Severn Barrage

Feasibility of “Tidal Reef” Scheme

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Plan Design Enable

Severn Barrage

Feasibility of "Tidal Reef" Scheme

prepared for the RSPB

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1. Summary

1.1 Context

The RSPB have approached Atkins for advice on the technical and economic feasibility of the "Tidal Reef" concept designed by Evans Engineering (see http://www.evans-engineering.co.uk/). The "Tidal Reef" is one of 10 tidal power schemes, including the Cardiff-Weston barrage, currently being examined by a government 2-year Severn Tidal Power Feasibility Study. The Study should enable Government to decide whether it could support a tidal power scheme in the Severn Estuary, and if so, on what terms.

1.2 Aim of this Report

The three issues explored in this Report are:

1. The overall power of the "Tidal Reef" scheme, i.e. whether the high water volume offsets the low energy per cubic metre

2. The capital cost of the "Tidal Reef" scheme, i.e. how the low level difference affects the cost of the barrage structure and of the turbines

3. The development work needed to take the "Tidal Reef" scheme to outline design stage within the timescale of the government 2-year Severn Tidal Power Feasibility Study.

This Report does not consider in detail the likely environmental effects of a 'Tidal Reef' scheme.

1.3 The Evans Engineering proposed "Tidal Reef" design

In essence, Evans Engineering's proposed "Tidal Reef" from Minehead to Aberthaw is a "greener" barrage design. It uses a single barrage at the most downstream location currently being considered, which is between Minehead and Aberthaw, see Figure 1 below (this is a location originally chosen in Government studies 30 years ago). However, it limits the level difference across it to 2m (much less then other barrages, which are designed to hold back the full height of the Severn tide). It thus involves the largest volume of water, but extracts the lowest energy from it, per cubic metre.

This low level of energy extraction should facilitate the safe passage of salmon and other fish through the barrage. The small level difference also minimises the change in the tidal cycle upstream, and the associated environmental impact.

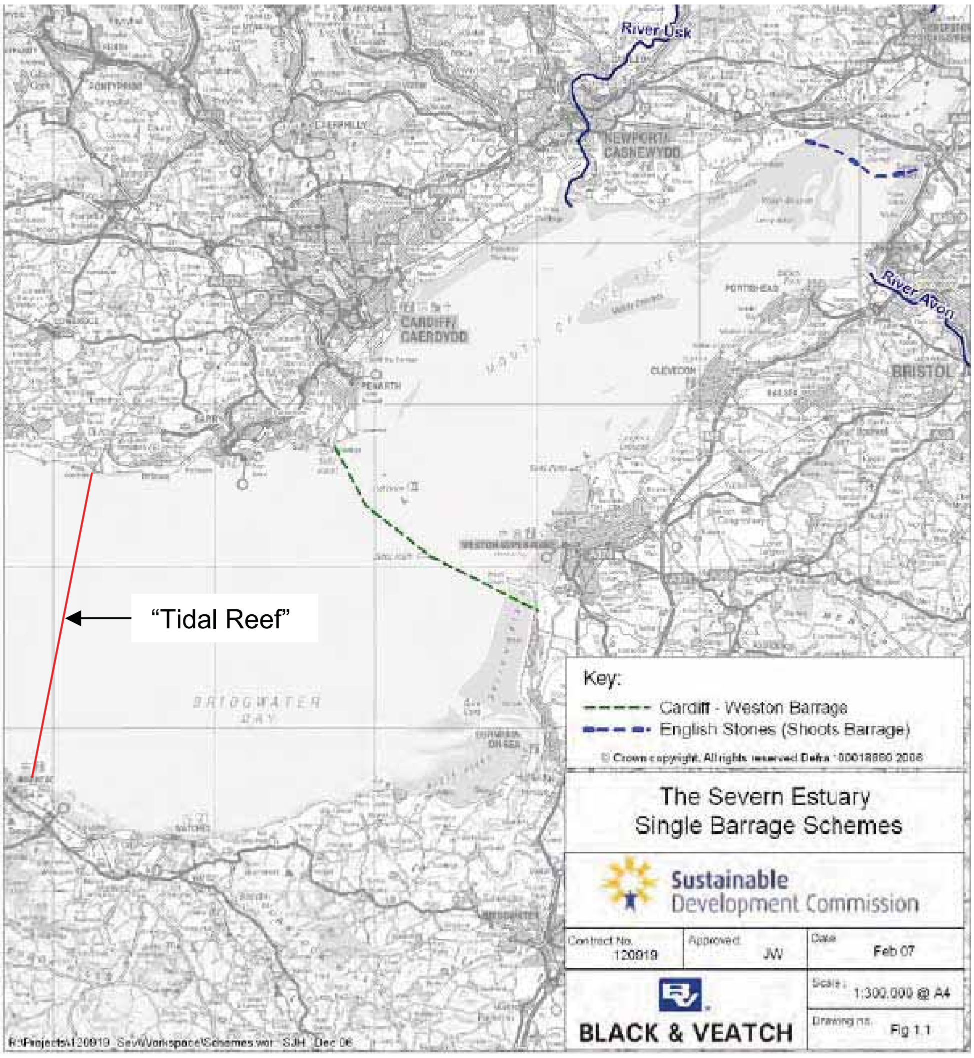

Figure 1. Barrage locations (taken from [3], fig 1.4).

The details of the Evans Engineering “Tidal Reef” are very novel. Above fully-immersed concrete caissons, there are steel modules, each of which acts as a siphon, and contains four low-head vertical-axis turbines. The modules are rotatable through 180 degrees about a vertical axis, so that sections of the “Reef” could open at certain times to allow free passage of shipping.

1.4 The conventionally engineered “Tidal Reef” design considered in this Report

The barrage design proposed by Evans Engineering has too many unknowns to allow a like-for-like comparison of costs with the Cardiff to Weston-super-Mare barrage. As there are a number of ways in which a “Tidal Reef” could be designed and still retain its potential environmental benefits, we consider a conventionally engineered version of the “Tidal Reef” in this Report. This version is a fixed concrete structure, with conventional turbine ducts rather than the rotatable siphoning modules proposed by Evans Engineering. However, the essential feature of the “Tidal Reef” concept is retained, which is large volume and low level difference.

1.5 Power generation potential of the “Tidal Reef” concept

This Report supports the power capture figure of 20 TWh/yr claimed by Evans Engineering using first-principles calculations of tidal flow. It compares with the 17 TWh/yr power capture claimed (see [3], p.32) for the Cardiff to Weston-super-Mare barrage.

1.6 Estimated cost of the “Tidal Reef” barrage structure and low-head turbines

Based on calculations of loads and Atkins recent experience in oil industry caissons, the conventionally-engineered “Tidal Reef” barrage structure should cost about £2bn less than the costs given in [3] for a Cardiff to Weston barrage. The saving is in the weight of concrete, the foundations, and the installation.

Costs of the low-head turbines are harder to estimate, but should be similar to those on the Cardiff to Weston barrage as the lower head is offset by higher utilisation (the turbines only cease generating as the tide turns).

Thus a conventionally engineered version of the “Tidal Reef” scheme from Minehead to Aberthaw should cost less, overall, than the Cardiff to Weston barrage in [3]. Therefore, the “Tidal Reef” concept appears to be competitive economically.

1.7 Development work needed to turn the “Tidal Reef” concept into an outline design

Evans Engineering propose that the “Tidal Reef” scheme could be taken to “outline design stage” within the timescale of the present 2-year government Severn Tidal Power Feasibility Study, for a £0.5m budget. This certainly appears feasible. In our view, it would be rational to address the most important economic uncertainties first as follows:

1) Improving on the 20TWh/yr estimate for the annual energy generation;

2) Improving the estimates of wave load on the barrage structure;

3) Improving on the estimates for the concrete weight needed for the caissons; and

4) Reducing the uncertainties of turbine cost and price by approaching developers.

The four tasks we propose above could be accomplished within the budget and timescale proposed, provided the work was efficiently organised.

2. Power Generation Potential

2.1 Non-technical summary

This Report supports the power capture figure of 20 TWh/yr claimed by Evans Engineering (see http://www.evans-engineering.co.uk/), using first-principles calculations of tidal flow. It compares with the 17 TWh/yr power capture claimed (see [3], p.32) for the Cardiff to Weston-super-Mare barrage. These calculations include a 75% efficiency factor to allow for turbine efficiency and kinetic energy losses.

2.2 Power estimate from present tidal flow

From the Admiralty Chart [1], the water depth at LAT (lowest astronomical tide) can be read off at 12 equally-spaced points across the barrage, as follows:

	Depth at LAT (m)
Aberthaw	0
	14.5
	19
	27
	20.5
	19
	23
	21
	14.5
	20
	15
	14
	11
Minehead	0
Average depth	16.8

Table 1. Depths at equally-spaced points along proposed barrage

According to the relevant tide tables ([2], p.170 and p.331), the mean sea level is about 6m above LAT, so the average depth d to mean sea level is d = 16.8+6 = 22.8m.

The same chart gives the maximum tidal stream in both directions, at points "P" and "Q", which are about 5 km upstream, and 5 km from either end of it, as follows:

	Current at point "P" (knots)	Current at point "Q" (knots)
Mean spring tides	+2.9, -3.0	+4.3, -4.4
Mean neap tides	+1.6, -1.6	+2.3, -2.4

Table 2. Maximum currents at two points across the barrage

The average of these figures is about ± 3.6 knots = ±1.8 m/s in the spring tides, and ±2.0 knots = ±1.0 m/s in the neap tides. Taking the variation of the current as sinusoidal between these maxima, the average current in either direction is $\pm(2/\pi)\times1.8 = \pm1.1$ m/s in the spring tides, and $\pm(2/\pi)\times1.0 = \pm0.6$ m/s in the neap tides. From the mean water depth d = 22.8m given above, and the barrage length of 20 km, the cross-sectional area A is given as $A = 22.8\times20{,}000 = 460{,}000\ \text{m}^2$. Thus the volume flow rates are:

$$1.1\times460{,}000 = 500{,}000\ \text{m}^3/\text{s} \quad \text{in the spring tides}$$

$$0.6\times460{,}000 = 270{,}000\ \text{m}^3/\text{s} \quad \text{in the neap tides}$$

These figures can be cross-checked by considering the area of the estuary above the barrage (which can be seen from Figure 1 to be approximately 1000 km^2 – the map shows 10km squares), and the tidal range in it (which averages approximately 10m in the spring tides, and 5m in the neap tides, see [2], p.170 and p.331). From the volume of water passing the barrage in the 12.3/2 hours between low and high tides, the average volume flow rate comes to:

$$10\times1000\times1000^2/(12.3\times3600/2) = 450{,}000\ \text{m}^3/\text{s} \quad \text{in the spring tides}$$

$$5\times1000\times1000^2/(12.3\times3600/2) = 230{,}000\ \text{m}^3/\text{s} \quad \text{in the neap tides}$$

These latter figures are likely to be more accurate, since they do not rely on the current profile across the channel.

As a first approximation, we can assume that these volume flow rates are unaffected by the presence of the barrage. With a constant head difference of 2m (i.e. assuming no flow is allowed until this head difference is reached), they correspond to average powers of:

$$450{,}000\times2\rho g = 9{,}000{,}000\ \text{kW} = 9{,}000\ \text{MW in the spring tides}$$

$$230{,}000\times2\rho g = 4{,}500{,}000\ \text{kW} = 4{,}500\ \text{MW in the neap tides}$$

taking the density ρ of seawater as 1.025 tonnes/m^3, and g as 9.81 m/s^2. These figures must be reduced to allow for the turbine efficiency, and for the kinetic energy losses in the exit water. Nevertheless, they are considerably in excess of the figure given in the recent study [3], which quotes (see [3], p.28) a figure of 20 TWh/yr (= 2,300 MW, on average), that appears to have been obtained 30 years ago by the Bondi Committee, apparently for a conventional high-head barrage.

2.3 Correction for change in tidal flow

To refine the above figures of 9,000 MW and 4,500 MW, it is possible to estimate the change in the tidal range produced by the barrage, using the 1-D model mentioned in [3], in which the tidal current is assumed to be uniform across the estuary (see [3], p.16), only varying with distance along it. This model is discussed in Sections 2.2 – 2.7 of [4], in which it is shown (see [4], p. 104) that the propagation of tidal waves through discontinuities such as a barrage, can conveniently be analysed by means of an electrical analogy. Pressure is the analogue of voltage, and volume flow rate is the analogue of electric current.

The reservoir upstream of the barrage is short compared with the wavelength of a tidal wave (except far upstream, where the depth is much less and the wavelength is accordingly much shorter), so it can be treated as a single electrical element. This will be a capacitor *C* because the pressure is proportional to the level, and thus to the integral of the volume flow rate at the barrage. The estuary downstream of the barrage is the source of the tidal waves, so it can be treated as a voltage generator, in series with the characteristic impedance of the channel, which is (see [4], p.104) $\rho c/A$, where c is the speed of the tidal wave (= $\sqrt{(gd)}$, see [4], p.95). Thus the whole estuary has the equivalent electric circuit shown on the left in Figure 2 below.

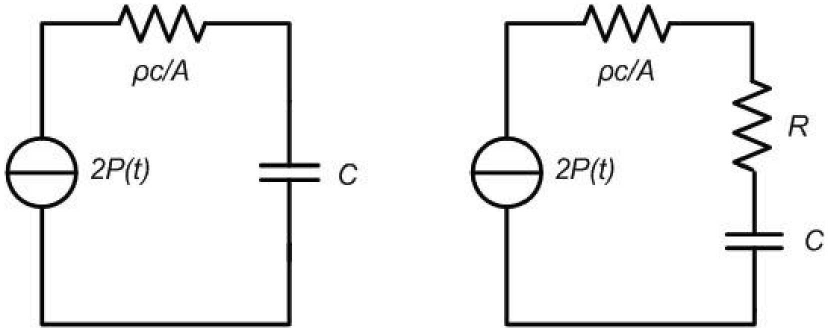

Figure 2. Equivalent electric circuit of tidal behaviour in estuary, without barrage (left) and with barrage (right)

The barrage has the effect of introducing an additional resistance *R*, as shown on the right in Figure 2. Its average value is approximately:

$$2\rho g/450{,}000 = 0.045 \text{ Pa}/(\text{m}^3/\text{s}) \quad \text{in the spring tides}$$

$$2\rho g/230{,}000 = 0.090 \text{ Pa}/(\text{m}^3/\text{s}) \quad \text{in the neap tides}$$

This compares with the characteristic impedance of the channel, which is:

$$\rho\sqrt{(gd)}/A = 0.034 \text{ Pa}/(\text{m}^3/\text{s})$$

and with the reactance of the capacitor *C* at the tidal period of 12.3 hours. Since a tidal oscillation of ±1m over this period produces a peak pressure of $\pm 1\rho g$ and a peak volume flow rate of $\pm 1000 \times 1000^2 \times 2\pi/(12.3 \times 3600)$, this reactance is:

$$\rho g/(1000 \times 1000^2 \times 2\pi/(12.3 \times 3600)) = 0.071 \text{ Pa}/(\text{m}^3/\text{s})$$

Thus the effect of the barrage is to multiply the tidal range upstream of it by a factor:

$$\sqrt{(0.071^2+0.034^2)\}}/\sqrt{(0.071^2+(0.045+0.034)^2)\}} = 0.74 \quad \text{in the spring tides}$$

$$\sqrt{(0.071^2+0.034^2)\}}/\sqrt{(0.071^2+(0.090+0.034)^2)\}} = 0.55 \quad \text{in the neap tides}$$

Since the flow rate is proportional to the tidal range, the power obtained reduces by the same factor. Including also a 75% efficiency factor to allow for turbine efficiency and kinetic energy losses (see Section 3.3), we conclude that the average power figures of 10,000 MW and 5,500 MW reduce to:

9,000×0.75×0.74 = 5,000 MW in the spring tides

4,500×0.75×0.55 = 1,900 MW in the neap tides

The above calculations are of course approximate, but they appear to support the figure of 20 TWh/yr (= 2,300 kW on average) originally given by the Bondi Committee for a barrage at this location, albeit that it was apparently for a conventional barrage rather than a “Tidal Reef”.

2.4 Other sites for the “Tidal Reef”

It also appears from the above calculations that some of the other barrage sites originally considered by the Bondi committee may be more attractive for the “Tidal Reef” concept than Minehead to Aberthaw. See Figure 3 below, which shows these sites.

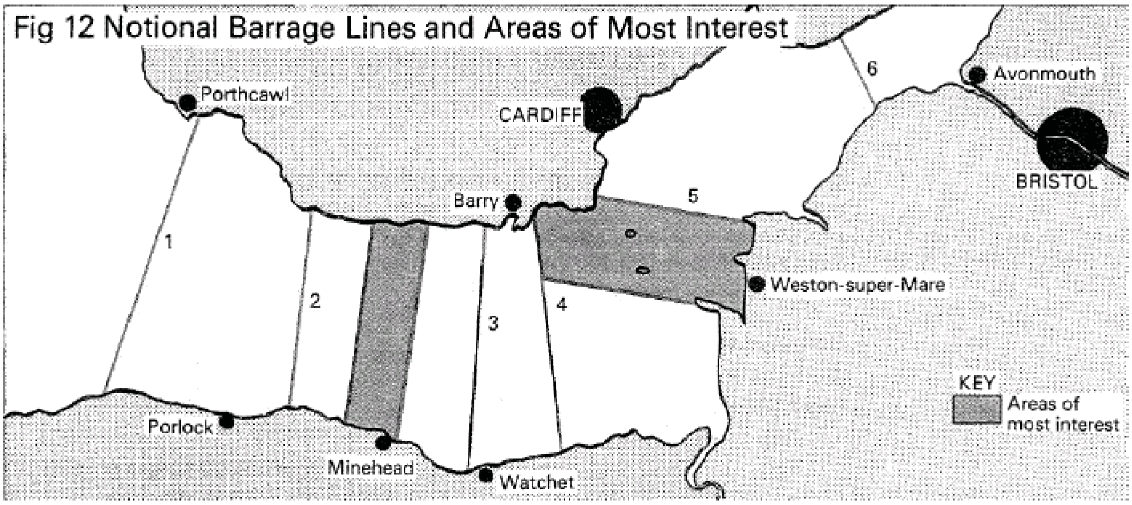

Figure 3. Barrage sites originally considered by the Bondi Committee (taken from [3] fig. 2.3 (1))

In particular, the site “2” from Porlock Bay to St. Donats, may be seen from [1] and [2] to offer greater currents and almost as much tidal range as Minehead to Aberthaw. The area of the reservoir upstream of the barrage is increased by approximately 20%, so the above calculation methodology would predict a power increase of the same order.

The same applies, to a greater extent, to site “1” from Lynmouth to Porthcawl, and to a site even further downstream, from Ilfracombe to Gower (not shown in Figure 3). However, the increased reservoir size has increasingly to be offset against the reduced tidal range and the greater barrage length (and wave load, see next section). The approximation above that the reservoir can be treated as a single electrical element also begins to break down.

3. Cost of the "Tidal Reef" barrage structure and low-head turbines

3.1 Non-technical summary

The barrage design proposed by Evans Engineering is not conventionally engineered, with too many unknowns to allow a like-for-like comparison of costs with the Cardiff to Weston barrage. A more conventionally engineered version of the "Tidal Reef" is therefore considered.

Based on calculations of loads and Atkins recent experience in oil industry caissons, the "Tidal Reef" barrage structure should cost £2bn less than the Cardiff to Weston-super-Mare barrage in [3], using the same costing methodology. The saving is in the weight of concrete, the foundations, and the installation.

The high utilisation of the low-head turbines will reduce their cost per unit output (the turbines only cease generating as the tide turns). Costs of the low-head turbines are harder to estimate, but should be similar to those on the Cardiff to Weston barrage as the lower head is offset by higher utilisation.

Overall, therefore, the "Tidal Reef" concept appears to be competitive economically.

3.2 Cost of barrage structure

Evans Engineering propose a very radical barrage design, see Figure 4 below.

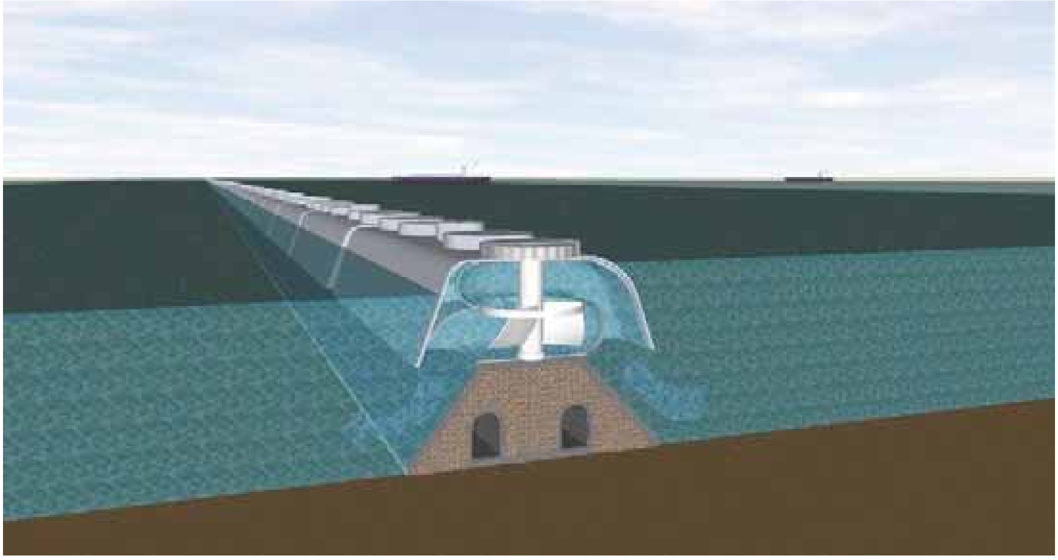

Figure 4. Evans Engineering's proposal for barrage design

It is not possible to cost such a structure without first resolving a number of key design uncertainties, for example the adequacy of the structural loadpath for the very large wave impact loads which will be felt by such a rigid structure. Also the adequacy of the pressure margin against cavitation at low tide, when the water pressure in the turbine is below atmospheric.

It is possible, however, to compare the cost of a conventional concrete barrage with the similar barrages proposed at the Cardiff to Weston and English Stones locations, for which a detailed cost breakdown is given in [3]. That cost breakdown is based on the design work carried out 25 years ago, on concrete barrage caissons. An example of this work is shown in Figure 5 below, taken from [3], p.47

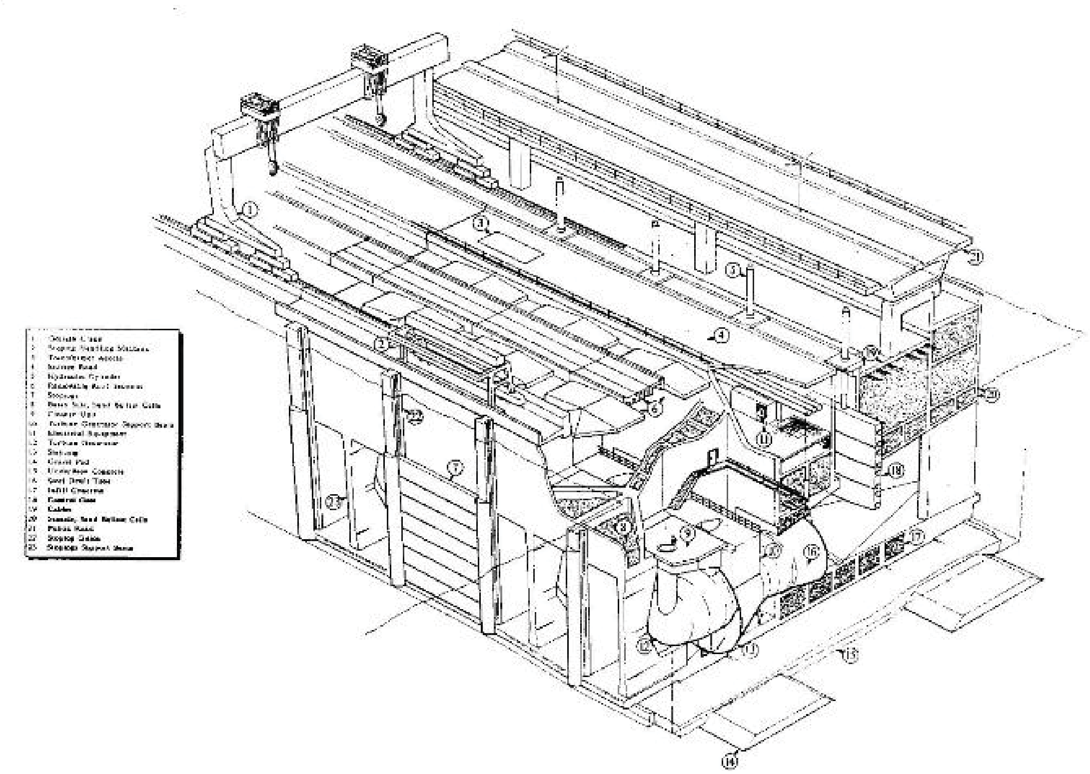

Figure 5. Caisson proposed for Cardiff to Weston barrage

The low head of only two metres in the Tidal Reef scheme requires much larger turbine duct areas than used in the Cardiff to Weston and English Stones barrages, or else the kinetic energy losses in the exit flow will be prohibitive. If the total area of the turbine ducts is one half of the channel cross-section A, for example, the velocity through the ducts will be double the free stream value. The latter is given in the previous section as $450{,}000/A = 1.0$ m/s on average, in the spring tides. When this is doubled in the exit flow, the Bernoulli pressure drop is:

$$0.5\{(2\times1.0)^2 - 1.0^2)\}/g = 0.15\text{m head}$$

This compares with the 2m turbine head, and implies a significant kinetic energy loss of 0.15/2 = 7.5%, albeit that it reduces substantially in the neap tides.

Also, the design of concrete caissons has developed significantly over the past 25 years, in the offshore oil industry, where they are used to store oil on the seabed. The early designs resembled Figure 5 in their complexity, but the latest designs are significantly simpler geometrically. This has been found to be more economic. Figure 6 below is a typical recent oil industry caisson.

Figure 6. Concrete caisson for the Wandoo offshore oil field, Australia

Based on this experience, a possible caisson configuration for the Tidal Reef is shown in cross-section in Figure 7 below. The turbine axis is inclined to the duct, in order that the turbine area can be comparable with that of the duct (or else the kinetic energy losses will be prohibitive, because there is no diffuser when the flow is upstream). This follows recent French practice, see Section 3.3.

Above water, the downstream side of the caisson is protected by concrete armour units. This is because the wave loading is significant. The 50-year extreme significant wave height for this location is approximately 6m, see [5] fig. 11.3, corresponding to a 50-year extreme individual wave height of approximately 11m. Thanks to the large duct, the caisson of Figure 7 is largely transparent to such waves; the remaining wave load will be associated with the horizontal acceleration of the water ahead of a wave crest. For the range of wave periods considered in Sect. 11.4.2 (c) of [5], this acceleration is limited to about $0.2g$. The worst case for this type of wave load will be when the caisson is almost fully immersed at high tide. Its cross-section is then approximately 30m ×10m, which will give a wave load of

$$1.5\times 30\times 10\times 0.2\rho = 90 \text{ tonnes per metre of barrage length}$$

where the factor 1.5 is to account for the hydrodynamic added mass. This is larger than the load from the head difference of 2m across the barrage, which is

$$30\times 2\rho = 60 \text{ tonnes per metre of barrage length}$$

Moreover, the barrage will be subject to a much more severe type of wave loading, not recognised in the offshore structure codes, but familiar to coastal engineers. This is the impact loading from breaking waves, which will occasionally be seen by the barrage even though the wave height is well below the water depth (which would be the threshold of breaking on a beach). See [6]. To mitigate this effect as much as possible, Figure 7 shows the exposed side of the barrage protected by large concrete armour units. These break up the wave crest, and prevent the “flip through” of the water surface responsible for impact loads.

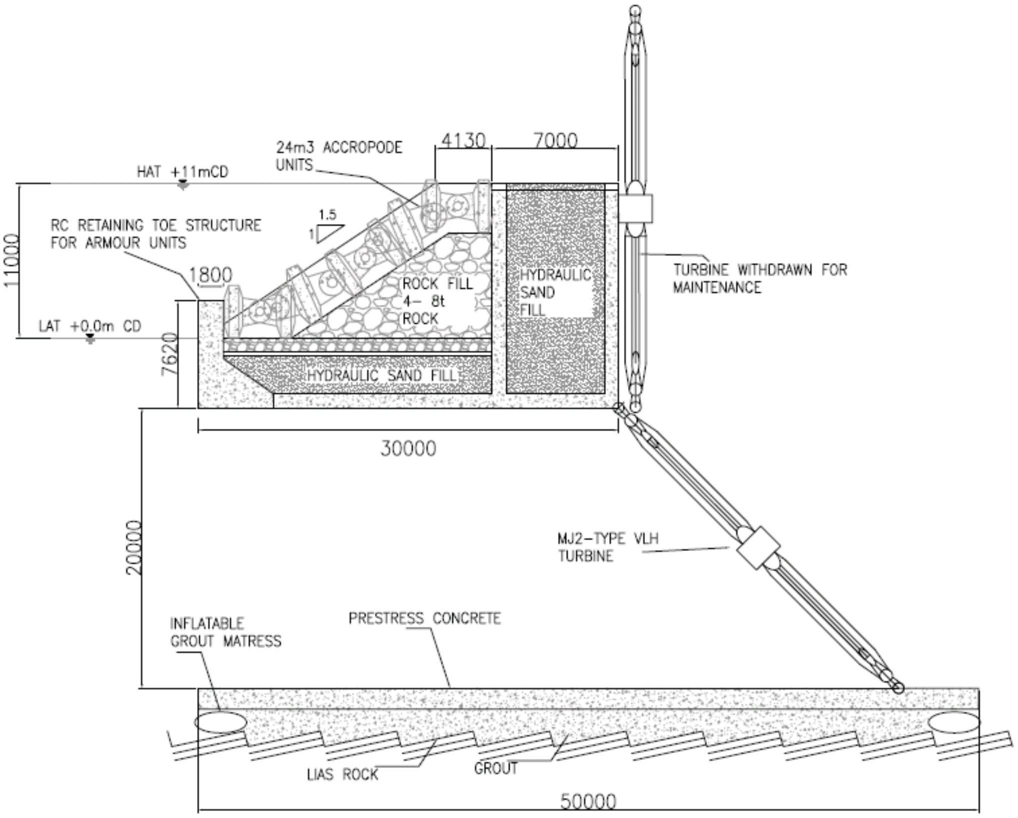

Figure 7. Cross-section of possible concrete caisson

The most severe case of breaking wave impact will not be at high tide (when high wave crests will pass harmlessly over the top of the barrage), but at low tide. In these circumstances the above 60 tonne/m load from the head difference will be reduced, and quite probably reversed. A reasonable estimate for the maximum combined head-difference and wave load is therefore 200 tonnes/m.

For a caisson 50m long, the total load is therefore 50×200 = 10,000 tonnes. This is very similar to the maximum wave load on a caisson of similar size currently being designed by Atkins, for installation on the Solan oilfield west of Shetland, in 2010. On the basis of that experience, our estimate for the weight of concrete in the caisson in Figure 7 is 25,000 tonnes, for a caisson 50m long.

It remains to check the foundation strength. At this point in the Bristol Channel, the seabed is swept clear of sediment by the tidal current, see [7] Figure 2.2. The exposed rock is lias mudstone, see [8]. Although a notoriously unpredictable material, because of the alternate layers of limestone and mudstone, this is a very strong rock by oil industry standards (most oil industry caissons are on sand or clay). Following recent practice on Dutch flood prevention caissons, the caisson can be placed directly on the seabed, and initially levelled by inflatable grout mattresses around the perimeter, as shown in Figure 7. The enclosed space under the caisson can then be pumped full of grout. In these conditions, the ratio of on-bottom weight to wave load can be safely reduced to about 2, implying a minimum on-bottom weight of 2×10,000 = 20,000 tonnes. The 25,000 tonnes of concrete, given above, will weigh approximately 15,000 tonnes in water, but the sand and concrete armour units shown in Figure 7 will comfortably take the weight above the required 20,000 tonnes.

It is now possible to make a rational like-for-like comparison with the cost of the Cardiff to Weston barrage, given in [3] Table 5.1(3) (B). With similar embankments, the length of the present barrage is about 15 km, which will require 300 caissons each 50m long. At 25,000 tonnes of concrete each (=10,000 m^3), that is 3,000,000 m^3 in all, and compares with about 5,000,000 m^3 for the Cardiff-Weston barrage, giving a saving of about £1bn at the rates given in [3] Table 5.1(3) (B). In addition the £1.25bn foundations cost of the Cardiff Weston barrage (£627m dredging + £622m foundations) should be greatly reduced with the grouted foundations described above.

The £244m installation cost could probably also be reduced - the winching scheme shown in [3] fig. 4.1(2) is not necessary with modern dynamically-positioned anchor-handling tugs, which are much more capable than the tugs available 25 years ago. They have a typical bollard pull of 150 tonnes (e.g. the Ulstein UT722, which is a typical modern tug), which is more than sufficient to hold a caisson in the average tidal stream of 1 m/s in the spring tides, calculated earlier in this section. This gives a current load on a 50m × 50m caisson of 25m draft as:

$$0.5\rho\times 50\times 25\times 1^2/g = 65 \text{ tonnes}$$

Overall, the cost of the barrage structure appears to be about £2bn less than that given for the Cardiff to Weston barrage in [3], when the same costing methodology is used.

3.3 Cost of turbines

Since there are only a small number of large-scale hydro-electric turbine manufacturers in the world, the cost of the turbines may differ substantially from the price. It is not therefore a simple matter to compare the prices of the turbines for the present barrage, with those given in [3] Table 5.1(3) (B) for the Cardiff to Weston barrage.

In principle, the costs of the turbines for the present barrage will be higher, because they are designed for a lower head, and therefore operate at lower velocities. This implies greater forces for the same power (since power = force × velocity), which in general means higher costs.

On the other hand the turbines for the present barrage operate for a greater portion of the time (only stopping as the tides turn), and therefore in principle can be of a lower power rating, which should reduce the cost pro-rata.

The turbine shown schematically in Figure 7 is a larger bi-directional version of the one manufactured by MJ2 Technologies and recently installed at Millau in the south of France, see http://www.waterpowermagazine.com/story.asp?storyCode=2049758 and Figure 8 below.

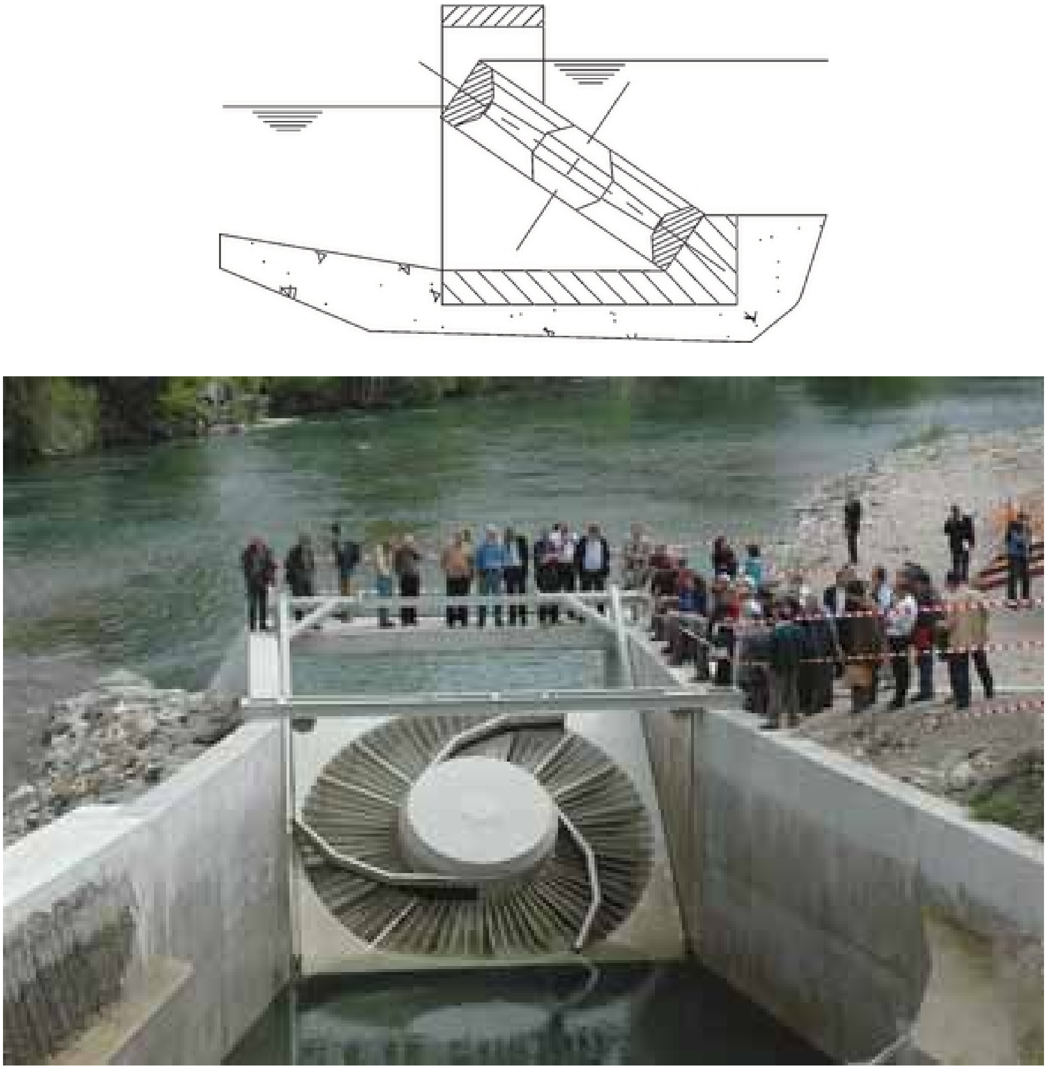

Figure 8. MJ2 Technologies turbine, schematic (top) and as installed at Millau, France (bottom).

This turbine has a very high solidity (ratio of blade area to blade swept area), so as to keep the blade velocity to a minimum and thus minimise the damage to fish. See http://www.waterpowermagazine.com/story.asp?storyCode=2049758 - fish damage appears to be an order of magnitude lower than with conventional turbines of the type proposed for the Cardiff-Weston barrage (for which see [3] p.174). According again to http://www.waterpowermagazine.com/story.asp?storyCode=2049758 the turbine itself has an efficiency of 90%. Allowing for an additional 10% loss from the kinetic energy in the exit flow (see Section 3.2), and a further 10% for electric conversion losses, gives an overall efficiency 0f $90\%^3$ = 75%. This is the figure used in Section 2.3.

If a higher blade velocity (and thus lower solidity) is acceptable, then the turbine torque will be less, which will reduce the cost. The Rotech Tidal Turbine (RTT), see http://www.lunarenergy.co.uk/productOverview.htm is an example of a turbine of this type. See Figure 9 below – Atkins were involved in the structural design of the RTT.

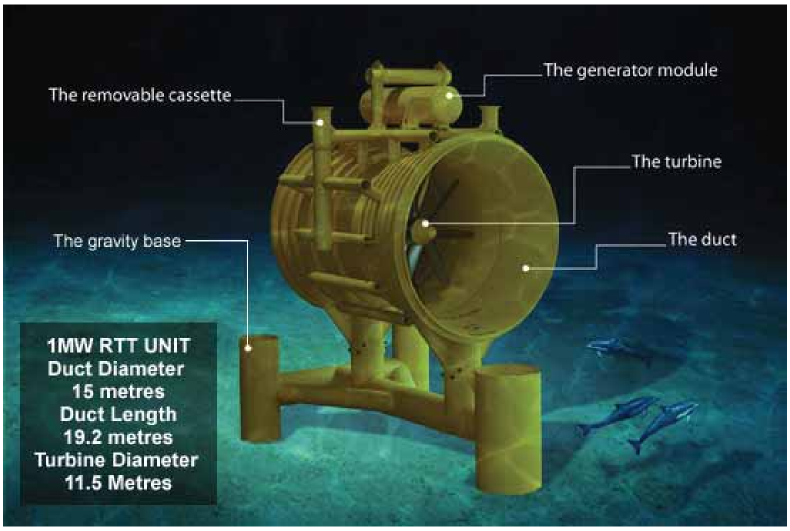

Figure 9. The Rotech Tidal Turbine

There are a number of manufactuers of low-solidity tidal current turbines, which may be adaptable to the present requirement. Another one in which Atkins had a design involvement is MCT’s “Seaflow” turbine installed off Lynmouth (further downstream in the Bristol Channel), see http://www.marineturbines.com/ and Figure 10 below.

Figure 10. MCT’s “Seaflow” tidal stream turbine (brought near surface for maintenance)

MCT have since developed a twin-rotor version “Seagen”, which is now installed in Strangford Lough, Northern Ireland.

Evans Engineering propose that turbines from several different manufacturers be fitted to the barrage, in order to keep the turbine supply competitive. This would certainly be feasible with the simple caisson geometry of Figure 7, on which different turbines could readily be interchanged.

Overall, there does not appear to be any strong reason for believing that the price of the turbines in the present barrage would be very different from those in the Cardiff to Weston barrage.

4. Suitable development work

Evans Engineering propose that the “tidal reef” scheme could be taken to “outline design stage”, within the timescale of the present 2-year government Severn Tidal Power Feasibility Study, and for a £0.5m budget.

This certainly feasible. In our view it would be rational to address the most important economic uncertainties first, as follows:

1. Improve on the 20 TWh-yr estimate for the annual energy capture, for a range of suitable barrage sites (see end of Section 2). This is a straightforward exercise for modern 3-D computer models. Atkins have a license for MIKE3, for example, see http://www.dhigroup.com/Software/Marine/MIKE3.aspx, which is also used by ABPmer. It would be prudent to run two different programs, however – another suitable program, for which HR Wallingford have a license, is TELEMAC, see http://www.telemacsystem.com/.

2. Improve on the above estimates of the wave load on the barrage. This is a straightforward exercise in physical model testing – again, HR Wallingford have a particular track record in this area.

3. Improve on the above estimates of concrete weight. This requires the caisson to be properly designed, with strength checks for all load cases. This is again a straightforward exercise, for a company such as Atkins with recent relevant experience.

4. Reduce the uncertainties in turbine cost and price. A number of turbine manufacturers could be approached.

These 4 tasks could be accomplished with the budget and timescale proposed, provided the work was efficiently organised.

5. References

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