

DEVELOPMENT OF THE ANACONDA ALL-RUBBER WEC

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Summary

The ANACONDA all-rubber WEC operates in a completely new way, capturing water waves as “bulge waves” in a giant water-filled rubber tube, aligned head-to-sea. It offers new possibilities for low capital and operational costs, based on the unique durability of rubber, and the single moving part (a conventional medium-head unidirectional water turbine). See www.bulgewave.com. Avon Fabrications LLP have recently taken an exclusive license to manufacture the device, which has been selected by the Carbon Trust for the Marine Energy Accelerator programme. Initial model tests show good capture width and wide bandwidth. The economics of the device depend on the price of the rubber, per unit of elastic energy stored in it over its lifetime, in p/kWh. This must be less than the selling price of the electricity produced over the device lifetime, again measured in p/kWh. On this basis the economics of ANACONDA are very promising.

1. Principle of Operation

It has been known for many years (see e.g. Lighthill, 1978, section 2.2) that bulge waves can propagate along a fluid-filled elastic tube – they are like sound waves, except that the elasticity of the tube walls increases the effective compressibility of the fluid, slowing the wave. The best-known example is physiological: the pressure pulse from the heart propagates relatively slowly along the arteries (much more slowly than the speed of sound in blood), because of the elasticity of the artery wall.

ANACONDA is a giant water-filled rubber tube, in which the natural propagation speed of bulge waves is matched to the speed of the water waves to be captured. There is then a resonant amplification of the bulge wave, and the water wave energy is captured as a bulge wave. There are several different ways of viewing the mechanism by which water waves excite bulge waves - which, critically, is equally effective whether the device is fixed on the seabed in shallow water, or floating just under the surface and bending to follow the wave profile.

1. If the tube were infinitely flexible like a very thin rubber balloon, the motion of the water inside would be the same as if the tube were not present. The tube would be flattened into an elliptical cross-section under wave troughs, and stretched into an elliptical cross-section under wave crests. Because its width would be the same everywhere, its cross-sectional area would reduce under wave troughs, and increase under wave crests. This suggests that bulge waves will be excited in the tube, whether it is lying on the seabed in shallow water, or floating just under the surface and bending to follow the wave profile.

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2. If the tube were infinitely stiff like a rigid pipe, and were lying on the seabed in shallow water, the water inside would be stationary, and so have constant pressure. The pressure outside would decrease under wave troughs, and increase under wave crests, so there would be a fluctuating pressure difference across the walls. This would clearly excite bulge waves in the tube, were it not rigid. If the tube were flexible enough to float just under the water surface and bend to follow the wave profile, but still not change its cross-sectional area, then again the axial velocity in it would be zero (or constant along it, by conservation of fluid volume, as in a pipe). The internal pressure would therefore rise hydrostatically in wave troughs and fall in wave crests. Thus although the external pressure was nearly constant (by the free-surface boundary condition on the water wave), there would again be a fluctuating pressure difference across the walls.

3. If the tube were lying on the seabed and propagating bulge waves of the same length and speed as the water waves, then by appropriate choice of the phase difference between them, we could arrange that the radial velocity of the tube wall (due to the bulging) was outwards when the external pressure was low (i.e. under a wave trough) and inwards when it was high (i.e. under a wave crest). The external water would then always be doing work on the tube, so wave energy would be extracted. However, if the tube is floating just under the water surface and bending to follow the wave profile, then the external pressure will be nearly constant, as already noted in (2). It is shown in the Appendix that the work done by the wave on the tube is now in *lifting* the tube, which bulges to weigh more when it is being lifted up on the front of a wave, than when it is going down on the back. So again energy is extracted from the wave.

There are also several different ways of viewing the resonance which occurs when the speed of the water wave matches the natural propagation speed of bulge waves in the tube. If the water wave is travelling at speed C , say, then its pressure excitation on the tube (e.g. the external pressure on a device on the seabed, as in (2) above) produces a bulge wave of the same speed C . But a bulge wave can propagate at its natural propagation speed C^* , say, without the need for any pressure excitation. Hence the pressure excitation from the water wave merely “makes up the difference” needed in the excitation, that arises because C is not equal to C^* . If C is close to C^* , this difference is small, so a small excitation from the water wave produces a large bulge wave in the tube. In Farley and Rainey (2006b), the final steady-state amplitude of the bulge wave is calculated, if the device were infinitely long, using the classical device of a frame of reference moving at the wave speed. The ratio of the pressures in the bulge and water waves is shown to be $(1 - (C/C^*)^2)^{-1}$, so the bulge wave amplitude is infinite on this analysis when $C = C^*$. This is exactly analogous to the resonance in a simple pendulum, excited by a lateral motion of its pivot, with an angular frequency Ω close to the pendulum’s natural angular frequency Ω^* . Again, the pendulum needs no excitation to oscillate at its natural frequency, so the external force merely “makes up the difference” which arises because Ω is not equal to Ω^* , and there is a dynamic amplification by a factor $(1 - (\Omega/\Omega^*)^2)^{-1}$.

An alternative analysis is given in Farley and Rainey (2006c, 2006d), using the conventional fixed frame of reference and the bulge-wave differential equation (see section 2). This confirms the earlier result and also allows the effect of hysteresis in the rubber to be included, and the growth of the bulge wave to be considered, starting from zero amplitude at the upwave end of the device. At resonance, it grows linearly down the device, with the bulge riding on the front face of the wave as predicted in (3) above, and the pressures reaching 3 times that in the water wave, after 1 wavelength. The performance of a device 150m long and 7m diameter is calculated, with various levels of hysteresis loss in the rubber. Figure 1 below is the computed capture width (i.e. bulge-wave power/{water wave power per unit crest length})

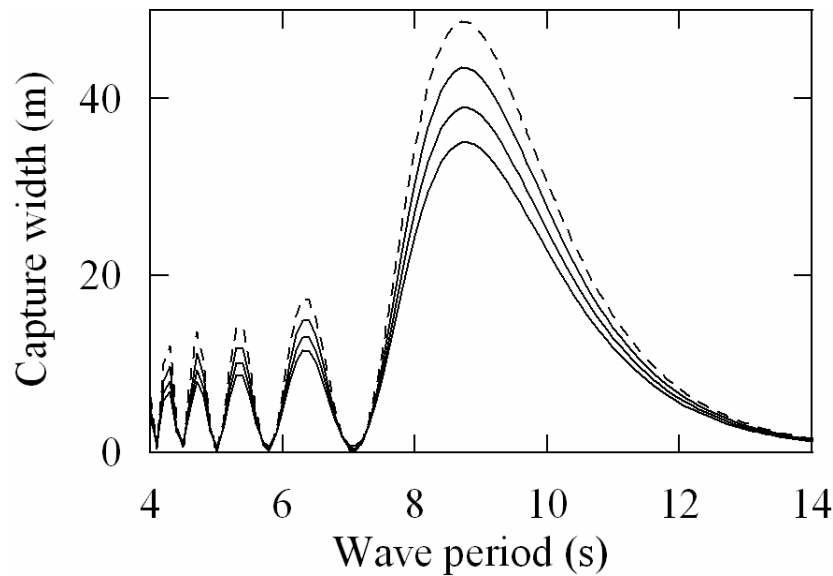


Figure 1. The power of the bulge wave in a 150m long 7m diameter ANACONDA with a distensibility such that the free bulge wave speed matches the speed of water waves of period 10s. The dashed line assumes zero losses in the rubber. Continuous lines assume hysteresis losses of 10%, 20% and 30% of the energy stored and recovered in each cycle.

This suggests a power output, before conversion losses, in the region of 1MW, at a site with an annual average incident wave power is 50kW/m.

2. Capture widths measured experimentally

The above conclusions have been confirmed experimentally. Details of our experiments are given in Chaplin et al (2007), which we summarise here.

A model tube, about 2.5m long and 78mm in diameter, was made from rubber sheet 0.15mm thick. Its Young's modulus E and loss coefficient β in the stress/strain relation $\sigma = E(\epsilon + \beta\dot{\epsilon})$ were approximately $E = 1.94$ MPa and $\beta = 0.0059$ s. The tube was installed at an elevation just below still water level on the centre-line of a wave flume 0.42m wide, 18m long, with a still water depth of 0.7m. Figure 2 below shows the model in place, responding to waves coming from the left. In these experiments, the tube was pressurised to an excess head of about 70mm, and then sealed. A transducer recorded the internal pressure at one end. Regular waves could

be generated in the tank with a flap-type wavemaker with active absorption, and those that passed the ANACONDA model were efficiently dissipated in a vertical wedge of firm poly-ether foam from which reflections are less than 3%. Wave gauges recorded water surface elevations ahead and behind the model.

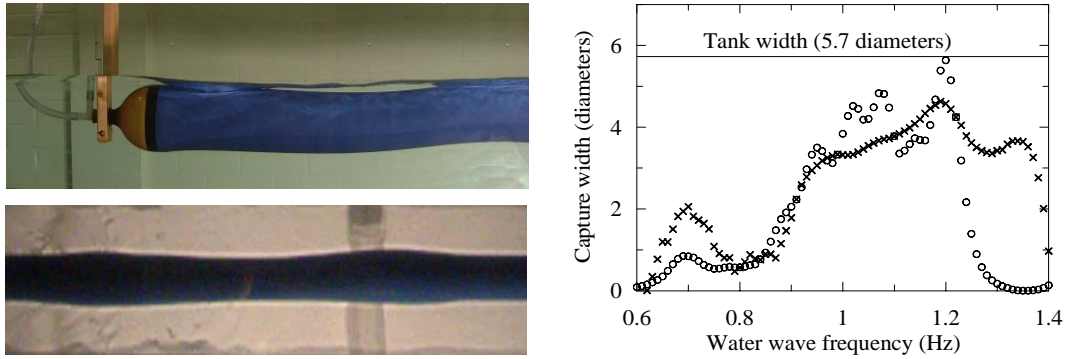


Figure 2. On the left, photographs of the model ANACONDA in waves in a narrow tank. The upper image shows the end of the tube in waves propagating from left to right. The view below is of bulge waves travelling in the same direction, as seen through the glass floor of the tank. On the right are shown capture widths inferred from internal pressure measurements (circles) and from measurements of incident, reflected and transmitted waves (crosses).

Initial estimates of bulge wave speed were made from observations of bulges started by hand, propagating along a water-filled tube lying on a horizontal surface in air. In these conditions the cross section of the tube was inevitably non-circular, but measured speeds were within 10% of the theoretical value for a circular tube of the same area. Theoretically the natural bulge wave speed C^* (in the absence of hysteresis, which has a weak effect on it) is equal to $(\rho D)^{-1/2}$, where D is the distensibility and ρ the water density (Lighthill, 1978, section 2.2). For a circular tube of diameter d and wall thickness δ , the distensibility $D=d/(E\delta)$. In the wave flume, with one end of the model mounted on the actuator, small bulge waves could be launched along the tube in still water by driving one end vertically with a servomechanism, with a step input of very small amplitude. A pressure transducer at the other end clearly recorded the arrival of the resulting bulge wave, and the measurements indicated a speed of 1.36m/s. The theoretical speed was $(\rho D)^{-1/2} = 1.93\text{m/s}$. It seems reasonable to link the difference in this case to the presence of the surrounding water.

Figure 2 gives the results obtained from the experiments, as a function of the ratio of the tube length L to the water wavelength λ . Two estimates of capture width are given.. Those plotted with crosses were calculated from measurements of incident, reflected and transmitted waves. Those plotted with open circles represent the energy losses in the rubber over the entire length of the tube, calculated from the damped bulge wave equation

$$\frac{\partial^2 p_b}{\partial t^2} - \beta \frac{\partial^3 p_b}{\partial t^3} = \frac{1}{\rho D} \frac{\partial^2}{\partial x^2} (p_b + p_w)$$

(Farley & Rainey, 2006d), where $p_b(x,t) + p_w(x,t)$ is the pressure inside the tube: p_w is the external pressure, and p_b the excess internal pressure that is supported by tension in the tube wall. Pressures at all points along the tube were estimated by using this equation with

appropriate closed end boundary conditions, and by matching the pressure at the downwave end of the tube with the measurements. From the resulting hoop stresses it was then possible to calculate hysteresis losses and the associated capture width.

In the results in Figure 2, some peaks can be associated with coincidences of the tube's length L with integer multiples of the water wavelength λ , while the greatest capture width (very close to the entire width of the tank) occurs when the water wave speed C equals the natural bulge wave speed C^* . Overall, the results are very encouraging – even in this narrow tank, ANACONDA has a capture width exceeding 3 diameters, over a wide bandwidth (frequency ratio 1.35:1).

3. Power take-off

The elastic tube in ANACONDA is merely the first stage in the power conversion process, concentrating the wave power into a bulge wave. It is then necessary to convert the bulge wave power into electricity. The oscillatory flow in a bulge wave resembles the air flow in a WEC of the oscillating water column (OWC) type, so the most obvious possibility is to follow OWC practice and use a Wells turbine (or similar), operating in water rather than air. The low conversion efficiencies of these turbines (typically 20%) is well-known, however, and arises because of the very large fluctuations in instantaneous power.

Most modern WEC designs therefore feature a hydraulic power take-off, incorporating hydraulic accumulators to smooth the power flow, allowing unidirectional hydraulic motors with a much higher efficiency to be used. In the case of ANACONDA, the water in the tube can be used as the active fluid. One-way valves in the tail of the device allow the water to pass into high and low pressure accumulators, as shown in Figure 3 below, which illustrates the case of a device on the seabed, where the accumulators can be fixed. A turbine (not shown) then operates in the smoothed flow between the accumulators – the head difference between them is several times the wave height, which is ideal for conventional small-scale hydroelectric turbines, which have conversion efficiencies of about 90%.

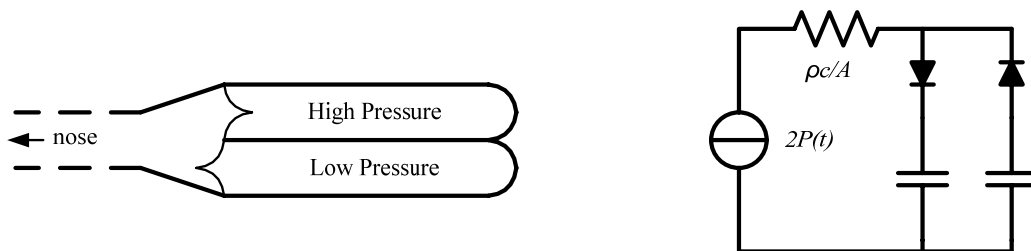


Figure 3. Power take-off scheme for seabed device. A conventional hydroelectric turbine (not shown) operates in the smoothed flow between the accumulators.

The equivalence between one-dimensional waves and electrical circuits is well-known (see e.g. Lighthill, 1978 p.104) – voltage is an analogue of pressure, and current is an analogue of volume flow rate. If the incoming bulge wave has a pressure $P(t)$ at the tail, and the reflected bulge wave has a pressure $R(t)$, then the total pressure $T(t)$ at the tail is $P(t) + R(t)$. If the cross-sectional area of the tube is A , and we assume that the incoming bulge wave is travelling at its free propagation speed c , then the volume flows is (Lighthill, 1978, p.94):

$$P(t)/(\rho c/A) - R(t)/(\rho c/A) = \{2P(t) - (P(t) + R(t))\}/(\rho c/A) = \{2P(t) - T(t)\}/(\rho c/A)$$

Thus the equivalent circuit is as shown in Figure 3 above, where the valves and accumulators are represented by diodes and capacitors. Assuming a sinusoidal incoming bulge wave and large capacitors (accumulators), the power absorption is readily calculated as matter of electrical engineering – it reaches a maximum of 92.3% of the incident bulge-wave power, if the accumulators are set to plus and minus 80% of the peak value of $P(t)$. And it remains over 50%, if they are set between 24% and 146% of it. The reflected wave (which will be re-reflected at the nose, so its power is not lost) is readily obtained too - at 92.3% absorption it is all higher harmonics – the 3rd and 5th have 6.7% and 0.8% of the incident power.

For floating versions of the device, the seabed is not available as a fixed reference. Instead, an additional length of non-distensible tube can be added, as an inertial reference.

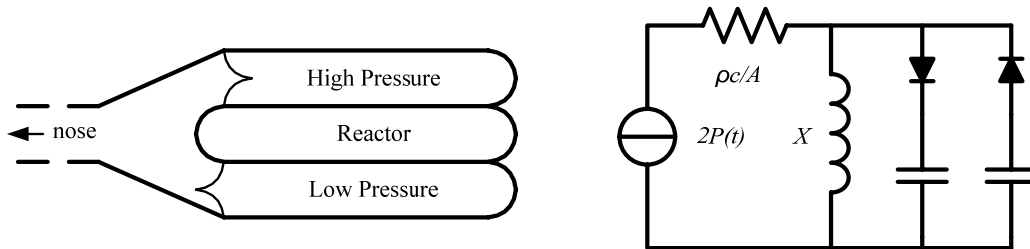


Figure 4. Power take-off scheme for floating device. The position reference is now a reactor mass, which need not be excessively large because the power is already concentrated in the bulge wave.

This modifies the equivalent circuit as shown in Figure 4. (Note that a free end is zero reactance and thus a short circuit.) If the length of this additional tube is $\lambda/2\pi$ (λ = wavelength), then its reactance X will have the same impedance $\rho c/A$ as the main tube. Thus a moderate additional length of tube is sufficient to make a good inertial reference, and give comparable performance to a seabed-mounted device. This is a reflection of the fact that the power is already concentrated, compared with the original water wave.

To maintain the advantages of all-rubber construction, the accumulators and reactor shown in Figure 4 can also be rubber tubes. For the reactor, the rubber can be fibre reinforced like a dracone (or a car tyre), to give the necessary rigidity when pressurised. By contrast the accumulators require maximum distensibility to give the required low entry impedance – ideally the pressure should not rise at all with entry velocity, like its electrical equivalent of a large capacitor. This can be accomplished by reinforcing the outer skin as in the reactors, but then adding an internal gas-filled bladder, as in a hydraulic bladder accumulator. The complete system is then as illustrated in Figure 5 below.

The gas-filled bladders in the two accumulators are shown in dark blue, and can communicate with each other because their height difference is (very conveniently) equal to the required head difference between them. Effectively, the power take-off is operating like a WEC of the “overtopping” type, with high pressure water entering a high-level reservoir, and low-pressure

water leaving from a low-level reservoir. Except that all the pressures are magnified, because they are the pressures in the bulge wave, not the water wave outside. Unlike an “overtopping” WEC, the head difference between the reservoirs is variable, rising to suit the wave conditions. The gas-filled bladders also communicate with two external bladders, which give the necessary pressurisation, and allow for volume fluctuations.

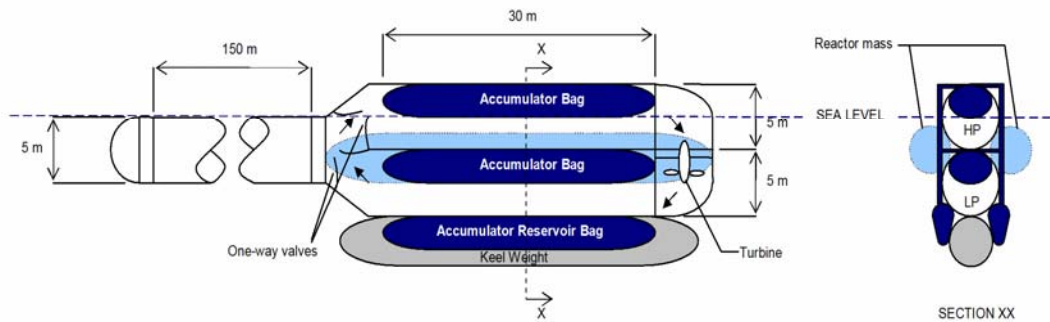


Figure 5. Anaconda complete with power take-off. Air-filled bladders shown dark blue.

3. Economics

The rationale for ANACONDA is the unique durability of rubber, whose attractions as a material for WECs were first highlighted (to the authors’ knowledge) by Prof. Michael French in the 1970s. The hovercraft, with its rubber skirt, is an excellent example of this. See Figure 6 below.



Figure 6. Hovercraft with rubber skirt designed and manufactured by Avon Fabrications LLP.

Despite their harsh treatment and the extremely hostile environment, skirts of this type last many years. This is partly because the fatigue life of rubber is extremely long, as is shown by the example of a car tyre, which can last for 100,000 km = 100,000,000 revolutions = 10^8 cycles, which comfortably exceeds the number of waves encountered by a WEC in 10 years.

The flexibility of rubber also offers unique advantages in handling and safety: ANACONDA is easy to transport and install, because it can be rolled up and carried as deck cargo, and it poses no danger to shipping, even if it breaks free from its moorings.

From the point of view of rubber engineering, the power take-off system in Figure 5 does not dominate the capital costs, because the material used is all inextensible, as in a dracone. It is the main tube which dominates the capital cost, because the rubber in it is required to store energy. In a bulge wave device, the stored elastic energy in the rubber (the dynamic energy, excluding the static component from the pressurisation) in one wavelength of tube (approximately equal to the length of ANACONDA) equals the electrical power output over one period. Thus the elastic energy stored in the whole device over its lifetime is approximately equal to its lifetime electrical energy output.

The proportion of energy-storing rubber in the circumference of the device can be chosen to make the best use of it (see Farley and Rainey, 2006a). Accordingly, the economics of the device reduce to the simple question: does the value of its lifetime electrical energy output exceed the rubber cost of its lifetime elastic energy storage capacity? Both can conveniently be expressed per kWh. For example, if we value the energy output at 20p per kWh (the present subsidised price in the UK and Portugal), can we store 1 kWh in a 20p sample of the material, over the duration of a lifetime test of that sample in a fatigue machine?

The fatigue life of rubber is discussed in Lake and Thomas (1988). It is shown there that for a long fatigue life, the strain in the rubber must not drop too low, i.e. the rubber must not relax completely while ANACONDA is producing power, but remain under some tension. See Figure 7 below, which shows that natural rubber (NR vulcanizate) has a fatigue life of 10^7 cycles, when the strain cycles between 50% and 250%. Since WEC's are typically designed to operate at their full rated power for about 30% of the time, they will reach 10^7 cycles of full-power operation in about 10 years. Thus a strain ranging between nominal limits of 50% and 250%, with a mean of 150% (i.e. a range of $\pm 100\%$), is acceptable at full power. This is the strain in the energy-storing sector of the tube circumference – as already noted, the overall strain in the tube can be adjusted to any lesser figure by including a suitable proportion of cheaper inelastic fibre-reinforced material, see Farley & Rainey (2006a).

More precisely, if the root-mean-square strain is 35%, it will (from the Rayleigh distribution) reach these nominal limits of $\pm 100\%$ only once every $e^{\{(100/35)^2\}/2} = 60$ cycles, which will do negligible fatigue damage. Figure 7 shows that it is the more extreme cycles which drop the strain down to 25%, that are important. These will occur once every $e^{\{(125/35)^2\}/2} = 600$ cycles, giving $10^7/600 = 17,000$ over the 10-year life,

which is a good portion of the life of 30,000 cycles shown in Figure 7. Thus 35% is a suitable root-mean square strain at full power.

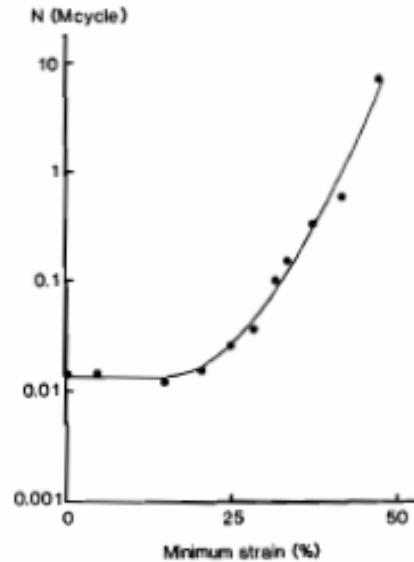


FIG 15-13. Variation of fatigue life with minimum strain for an NR vulcanizate (maximum strain is 250 per cent).

Figure 7. Rubber fatigue curves, from Lake & Thomas (1988)

Natural rubber has a Young’s modulus $E = 1 \text{ MPa}$, so 35% RMS strain corresponds to a dynamic stored energy per m^3 of $(1 \times 0.35) \times 0.35 = 0.123 \text{ MJ}$. So with the notional design life of 10 years, the total stored energy per m^3 is $0.123 \times 10^7 \text{ MJ} = 0.35 \times 10^6 \text{ kWh}$. The price of natural rubber fabrications is about $\text{£}7000/\text{m}^3$, so that is $\text{£}7000$ per $0.35 \times 10^6 \text{ kWh}$, or 2p per kWh. This suggests that ANACONDA is economic, although there are of course other costs. It also implies that a device with a maximum continuous power absorption of 1 MW, say, operating in waves with a typical period of 12s, will be storing $1 \times 12 = 12 \text{ MJ}$ and thus require $12/0.123 = 100 \text{ m}^3 = 100 \text{ tonnes}$ of rubber. This is an exceptionally light WEC for its power.

Much higher performance may be possible with specially-developed rubbers – Figure 7 is merely typical published data.

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APPENDIX – WORK DONE ON TUBES BY EXTERNAL PRESSURES

The radial velocity of a tube wall can be split into two components:

- A radial velocity which varies around the tube, caused by its rigid-body velocity
- A radial velocity which is constant around the tube, caused by its bulging

Likewise the external pressure on a tube can be split into two components:

- A pressure which varies around the tube, caused by the pressure gradient
- A mean pressure, which does not vary around the circumference of the tube

Table 1 below shows the power extracted by the tube, per unit length, by the various combinations of these two components of radial velocity and pressure

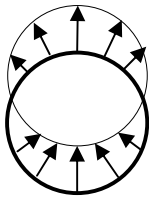
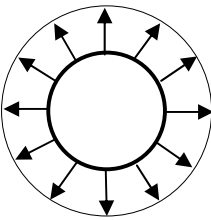
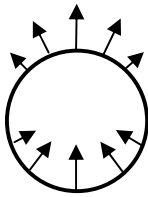
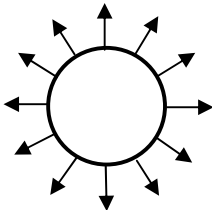
			Radial surface velocity	
			Due to rigid-body velocity	Due to bulging
				
Surface Pressure	Component due to pressure gradient		Power per unit tube length = {rigid-body vel.} ×{press. gradient} ×{cross-sect. area}	Power = 0 by symmetry
	Mean component of pressure		Power = 0 by symmetry	Power per unit tube length = {rate-of-change of cross-sect. area} ×{mean pressure}

Table 1. Power from various combinations of radial velocity and pressure

By symmetry, power is only obtained in the shaded squares on the diagonal of the Table, as can be seen.

Table 2 below is the same Table, extended in two respects:

- There is a additional column on the right, for rigid-body velocity and bulging combined
- Two kinds of pressure are considered⁶, the wave pressure and the hydrostatic pressure.

⁶ The strict definitions of the mathematical literature are understood here (e.g. Lamb (1932) Art 227 eqn (3)), so that for example at a wave crest the wave pressure is positive and cancels out the negative hydrostatic pressure caused by the elevation of the crest above the still-water position







		Motions		
		Rigid-body Velocity  Position = $b\cos(\omega t + \phi)$	Bulging  X-area = $A + A'\cos(\omega t + \theta)$	Rigid-body Velocity + Bulging
Wave Pressure	Force from gradient =  $-2(ka)\rho g A \cos \omega t$	$-2(ka)\rho g A \cos \omega t$ $\times -b\sin(\omega t + \phi)$ Max. average value = $\rho g \omega A (kb)a$	0 by symmetry	Max. average value = $\rho g \omega A (kb)a$ + higher order terms
	Pressure =  $\rho g a \cos \omega t$	0 by symmetry	$\rho g a \cos \omega t$ $\times -A'\sin(\omega t + \theta)$ Max. average value = $\rho g \omega A' a/2$	Max. average value = $\rho g \omega A' a/2$ + higher order terms
Hydro- static Pressure	Force from gradient =  $\rho g A$	$-\rho g A b \sin(\omega t + \phi)$ = 0 on average	0 by symmetry	$\rho g A' \cos(\omega t + \theta)$ $\times -b\sin(\omega t + \phi)$ Max. average value = $\rho g \omega A' b/2$
	Pressure =  $\rho g h$	0 by symmetry	$-\rho g h A' \sin(\omega t + \theta)$ = 0 on average	$-\rho g b \cos(\omega t + \phi)$ $\times -A'\sin(\omega t + \theta)$ Max. average value = $\rho g \omega A' b/2$

Table 2. Power available from various types of motion (columns), exploiting various pressure features (rows). The red (top), orange (middle) and green (bottom) shaded squares represent Evans' Cylinder (red), ANACONDA on the seabed (orange), and ANACONDA on the surface (green).

The red square gives the power obtained by a vertical tube velocity (the vertical position of the tube is $b\cos(\omega t + \phi)$), where b is the motion amplitude, ω is the wave frequency, and ϕ is a phase angle) combined with a vertical gradient of the wave pressure. This vertical gradient is proportional to the vertical acceleration in the wave (by Newton's equation of motion), and close to the surface of a wave with surface elevation $a\cos\omega t$ (a = wave amplitude = waveheight/2) this acceleration is $-(ka)g\cos\omega t$ upwards, where k is the wavenumber ($= 2\pi/\text{wavelength}$) and g the acceleration due to gravity. It produces an upwards force on the tube of $-2(ka)\rho g A \cos\omega t$ per unit length, where a is the local wave amplitude (= waveheight/2), ρ is the density of water, and A the cross-sectional area of the tube. If the phase ϕ of the motion is chosen optimally, so that the velocity of the cylinder is exactly in phase with the wave force on it, then the average power extracted has its maximum value of $\rho g \omega A (kb)a$, as shown in the Table. This is the type of power extraction in Evans' Cylinder, which is thus represented by this red square.

The orange square represents ANACONDA on the seabed. Its varying cross-sectional area is $A + A'\cos(\omega t + \theta)$, which exploits the varying wave pressure $\rho g a \cos\omega t$. If the phase θ is chosen optimally, so that the radial surface velocity of the device is exactly in phase with the wave pressure, then the average power extracted has its maximum value of $\rho g \omega A' a/2$, as shown in the Table.

Consider now the hydrostatic pressure, in the bottom two rows of the Table. Its gradient produces the buoyancy force $\rho g A$ per unit length, which will do work when the device moves vertically, as shown in the first column. However, the buoyancy force is constant, not time-varying, so it is not possible to choose a phase to extract power – although work is done on the cylinder as it moves upwards, the energy is returned as it moves downwards, and no net power is produced, as shown in the Table. The same is true of the hydrostatic pressure $\rho g h$ itself (h = immersion depth of the device below still water level, assumed small compared with a wavelength): this will do work on the device when it bulges in, but the energy is returned when it bulges out, so that no net power is produced, as shown in the Table.

The final column of the Table shows the effect of combining motion and bulging, as in the floating version of ANACONDA. Considering first the hydrostatic pressure in the last two rows, it is now time-varying, because the immersion depth h below the still water level is varying. If the device is following wave surface with elevation $a \cos \omega t$, then this variation in h is $-a \cos \omega t$, and average power can be extracted from both the pressure gradient and the pressure, by suitable choice of the phase angles φ and θ . However, the two *cancel out*, as they must, or else it would be possible to extract power from still water.

If we argue that ANACONDA cannot extract power if it follows the wave profile, since the external pressure is constant (wave and hydrostatic pressure components cancelling out, as they do on the surface), we are saying that the orange square is being cancelled by the square at the bottom right-hand corner of the Table⁷, and indeed it is. But this latter square is itself cancelled out by the green immediately above it, as just established. Thus it is the green square which remains, and explains the principle of operation of ANACONDA on the surface.

It is extracting power from the varying buoyancy – when it is going up, it bulges out so that the waves have to do more work in lifting it. When it is going down, it does the opposite, so that overall it extracts power.

⁷ The red “Evans Cylinder” square is also giving zero power, because the motion is in anti-phase with the particle acceleration, and thus 90 degrees out of phase with the velocity. Thus the device appears at first sight to be extracting no power, which is why its principle of operation as a floating device is not obvious.