent repeatable data which can be used for comparison with the theory. The measured flow regimes are compared with theoretical disturbance amplification factors in Figure 8. Figure 9 shows the measured and predicted spectral density peak frequencies which correlate well. Figure 10 shows the variation of intermittency with axial position. The uncertainty bands indicate the spread of the experimental data over different runs. The results at a tunnel speed of 14 ms^{-1} are somewhat inconsistent with the rest of the data, but the model was affected significantly by vibration at this speed. The effect of filtering the tunnel water, shown in Figure 11, results in a small increase in transition Reynolds number. Figures 10 and 11 indicate that transition is not instantaneous but occurs gradually over a finite longitudinal distance. The extent of the transition region was estimated crudely by calculating the approximate slope of the intermittency curve at an intermediate value and extrapolating to 0 per cent and 100 per cent. Figure 12 shows the extent of the transition region estimated in this way, which is generally in the range 0·25D - 0·40D (0·055m - 0·085m). The onset of transition, corresponding to the start of turbulent bursting, appears to correspond with e^9 at low tunnel speeds and e^7 at high speeds. Pearce and

Turner (Reference 12) suggested that, at high tunnel speeds, transition is affected by model vibration. Power (Reference 18) has conducted an experiment over a similar Reynolds number range on a 3·6 to 1 ellipsoidal nose and observed that the onset of transition corresponded to between e^8 and e^{12} depending on Reynolds number. For other body shapes over the same Reynolds number range, he obtained values between e^7 and e^{12}. Power's experiments were conducted in a towing tank which probably had a lower level of turbulence than the ARE Water Tunnel.

In boundary-layer and drag calculation methods which assume that transition is instantaneous and require a value for transition location to be specified, the experimental value corresponding to 50 per cent intermittency is often used. These values are indicated on Figure 12 and the effect of filtering the tunnel water is also shown. The transition Reynolds numbers Us/ν, based on tunnel speed and surface arc length, were calculated at 50 per cent intermittency. The average increase as a result of filtering was about 2 per cent.

5.2. Heated body

Because of the lack of reliable information regarding the temperature or power variation over the heated region, no direct comparison of theory and experiment is possible. However, an attempt to correlate theory and experiment is desirable with a view to making recommendations for a future experiment.

In the experiment, the total power supplied to the heating coil was calculated, assuming a flow rate of 2 gallons per minute, according to the formula

$$\text{Heating power (Watts)} = 0{\cdot}15\ C_p\ (T_{in} - T_{out})$$

where

$$C_p = 4190\ \text{J kg}^{-1}\ {}^\circ\text{C}^{-1}$$

Figure 13 shows the total power supplied to the heating coil at tunnel speeds of 8, 10 and 12 ms^{-1}, which is plotted against the excess temperature, T - T(ambient), as measured by the thermocouple embedded in the model skin at $x/D = 2{\cdot}2$. There is considerable scatter in the data and so straight-line least squares fits were obtained which are the broken lines. The continuous lines are theoretical curves of the total power used to heat the surface over the coil region plotted against the excess temperature on the surface at the same location. A linearly decreasing heat flux profile was assumed. In order to obtain the same temperature as measured experimentally at the thermocouple location, the theoretical power used to heat the surface is only a small fraction (calculated to be between 4 per cent and 10 per cent) of the total power supplied to the coil in the experiment.

Figure 14 shows theoretical curves of the variation of axial position, corresponding to an amplification factor of e^9, with power used to heat the surface at flow speeds of 8, 10 and 12 ms^{-1}. Once again, a linearly decreasing heat flux profile was used. These results indicate that a power input of 1 kW should give an increase in transition Reynolds number of about 40 per cent at all three flow speeds. The relatively few heated measurements available are listed in Table 1 and these show increases in transition Reynolds number of between 17 per cent and 40 per cent. The total power supplied to the heating coil varied from 4·7 kW to 10·9 kW. The measurements of intermittency (Reference 12) suggest that filtering the tunnel water has a greater effect on transition on a heated body, as compared with an unheated body. A direct comparison between unfiltered and filtered water was only possible at one condition (10 ms^{-1} and 5 kW input power) and this gave an increase of about 6 per cent in transition Reynolds number.

Figure 14 also shows the unheated body measured transition locations (the circles indicating the experimental points correspond to 50 per cent intermittency). The theoretical power inputs which would give the same measured increase in transition Reynolds number are also shown in Table 1 and Figure 14. These values range from 7-13 per cent of the total power supplied to the heating coil. It was possible to estimate the peak frequency of the Tollmein-Schlichting waves for some of the measurements, and these are compared with theoretical predictions in Figure 15. It was assumed that 10 per cent of the power supplied to the coil was used to heat the surface. The measurements and predictions are reasonably consistent, although, at the higher power input, the measured peak frequencies are higher than predicted.

The previous discussion suggests that the theoretical power inputs required to achieve the measured thermocouple temperatures are similar to those giving the measured increases in transition Reynolds number. This implies that in the experiment, only a small amount (5-10 per cent) of the heat supplied to the coil actually reached the portion of the body surface where the coil was located. One possible explanation for this is that there may have been significant heat conduction along the model surface towards the nose or tail regions. Some numerical calculations were carried out with heat supplied to the nose region as well as the coil region, and these showed that the extra heat supplied to the nose region has a relatively small effect on transition, because the unheated boundary layer is stable in this region. In view of the simplicity of the experiment and the limited instrumentation, further discussion of the results is of limited value. A detailed quantitative validation of the theory clearly requires a much more sophisticated and better instrumented model.

6. CONCLUSIONS AND FURTHER RESEARCH

A theoretical transition prediction capability, based on linear stability theory, has been developed for axisymmetric underwater bodies, which includes the effects of surface heating. The 30-inch Water Tunnel at ARE (Teddington) has been used for a simple transition experiment involving measurements of intermittency using hot-film gauges. The experiment showed that transition was affected by model vibration and filtering the tunnel water (more so with heating than without heating). Heating the body surface also appeared to modify the Tollmein-Schlichting wave spectrum in the way suggested by the theory.

In the absence of heating, the measured transition locations corresponding to the start of turbulent bursting agree with predictions of peak amplification ratios of e^9 at low tunnel speeds and e^7 at high speeds. The difference at high speeds is thought to be due to model vibration. The signals from the hot-film gauges indicate the existence of Tollmein-Schlichting waves and the predicted and measured spectral peak frequencies agree well.

Numerical calculations for the heated body using different heat flux profiles have shown that a linearly increasing profile has a more favourable effect on transition than a corstant profile which is, in turn, more favourable than a linearly decreasing profile. The measurements suggest that the latter profile most closely matches the experimental situation. Comparison of theory and experiment suggests that only a small fraction (about 10 per cent) of the power supplied to the coil was used to heat the surface. The theory suggests that much greater increases in transition Reynolds number are possible than those measured experimentally (17-40 per cent) by improving the efficiency of the heating system and distributing the heat differently over the model surface.

The 30-inch Water Tunnel can be used for transition experiments, but it is desirable to reduce the turbulence levels in the working section. A new closed working section can be fitted which achieves this. The theory has been validated quantitatively for unheated bodies and qualitatively for heated bodies. In order to achieve a quantitative validation of the theory for heated bodies, a more sophisticated experiment with controllable heat distribution and detailed and accurate temperature measurement over the whole body surface is required. Further investigations of the receptivity of heated boundary layers to external disturbances and of non-linear effects are also needed.

7. ACKNOWLEDGMENTS

The experimental investigation was carried out by Mr A F Turner and most of the numerical calculations were carried out by Mr M D Thomas. The authors are grateful to Professor M Gaster of Cambridge University for helpful discussions.

REFERENCES

1. A R WAZZAN, et al. The Stability of Water Flow Over Heated and Cooled Flat Plates. Trans ASME J Heat Transfer, Vol 90 No 1, 109-114 (1968).

2. A R WAZZAN, et al. The Stability and Transition of Heated and Cooled Incompressible Laminar Boundary Layers. Proc Fourth Int Heat Transfer Conf, publ Elsevier, Paper no FC1.4 (1970).

3. A J STRAZISAR, et al. Experimental Study of the Stability of Heated Laminar Boundary Layers in Water. J Fluid Mech, Vol 83 No 2, 225-247 (1977).

4. S J BARKER and C JENNINGS. The Effect of Wall Heating upon Transition in Water Boundary Layers. Paper 19 from AGARD CP-224 (Laminar-Turbulent Transition) (1977).

5. S J BARKER and D GILE. Experiments on Heat-Stabilized Laminar Boundary Layers in Water. J Fluid Mech, Vol 104, 139-158 (1981).

6. G C LAUCHLE and G B GURNEY. Laminar Boundary-Layer Transition on a Heated Underwater Body. J Fluid Mech, Vol 144, 79-101 (1984).

7. E W HENDRICKS and D M LADD. Effect of Surface Roughness on the Delayed Transition on a 9:1 Heated Ellipsoid. AIAA J, Vol 21 No 10, 1406-1409 (1983).

8. D M LADD and E W HENDRICKS. The Effect of Background Particulates on the Delayed Transition of a Heated 9:1 Ellipsoid. Experiments in Fluids, Vol 3, 113-119 (1985).

9. R L LOWELL and E RESHOTKO. Numerical Study of the Stability of a Heated Water Boundary Layer. Case Western Reserve University FTAS TR 73-93 (1974).

10. W ASRAR. Stability of Heated Boundary Layers. PhD Thesis. Virginia Polytechnic Institute and State University (1983).

11. D J ATKINS. Description of Computer Programs for Transition on Heated Underwater Bodies. ARE TM(UHA)88509 (1988).

12. S J PEARCE and A F TURNER. Transition Measurements on a Heated Forebody in the 30-inch Water Tunnel at ARE (Teddington). Unpublished MOD Report (1988).

13 G J K WILLIS. An Eigenvalue Finder for Flows Over a Rigid Heated Surface. NMI Project no 352052 (1984). COMMERCIAL-IN-CONFIDENCE.

14. A M O SMITH and N GAMBERONI. Transition, Pressure Gradient and Stability Theory. Proc 9th Int Congress on Appl Mech, Vol 4, 234. Brussels, Belgium (1956).

15. D J ATKINS. Calculation of the Stability of Heated Boundary Layers Using the Compound Matrix Method. ARE TM(UHA)86514 (1986).

16. M D THOMAS. Comparison of the Compound Matrix and Orthonormalisation Methods for Calculating the Stability of Heated Water Boundary Layers. ARE TM(UHA)88505 (1988).

17. J L HESS and A M O SMITH. Calculation of Potential Flow About Arbitrary Bodies. Prog Aeronaut Sci, Vol 8, Pergamon Press (1966).

18. J L POWER. Drag, Flow Transition and Laminar Separation on Nine Bodies of Revolution Having Different Forebody Shapes. DTNSRDC 77-0065 (1977).

19. H SCHLICHTING. Boundary-Layer Theory. McGraw-Hill (1968).

20. E H LEVER et al. The Rotating-Beam Channel and 30-inch Water Tunnel at Admiralty Research Laboratory. Proc Inst Mech Eng, Vol 171 No 4, 159-185 (1957).

21. L-S YAO et al. Buoyancy-Driven Asymmetric Water Boundary Layer Along a Heated Cylinder. J Fluid Mech, Vol 98 No 2, 417-434 (1980).

Reports quoted are not necessarily available to members of the public or to commercial organisations.

Table 1

HEATED BODY TRANSITION MEASUREMENTS

Flow Speed	Filtered/ Unfiltered	$T_w - T_\infty$ (x/D=2·2)	Power Input Expt.	Power Input Theory*	Theory/Expt.	Transition Location Unheated	Transition Location Heated	Transition Reynolds Number Unheated	Transition Reynolds Number Heated	%Inc.
(m/s)		(°C)	(kW)	(kW)	(%)	x/D	x/D			
8	U	1.7	4.7	0.6	13	1.95	2.45	3.38×10^6	4.18×10^6	24
10	U	1.0	5.0	0.35	7	1.78	2.10	3.87×10^6	4.52×10^6	17
10	F	1.7	5.0				2.25		4.82×10^6	
10	U	4.0	9.9	0.9	9	1.78	2.45	3.87×10^6	5.22×10^6	35
12	F	2.6	8.5				2.45		6.27×10^6	
12	U	2.7	10.9	0.9	8	1.6	2.3	4.22×10^6	5.91×10^6	40

*Theoretical input power giving the same percentage increase in transition Reynolds number.

Appendix A

DESCRIPTION OF THE EXPERIMENT

A survey of the available Test Facilities indicated that the 30-inch Water Tunnel at ARE (Teddington) (Reference 20) would be the most suitable for a preliminary transition experiment, because of the relatively high Reynolds numbers obtainable. The tunnel has a slotted wall working section 4·58 m long and 0·76 m in diameter designed to accommodate relatively large models (up to 0·25 m in diameter), and flow speeds of up to 20 ms^{-1} can be achieved. The objectives of the experiment were to determine whether or not the 30-inch Water Tunnel is suitable for transition experiments, to develop suitable instrumentation techniques for measuring transition on heated bodies, to determine the effect of small increases in surface temperature on transition for a body with a mildly adverse pressure gradient, and to provide data for an initial validation of the theory. The four-to-one ellipsoidal nose (see Figure 1) was specially manufactured and connected to an existing cylindrical afterbody. The joint, at 0·518 m from the nose (x/D = 2·4), was hydrodynamically rough, which meant that no measurements could be carried out downstream of this position. Profile tolerances were ± 0·0001 m with a limit of waviness slope of 0·001. Hendricks and Ladd (Reference 7) have shown that the surface finish is more critical for a heated body experiment than for an unheated experiment, and, based on their results, a surface finish of 0·2 μm rms was used.

The nose was heated by pumping hot water around a copper coil of 0·01 m internal diameter wound helically inside the model. The extent of the coil was from 0·162 to 0·476 m from the nose (x/D = 0·75 to 2·20). The gap between the coil and the inner surface of the model was filled with low melting point Serrabend (a lead/aluminium alloy) to improve thermal contact between the surfaces. Hot water was supplied from an external tank fitted with three 3 kW immersion heaters and pumped from the front to the back of the model at a nominal flow rate of 2 gallons/min (0·15 kg s^{-1}). For one run, the direction of flow was reversed. Intermittency was measured using DANTEC type 55R47 glue-on hot-film gauges positioned at x/D = 1·5, 1·75, 2·0, 2·2 and 2·35. These were used rather than the more sophisticated flush-mounted probes to simplify the model manufacturing process. Because the gauges were designed primarily for use in air, they were given added protection by coating with an air-drying polyeurethane coating and the leading edges of each foil were trimmed to avoid premature tripping of the boundary layer by the gauge. Temperature was measured using K-type (NiCr/NiAl) thermocouples which were positioned in the tank, the coil inlet and outlet and the model shell 0·001m from the outer surface at x/D = 2·2. The ambient temperature of the water in the tunnel was also measured and found to be relatively constant having a value of approximately 17°C. The hot-film gauges at x/D = 2·0, 2·2 and 2·35 were also calibrated as thermocouples, but the repeatability of the temperature measurements so obtained was poor.

Appendix B

ESTIMATION OF BUOYANCY EFFECTS

It is important to consider buoyancy effects in the laminar boundary layer on a heated underwater body. Although no study appears to have been made on conventional vehicle shapes, Yao et al (Reference 21) studied theoretically the development of a three-dimensional water boundary layer along a heated longitudinal cylinder. They concluded that near the leading edge, the boundary-layer flow is forced-convection dominant, but further downstream, it becomes free-convection dominant. Their numerical results for uniform surface temperature show that buoyancy effects are negligible when

$$x < 0{\cdot}1\ a/\sqrt{\epsilon} \tag{A1}$$

and small up to

$$x = 0{\cdot}3\ a/\sqrt{\epsilon} \tag{A2}$$

where a is the cylinder radius, and

$$\epsilon = Gr/Re^2 \tag{A3}$$

In equation (A3), Re is the Reynolds number and Gr the Grashof number, given by

$$Re = u_\infty\ a/\nu_\infty \tag{A4}$$

$$Gr = \beta g a^3 (T_w - T_\infty)/\nu_w^{\,2} \tag{A5}$$

Hence, buoyancy effects are significant for large overheats and small flow speeds. Applying the results of Yao directly to the present geometry with a 50°C overheat and a flow speed of 5 ms^{-1}, then an approximate calculation gives

$a = 0{\cdot}108m$

$\nu_\infty = 1{\cdot}08 \times 10^{-6}\ m^2s^{-1}$

$\beta = 5 \times 10^{-4}\ °C^{-1}$

$Re = 5 \times 10^5$

$Gr = 1{\cdot}5 \times 10^9$

$\epsilon = 6 \times 10^{-3}$

The above calculation suggests that buoyancy effects are negligible for $x < 0{\cdot}14m$ and small for $x < 0{\cdot}40m$. The total streamwise extent of the heated region is 0·314m and furthermore the maximum overheat only extends over a relatively short region. Hence buoyancy effects are probably at worst very small in the present experiments. However, if it was required to move the transition location much further back in a future experiment, then buoyancy effects might become more important.

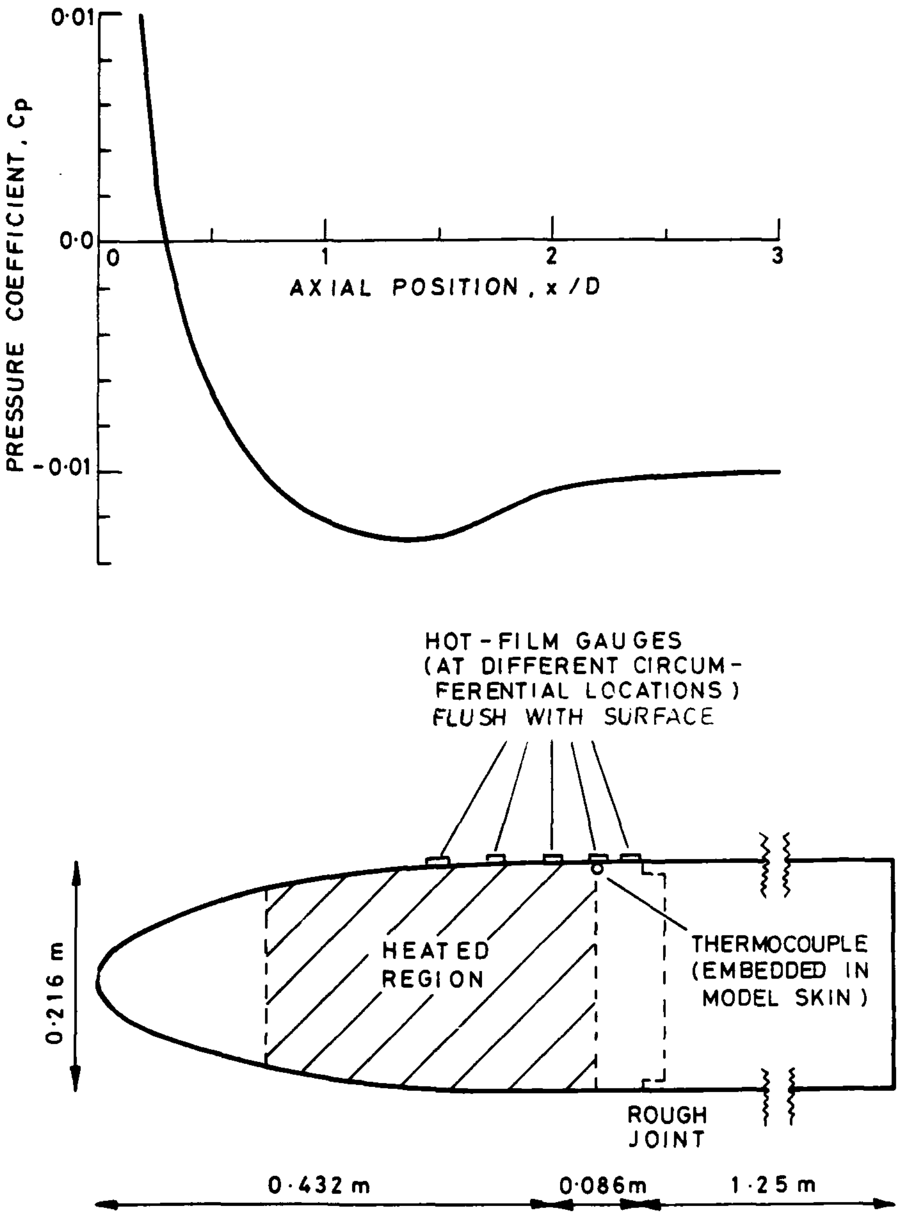

FIG. 1 TEST MODEL GEOMETRY AND PRESSURE COEFFICIENT
(FOUR-TO-ONE ELLIPSOIDAL NOSE)

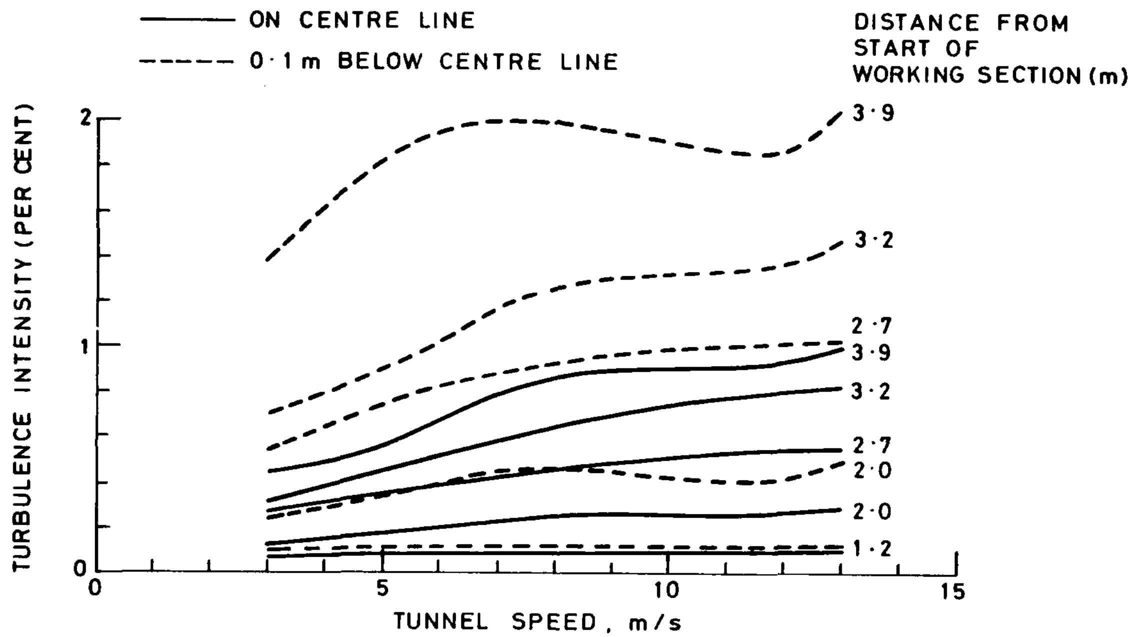

FIG. 2 TURBULENCE INTENSITY MEASUREMENTS IN WORKING SECTION OF 30-INCH WATER TUNNEL

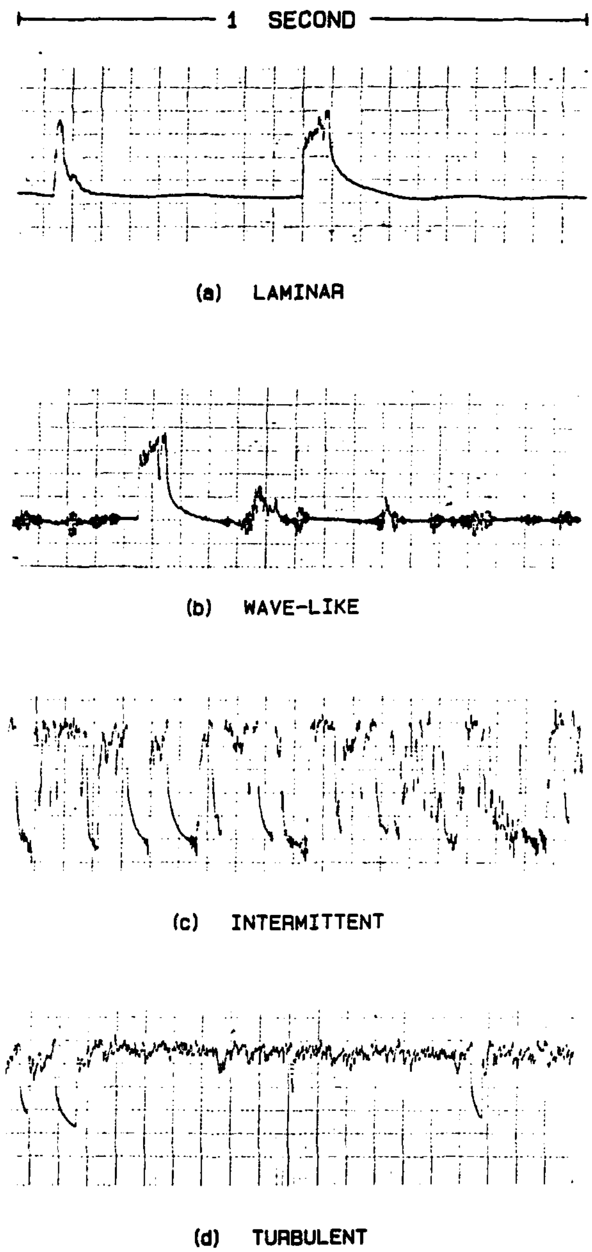

FIG.3 TYPICAL HOT-FILM SIGNALS FOR VARIOUS FLOW REGIMES

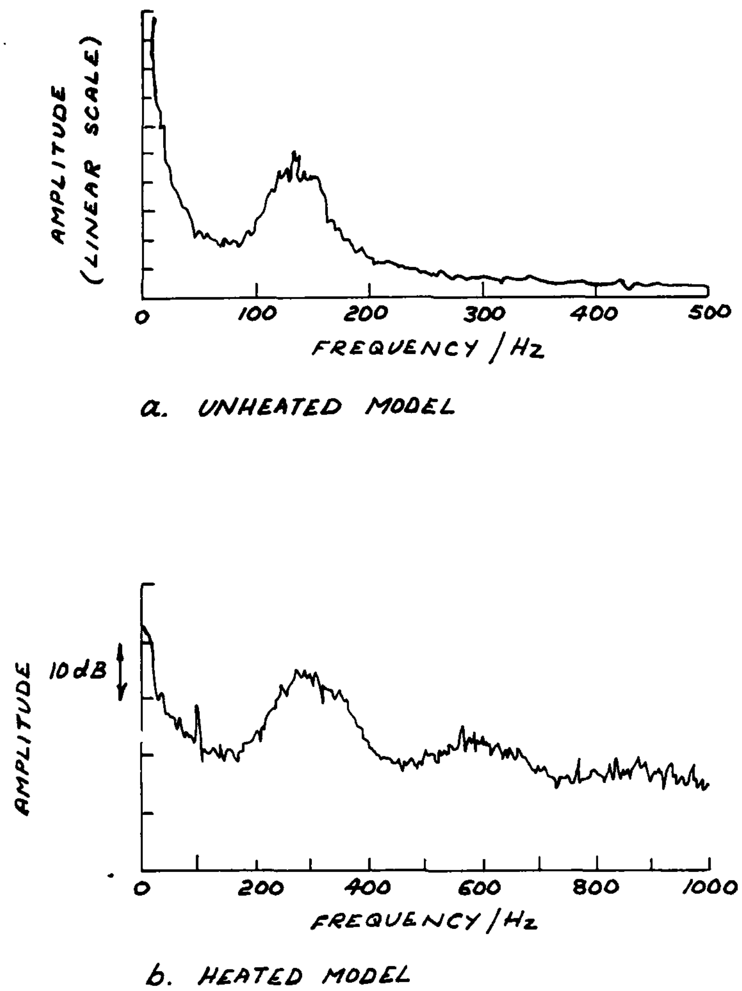

FIG. 4. SPECTRAL DENSITY OF TYPICAL HOT-FILM SIGNAL

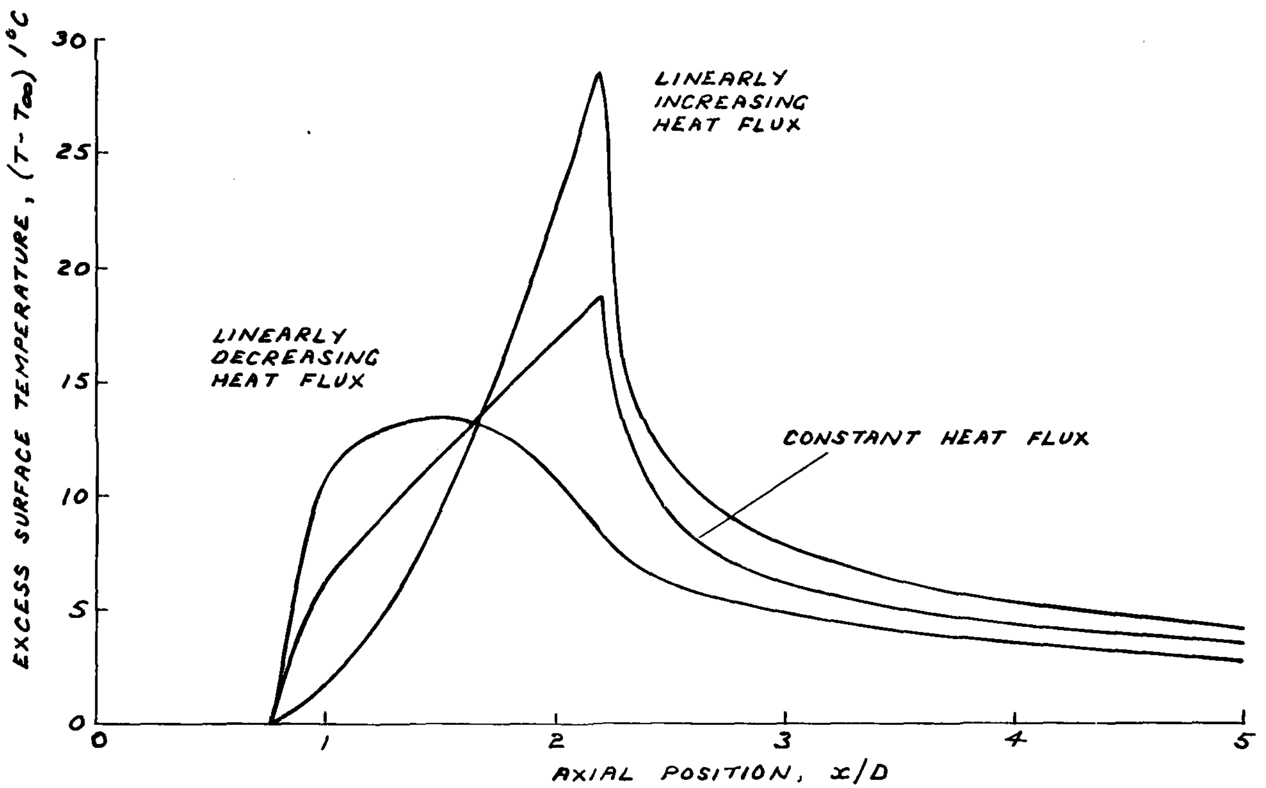

FIG. 5. THEORETICAL VARIATION OF SURFACE TEMPERATURE USING DIFFERENT HEAT-FLUX PROFILES

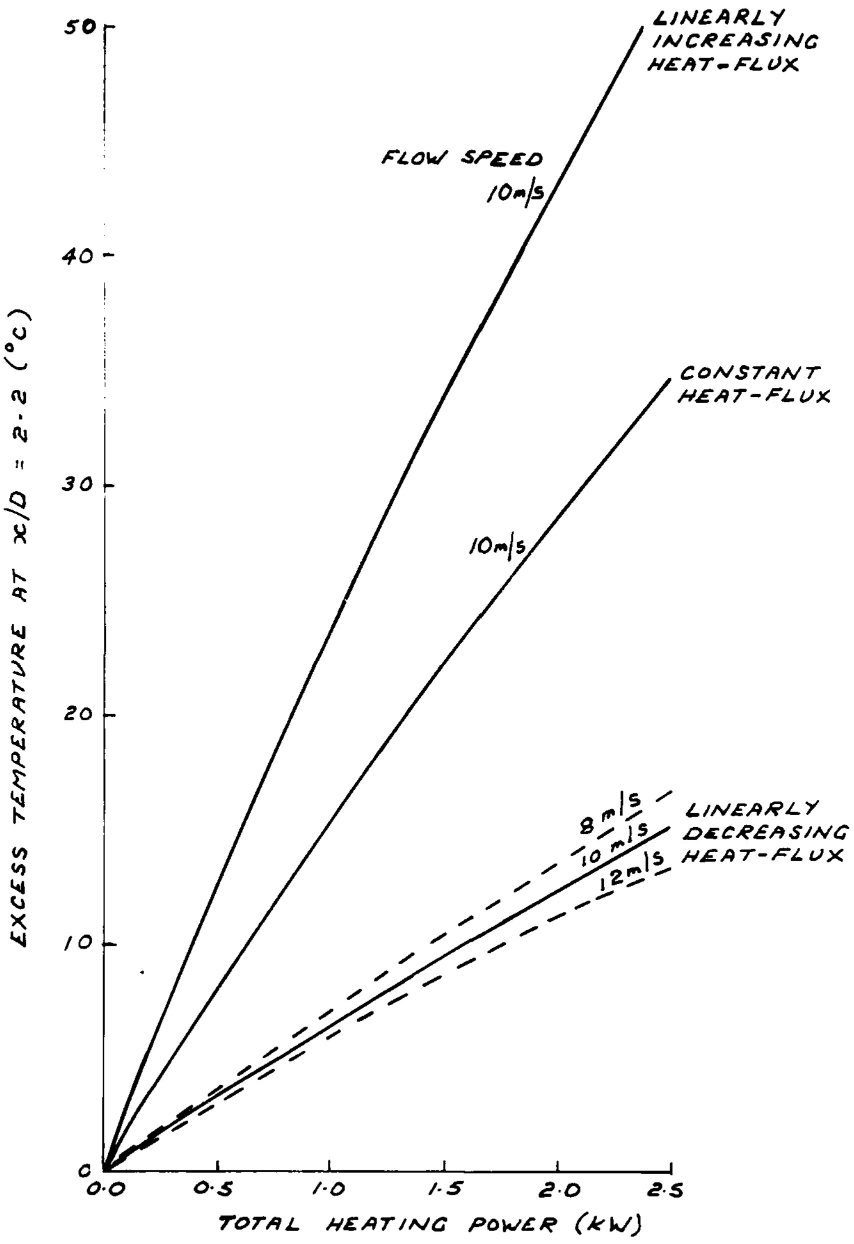

FIG. 6. THEORETICAL VARIATION OF SURFACE TEMPERATURE AT x/D = 2·2 WITH DIFFERENT HEAT-FLUX PROFILES

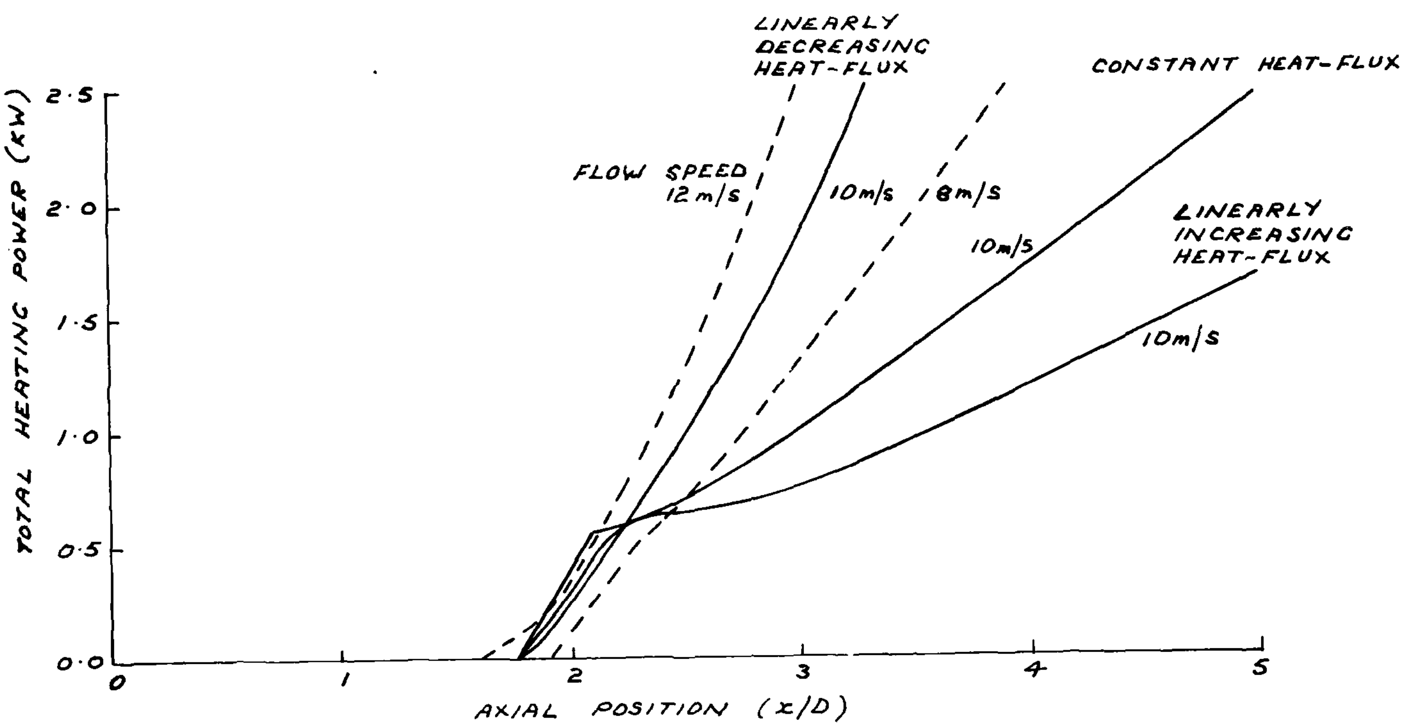

FIG. 7. EFFECT OF DIFFERENT HEAT-FLUX PROFILES ON PREDICTED TRANSITION LOCATION

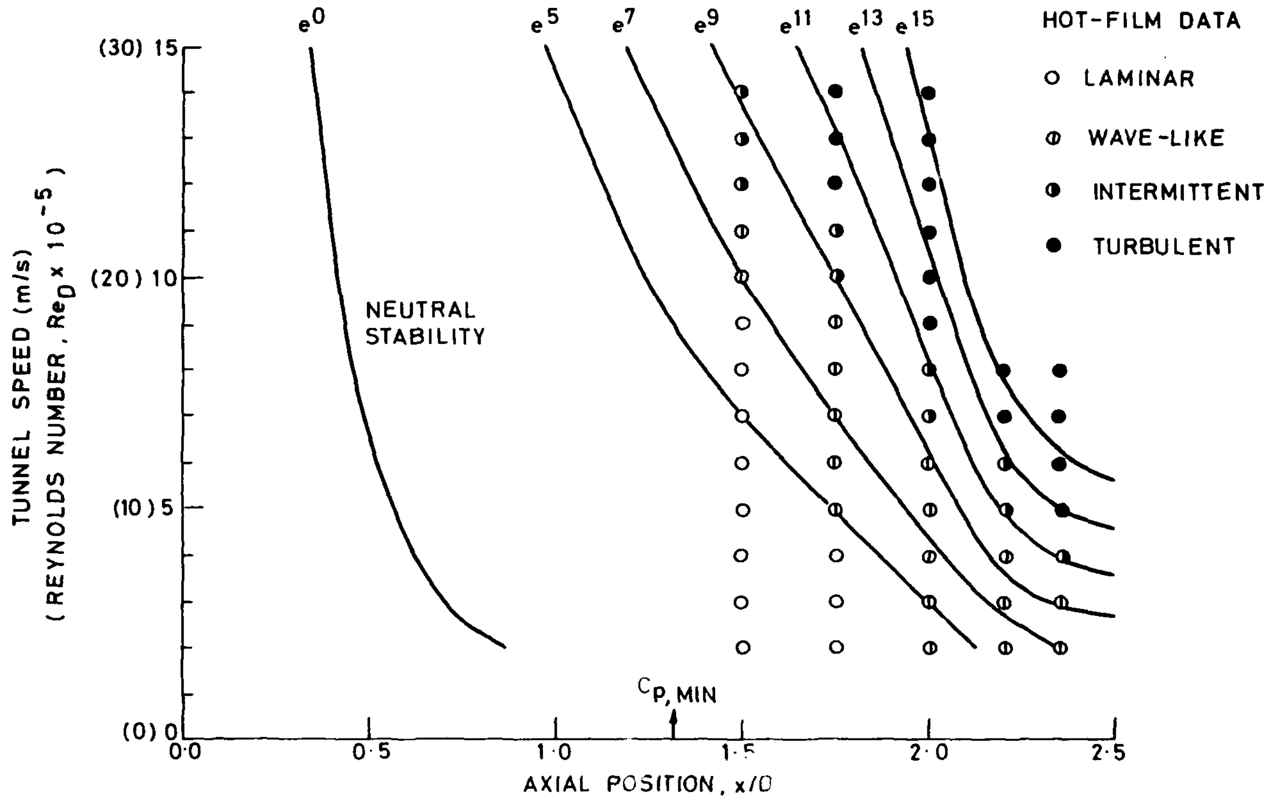

FIG. 8 COMPARISON OF MEASURED FLOW REGIMES WITH AMPLIFICATION FACTOR, UNHEATED BODY

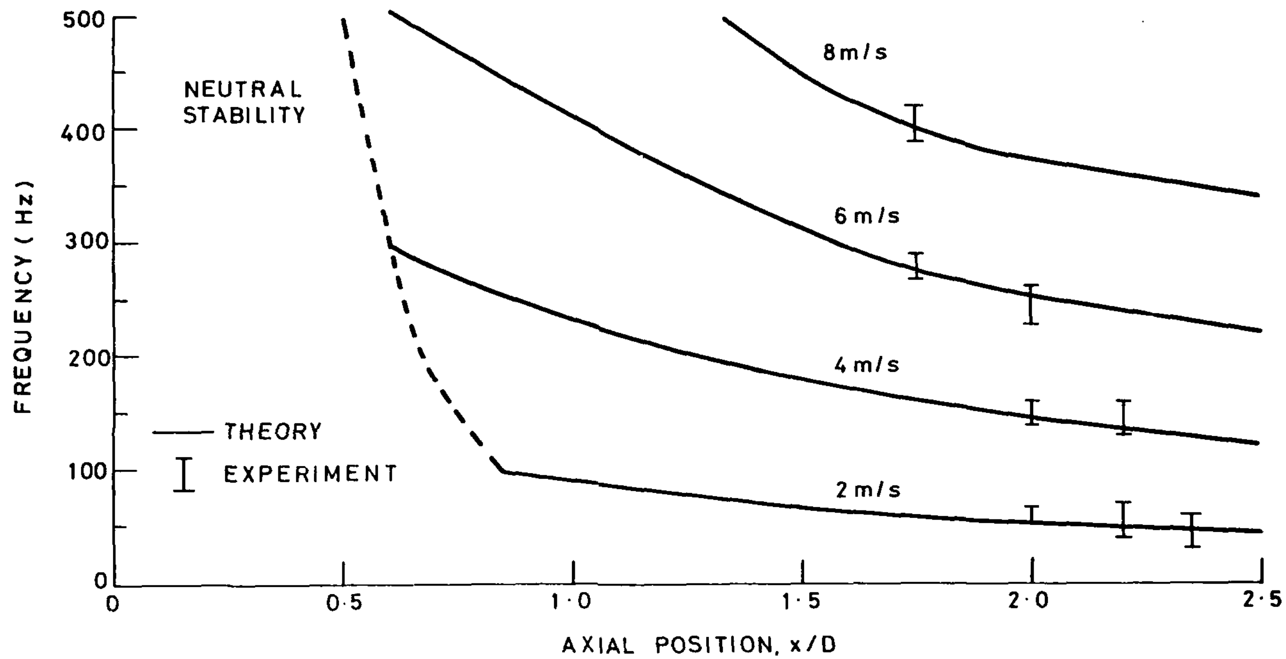

FIG. 9 VARIATION OF SPECTRAL PEAK FREQUENCY WITH AXIAL POSITION (UNHEATED BODY), THEORY AND EXPERIMENT

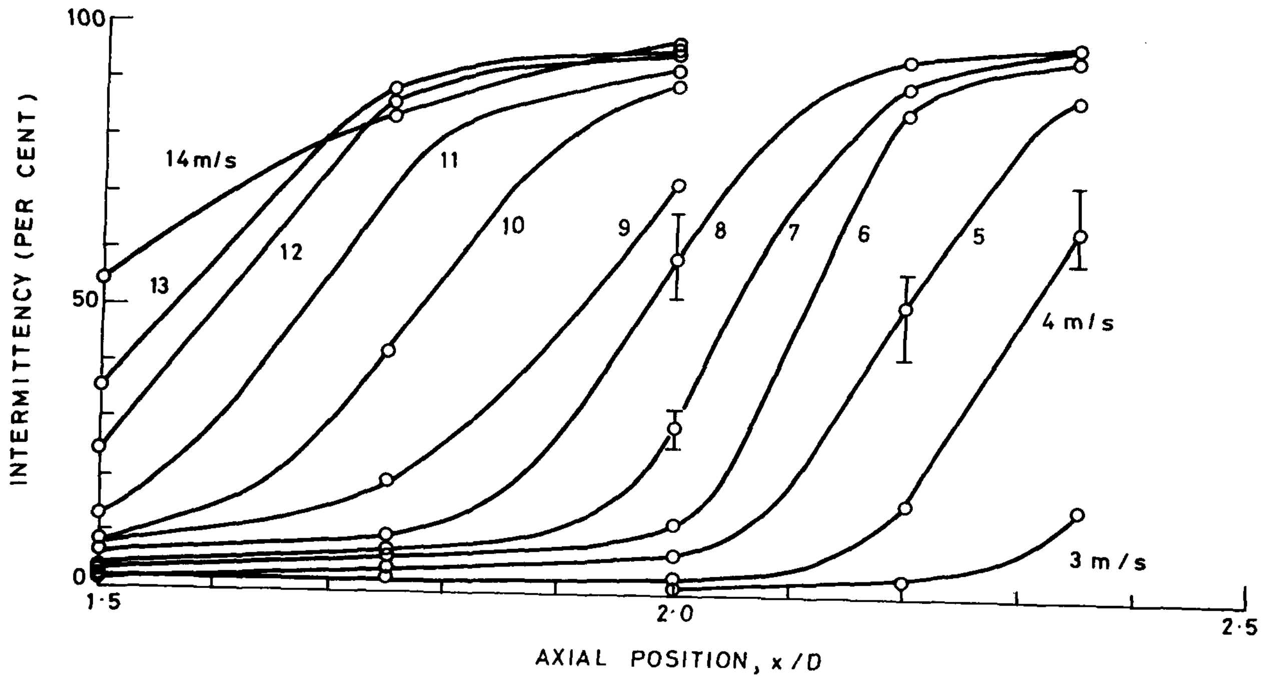

FIG. 10 VARIATION OF INTERMITTENCY WITH AXIAL POSITION, UNHEATED BODY BEFORE FILTERING

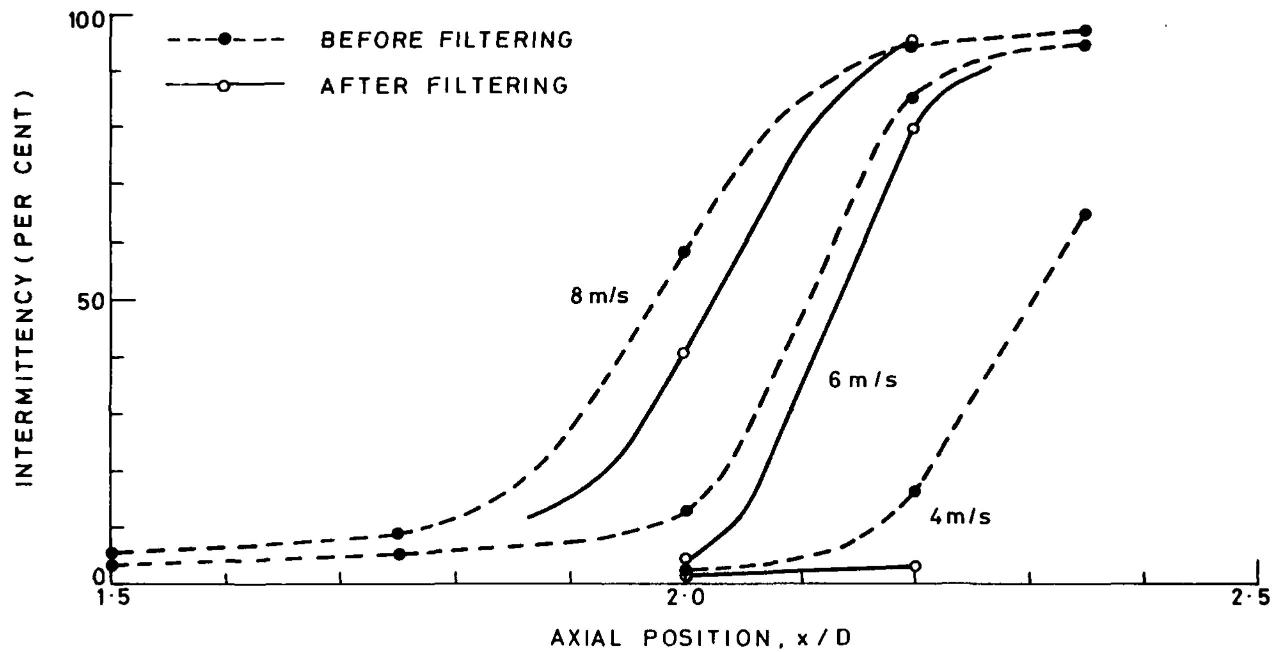

FIG. 11 EFFECT OF FILTERING THE TUNNEL WATER ON INTERMITTENCY, UNHEATED BODY EXPERIMENT

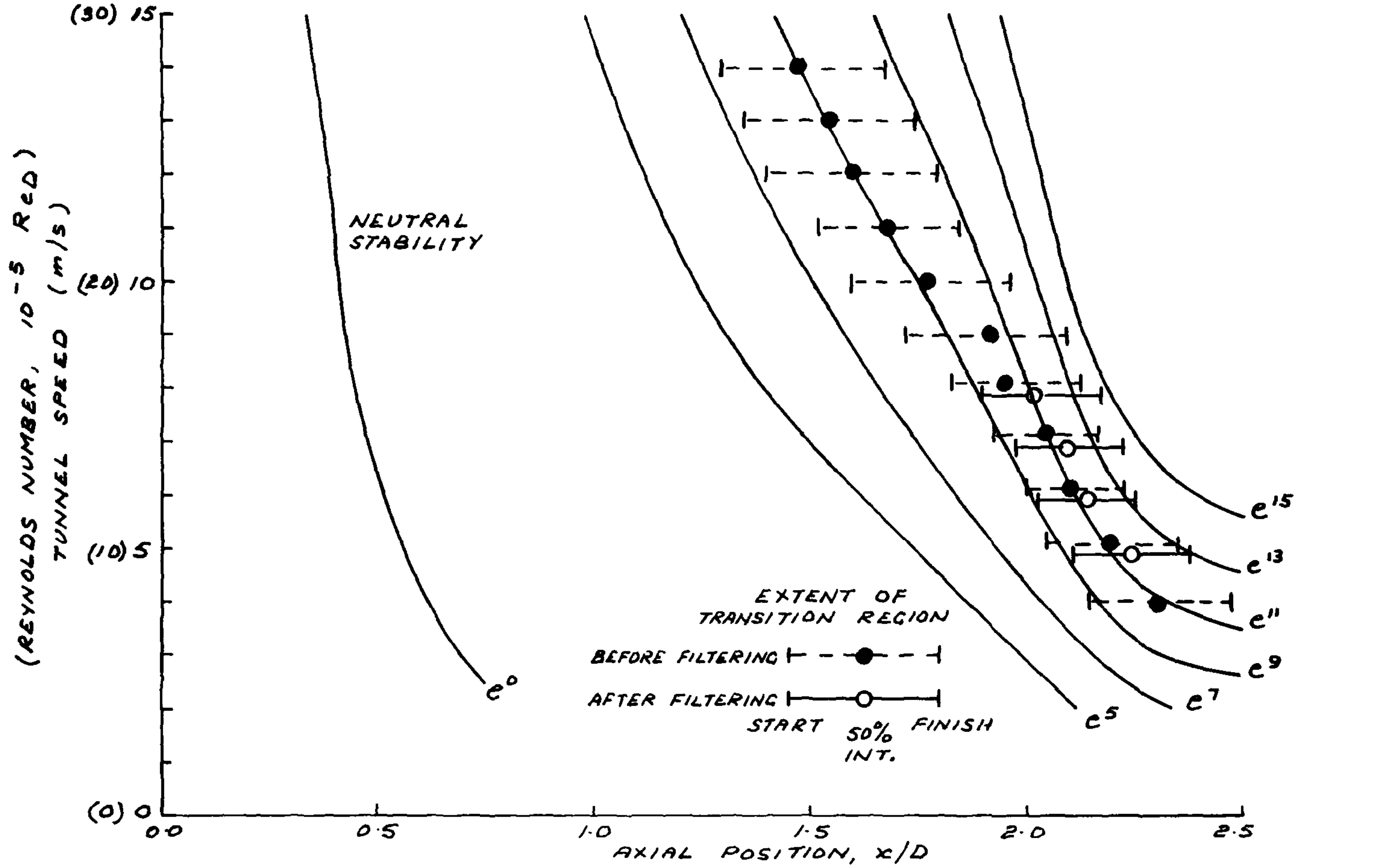

FIG. 12. EXTENT OF MEASURED TRANSITION LOCATIONS AND COMPARISON WITH AMPLIFICATION FACTOR (UNHEATED BODY)

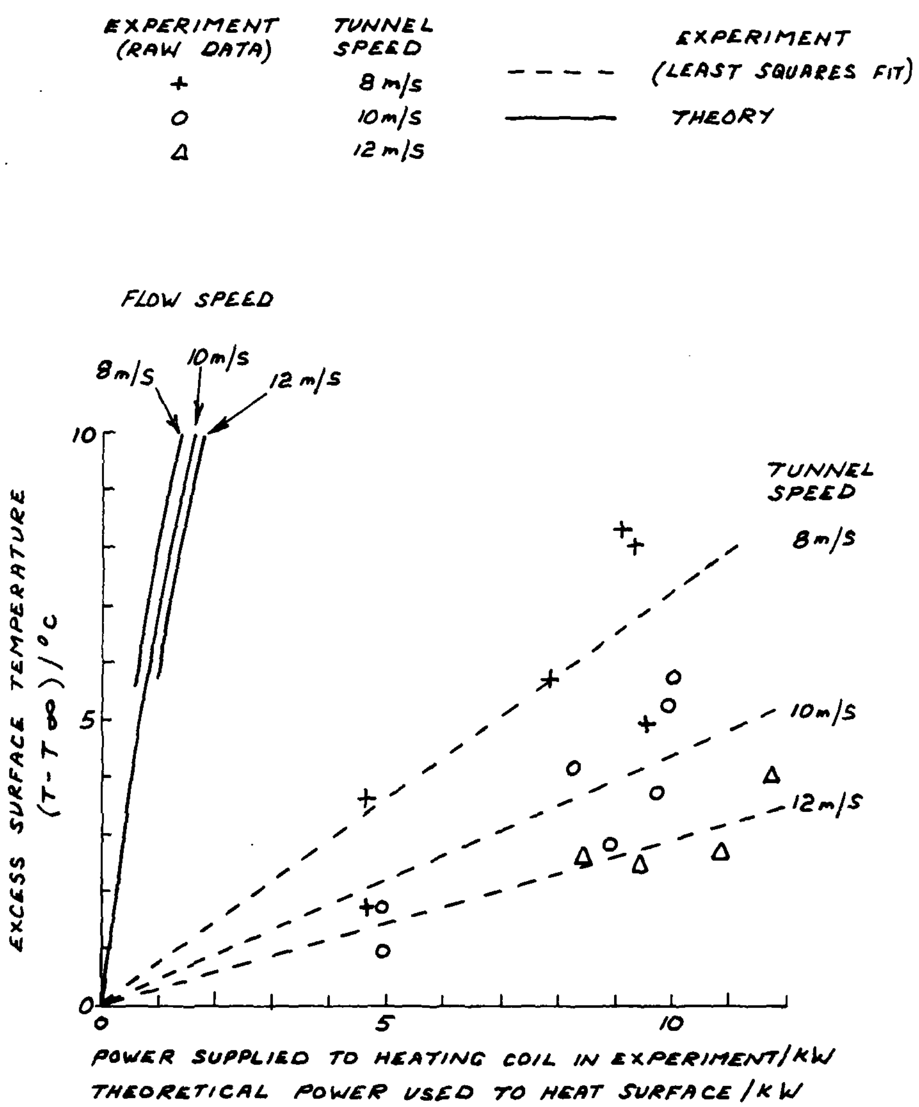

FIG. 13. CORRELATION OF THEORETICAL AND EXPERIMENTAL POWER INPUTS WITH SURFACE TEMPERATURE AT x/D = 2·2

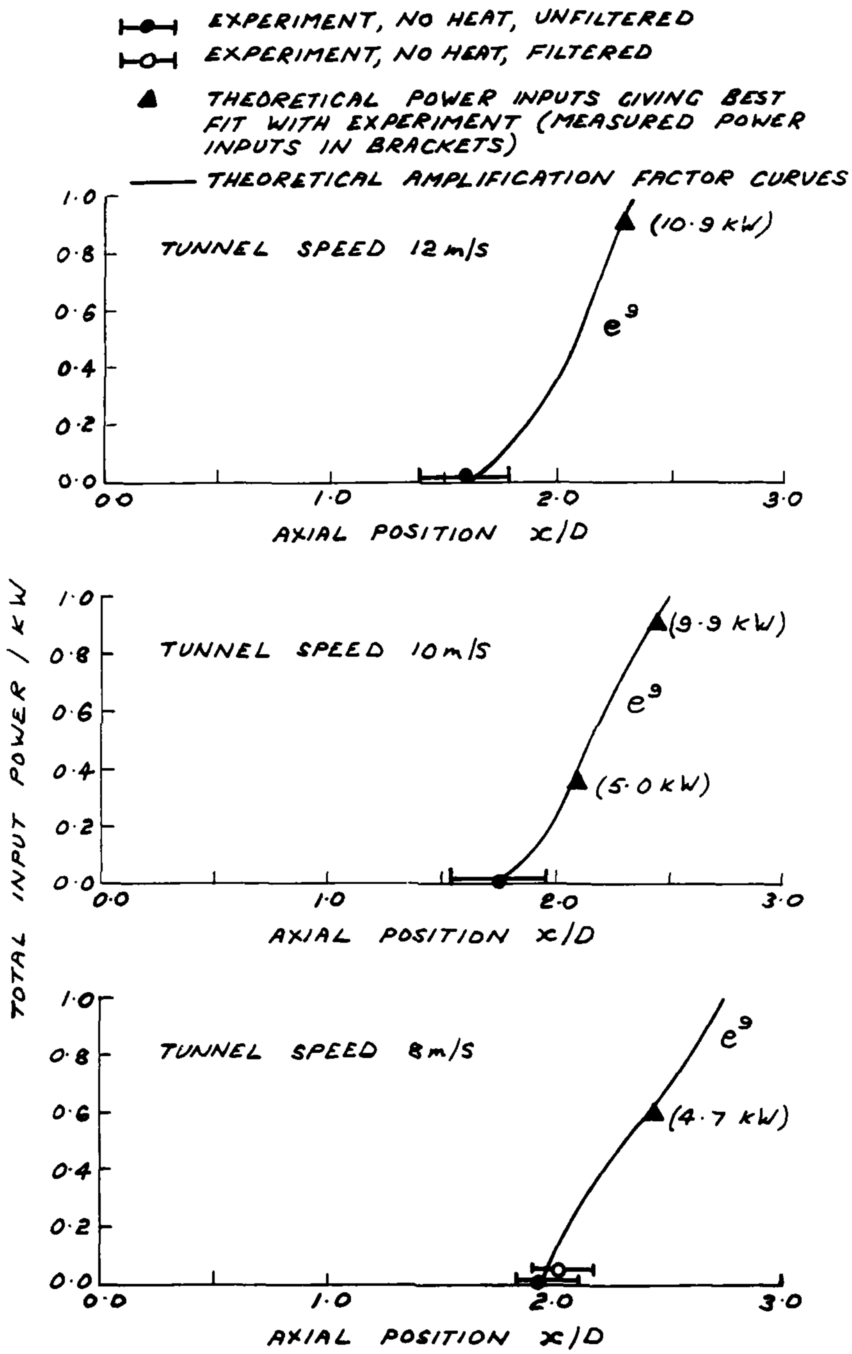

FIG. 14. EFFECT OF SURFACE HEATING ON TRANSITION LOCATION (THEORY AND EXPERIMENT)

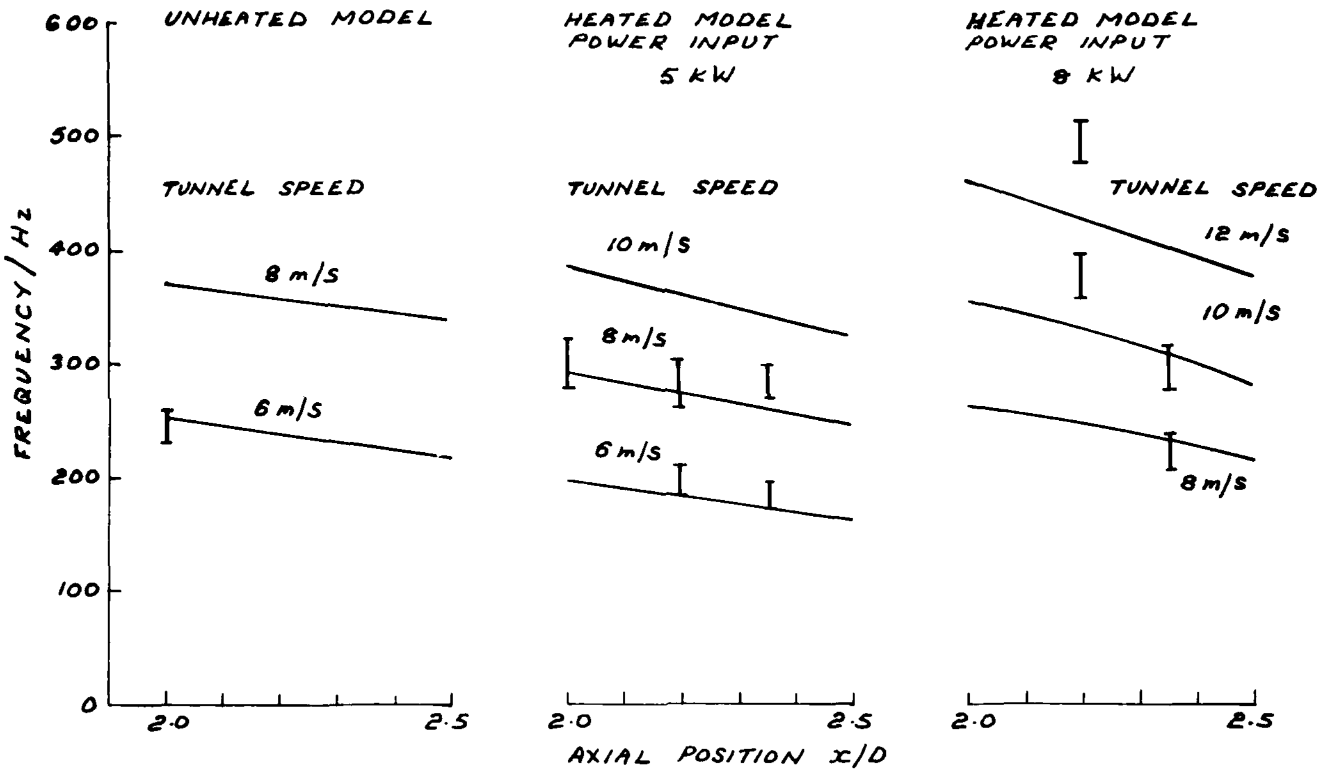

FIG. 15. EFFECT OF SURFACE HEATING ON SPECTRAL PEAK FREQUENCIES (THEORY & EXPMT.)

Distribution

Copy Numbers

1	ARE/DD(U)
2	DES Washington
3	CS (R) 2e Navy
4	ARE/UT
5	ARE/UTW
6	ARE/UDU
7	ARE/UH
8	ARE/UHR
9-36	DRIC
37	RAE Farnborough Library
38-39	ARE Portland Library
40-41	ARE Portsdown Library
42-55	ARE Haslar Library
	DSc (Sea) Abstract only

REPORT DOCUMENTATION PAGE DRIC Reference number (if known)

Overall security classification of sheet UNLIMITED

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the field concerned must be marked to indicate the classification, eg (R), (C) or (S).

Originator's Reference/Report No	Month	Year
ARE TR88503	JULY	1990

Originator's Name and Location
ADMIRALTY RESEARCH ESTABLISHMENT
HASLAR GOSPORT HAMPSHIRE PO12 2AG

Monitoring Agency Name and Location

Title
TRANSITION CONTROL VIA BOUNDARY LAYER HEATING

Report Security Classification	Title Classification (U, R, C or S)
UNLIMITED	U

Foreign Language Title (In the case of translations)

Conference Details

Agency Reference	Contract Number and Period
Project Number	**Other References**

Authors	Pagination and Ref
D J ATKINS S J PEARCE	

Abstract
This Report describes a theoretical method, based on linear stability theory, for predicting flow transition on axisymmetric heated underwater bodies, and a simple experiment using a four-to-one ellipsoidal nose in the 30 inch Water Tunnel at ARE (Teddington). The experiment showed that filtering the tunnel water and vibration of the model have an effect on transition.

Abstract Classification (U, R, C or S)
U

Descriptors
AXISYMMETRIC BODIES BOUNDARY LAYER CONTROL BOUNDARY LAYER TRANSITION
BOUNDARY LAYERS CONVECTIVE HEAT TRANSFER DRAG REDUCTION
FLOW MEASUREMENT

Distribution Statement (Enter any limitations on the distribution of the document)
UNLIMITED