(Reprinted from Nature, Vol. 263, No. 5574, pp. 223–226, September 16, 1976)

Wave power availability in the NE Atlantic

FOLLOWING Salter's[1] proposals for the extraction of energy from sea waves, we are working on the prediction of wave power output from devices situated at favourable coastal sites around the UK. While it is hoped that adequate spectral data from sites closer inshore will become available within the next year or so, the best present data for the North-east Atlantic are from O.W.S. India[2]. We describe here the power available and, on simplified assumptions, the amount that might be extracted by ducks of various diameters. (The Salter 'duck' is a rocking cam-shaped device which is designed to give a high efficiency of energy extraction over a wide frequency band[3].) Confirmation of the validity of the important assumption of additivity of power outputs from wave components of different periods is provided in a separate paper[4].

The power, P, in a sinusoidal wave train in deep water is kTH_{rms}^2 per unit width of wave front, where H_{rms} is the root mean square displacement (that is, the standard deviation) of the water surface, T is the wave period and $k = \rho g^2/4\pi \simeq 7.82$ kW m^{-3} s^{-1}. Thus for a mixed wave train of spectrum dS ($H_{rms}^2 = \int dS$), on linear theory

$$P = k\int T dS = kT_e H_{rms}^2$$

where T_e is called the energy period.

The seasonal joint distributions of T_e and H_{rms} at O.W.S. India are shown in Fig. 1, with contours of P. They are calculated from Hoffman's set of 307 spectra[2] which were selected from a random sample of just over a thousand 10–15 min wave records, taken over the period 1954–67; we weighted each spectrum to restore the correct frequency of occurrence of each band of windspeed in each season. The overall average power is 91 kW m^{-1}.

The predictions given here are for ducks operating with a simple power output limit and (as in the laboratory) relative to a fixed axis. More realistic physical limits on the torque and angular displacement are important for the estimation of the most economic size and characteristics for full-scale ducks, but should not much affect the range of predicted outputs. The related problems of backbone (axis) movement and the directional wave spectrum are more serious; accurate predictions must await laboratory experiments using a less constrained mounting and data on directional spectra at likely wave power sites.

Figure 2 shows the distribution of power by frequency. (For clarity, autumn and spring are omitted; the former would be close to, the latter rather below, the whole year histogram.) Superimposed are efficiency curves for ducks of diameter d = 6, 10 and 16 m, scaled up from the experimental curve (for d = 10 cm) of Salter, Jeffrey and Taylor[3]. This curve is the result of attempts to optimise performance at low frequencies, so as to minimise the size of duck required for a given sea. The falling off of efficiency at low frequencies is not unexpected, since it cor-

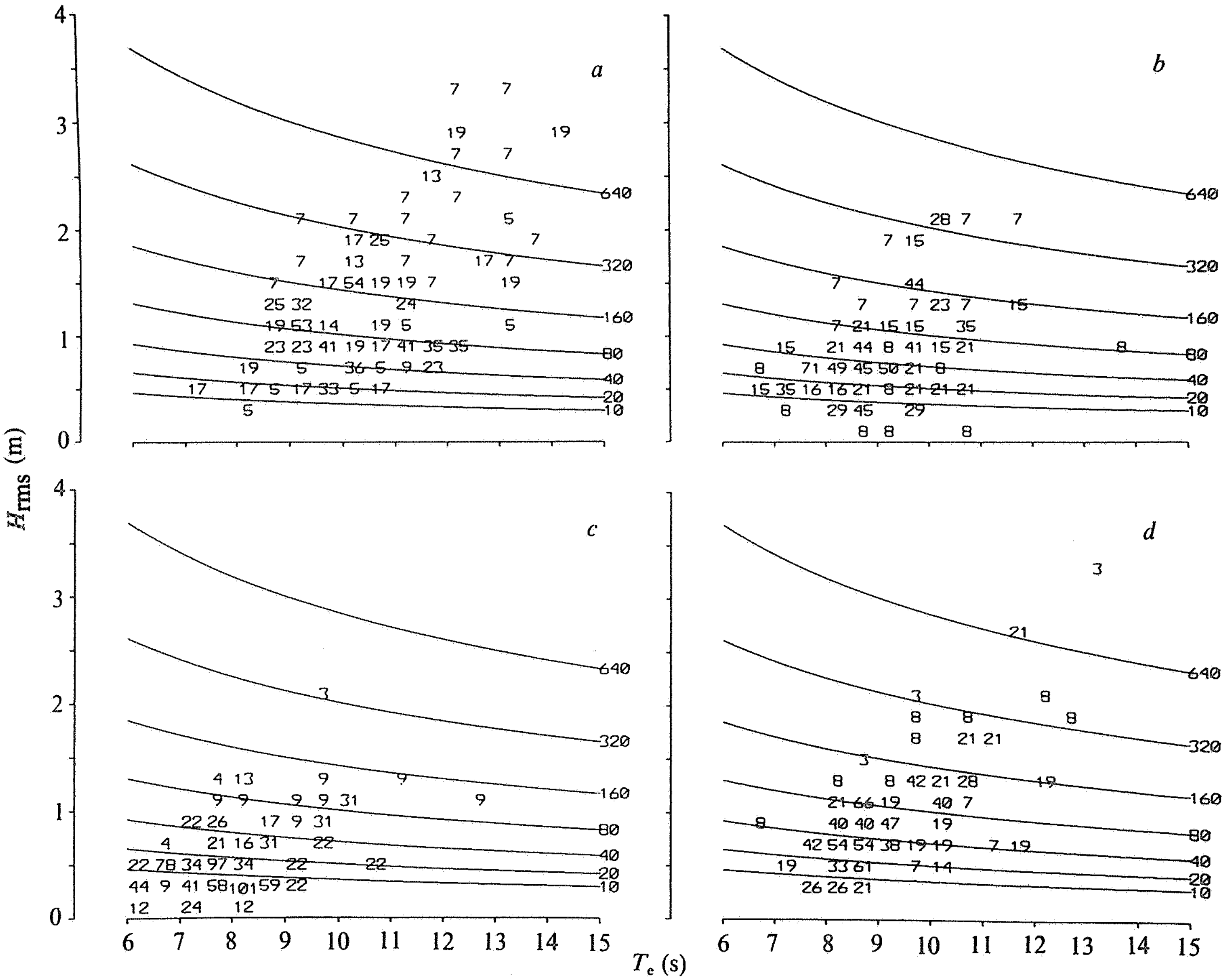

Fig. 1 Frequency of occurrence at O.W.S. India in ‰ of the possible combinations of T_e and H_{rms}, with contours of P in kW m^{-1}. *a*, Winter (Dec-Feb); *b*, spring (Mar-May); *c*, summer (Jun-Aug); *d*, autumn (Sep-Nov).

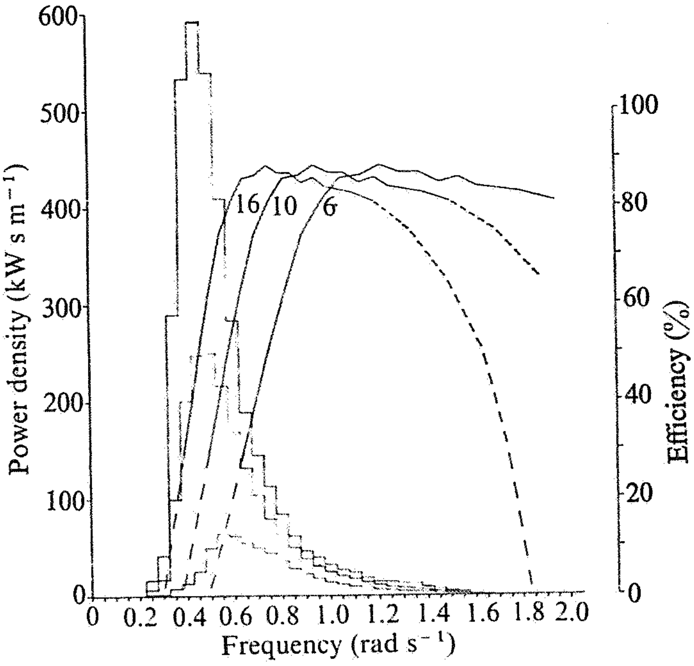

Fig. 2 Distribution of power by frequency for the whole year (middle histogram), winter (top) and summer (bottom); together with predicted efficiency curves for ducks of 6, 10 and 16 m diameter (dashed lines indicate extrapolation outside experimental range).

responds quite closely to the proportion of energy travelling in the water layer above depth d ($= 1 - \exp\{-2d\omega^2/g\}$).

The average output for a particular duck size and season, if no power limits are imposed, can then be found simply by multiplying the appropriate two curves in Fig. 2 and integrating. This is the power transferred from sea to duck; the conversion to electricity and transmission to a distant load-centre in a hydrodynamically underprivileged area, such as South-east England, can be done with presently available technology with an efficiency of $\sim 60\%$. To investigate the variability of power levels, it is of course necessary to refer to the individual spectra. The proportion of time for which power outputs might exceed any given level is shown in Fig. 3, with the total power available for comparison.

We have investigated the effect on power output calculations of replacing the real sea spectra by two-parameter (H_{rms} and T_{e}) spectra of standard shape, the shape chosen being that of the Pierson–Moskowitz spectrum[5]

$$\int_0^{\omega} \mathrm{d}S = H_{\mathrm{rms}}{}^2 \exp\{-b(\omega T_{\mathrm{e}})^{-4}\}$$

where $b \simeq 1{,}052$ (dimensionless).

This is not only convenient for present computational purposes, but should also greatly facilitate predictions of the effects of physical and torque overloads and the directionality of real seas. This replacement has little effect on the distributions of power input (see Fig. 3, dashed lines), though estimates for individual spectra have s.e. 4.55%. The largest effects on the predicted average output over the range of diameters 6–18 m are -0.5 kW m^{-1} (for $d = 6$ m in the summer) and $+1.5$ kW m^{-1} (for $d = 12$ m in the winter) which may be attributed to real spectra being respectively broader in calm, and narrower in rough conditions than the standard spectra. We conclude that, while further checks are advisable, such standard spectra appear sufficiently accurate for our present approximate predictive purposes. (When directional data become available we intend to extend this investigation to see whether the addition of one further parameter to allow for directional spread yields a similarly adequate description for predicting behaviour of free-floating duck strings in directionally mixed seas.)

Directional problems apart, there are three limitations on output which we have not considered so far: physical (swept-volume), torque and transmission limits. Because of the high costs of transmission lines[6] the last of these is probably the most critical, though swept-volume overload limits will be important for ducks of diameter < 10 m.

The mean power available when simple power output limits

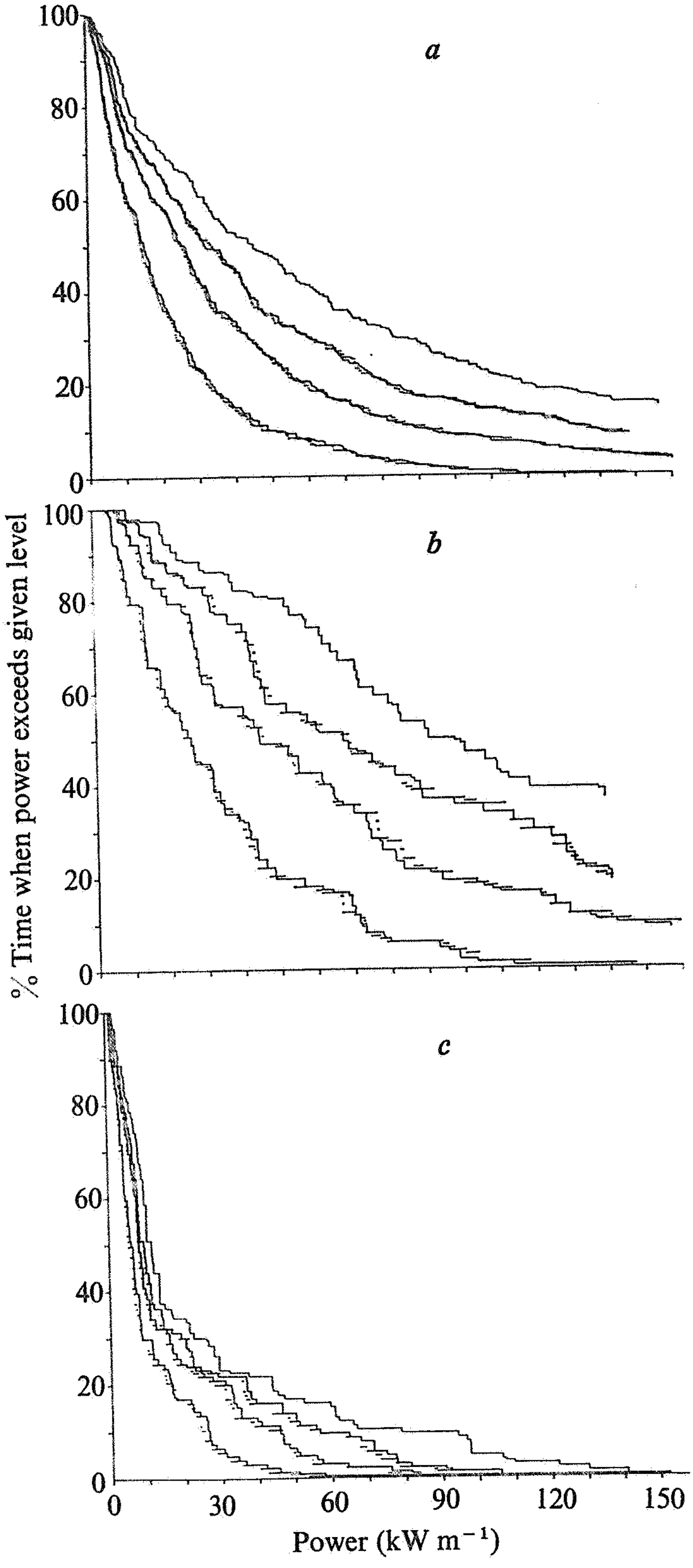

Fig. 3 The proportion of time for which each power level is exceeded for: *a*, whole year; *b*, winter and *c*, summer. In each case the top curve refers to the total power available; the other solid curves, in descending order, to predicted power output from ducks of 16, 10 and 6 m diameter. The dashed curves (verticals omitted) show the effect, for each of these three cases, of replacing real spectral data by two-parameter standard spectra (see text).

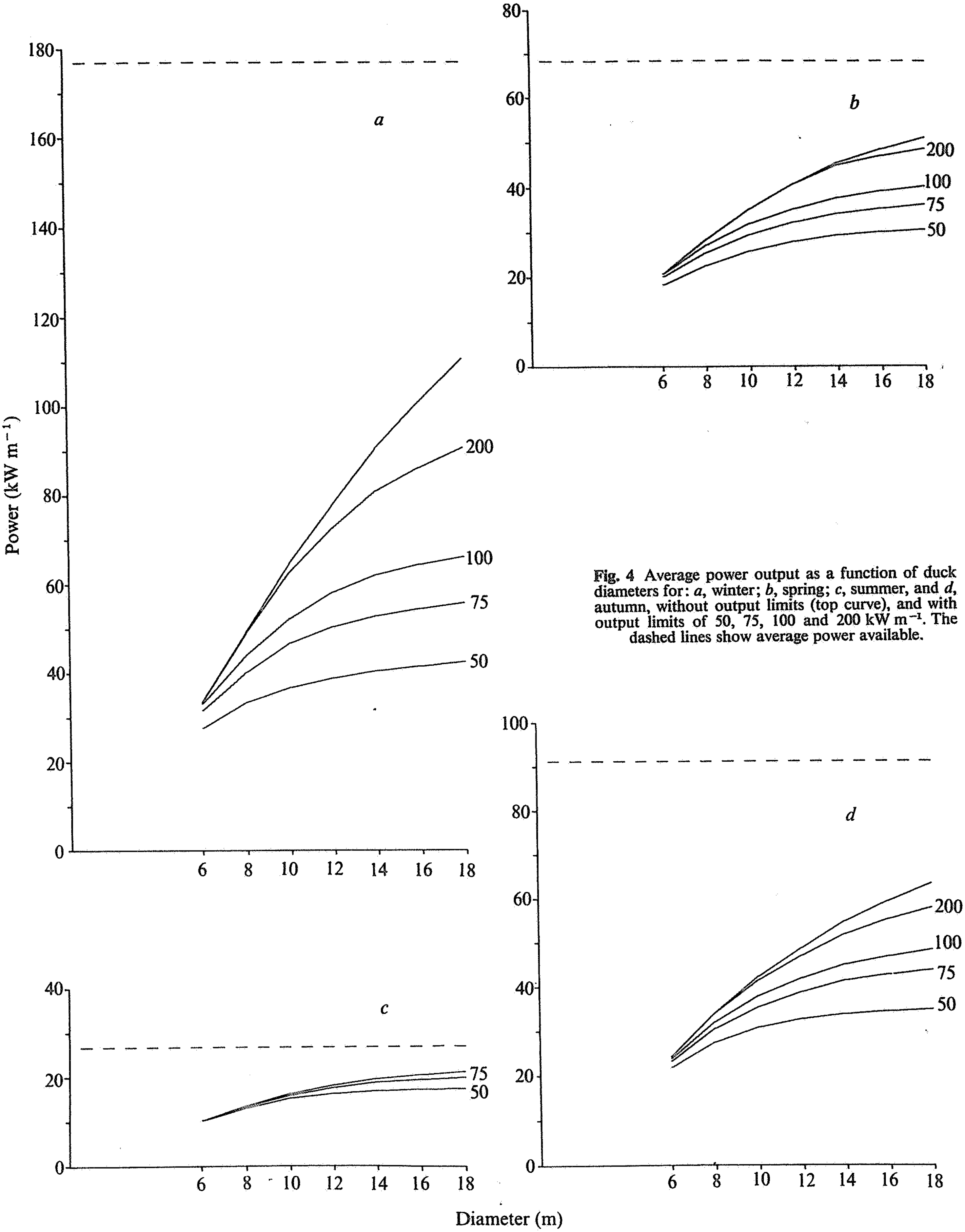

Fig. 4 Average power output as a function of duck diameters for: *a*, winter; *b*, spring; *c*, summer, and *d*, autumn, without output limits (top curve), and with output limits of 50, 75, 100 and 200 kW m^{-1}. The dashed lines show average power available.

are imposed is easily calculable as the area under the relevant curve of Fig. 3 to the left of the desired limit. This is plotted as a function of duck diameter in Fig. 4. As might be expected, the effect of such limits is more severe in winter. Even then the lowest (50 kW m^{-1}) limit considered gives a substantially higher load factor (~ 80% for $d \geq 12$ m), a further reason for preferring a relatively low rated transmission line, rather than going for maximum average output.

This work was supported by the SRC and the Department of Industry.

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Received March 11; accepted July 28, 1976.

1 Salter, S. H., *Nature*, 249, 720–724 (1974).
2 Hoffman, D., *Sampling of Ocean Wave Spectra at North Atlantic Station India* (SNAME, New York).
3 Salter, S. H., Jeffrey, D. C., and Taylor, J. R. M., *The Naval Architect*, 1, 21–24 (1976).
4 Mollison, D., Salter, S. H., and Taylor, J. R. M., *Edinburgh Wave Power Project Report No. 32* (1976).
5 Pierson, W. J., and Moskowitz, L., *J. geophys. Res.*, 69, 5181–5190 (1964).
6 Whittington, H. W., *Edinburgh Wave Power Project Report No. 33* (1976).

Printed in Great Britain by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset