Severn Tidal Power Reef

Contents

1. INTRODUCTION

1.1 The main objective of the **'Tidal Reef Project'** is to be environmentally benign, and yet generate the greatest output of renewable energy of any of the tidal power proposals. From the outset the needs of the wildlife, migratory fish and navigation have been taken into account. In addition, flood alleviation low visual impact and the impact on local communities have been considered. I argue that other projects start with the 'engineering solution or technology' and then consider the environmental and local impacts later in the process and in the form of mitigation measures that may or may not work. The press is full of 'the latest gadget to harness the tides' rather than the best method of reconciling the different interests and environmental constraints.

1.2 The 'Tidal Reef Project' comes technically somewhere between 'Tidal Stream Turbines' and the 'Big Barrage' projects in terms of impact and power generation. Tidal stream turbines, for which I built the first UK prototype, are more suited to single point remote applications. Linking them into a 'fence' structure where there is little or no hydraulic head, simply won't work hydraulically. The 'Big Barrages' and 'Lagoons' have varying degrees of environmental impact according to the degree of modification of the natural tidal cycles, and the period that they can operate is often very limited. This irregular generation puts additional strain on the already inefficient grid system.

Early tests carried out on our prototype in Scotland some fifteen years ago laid the groundwork for this now familiar technology.

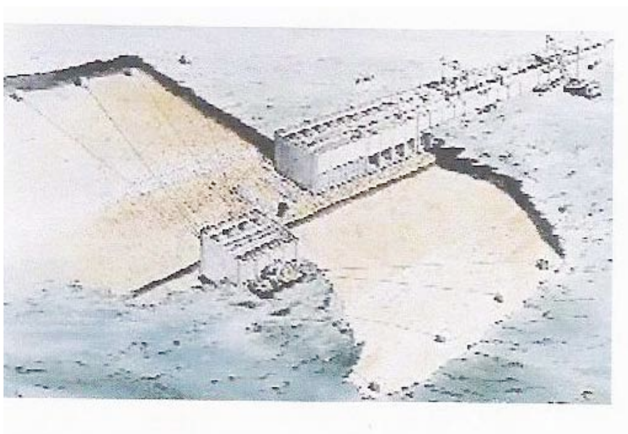
1.3 The 'Reef' design is based on a relatively light impounding structure that maintains a small head difference of about two metres between the sea and the inner estuary. This in turn introduces only a short delay to the natural tidal cycle and thus avoids almost all the adverse environmental consequences of a large fixed barrage. The 'Reef' is also proposed as an 'active system' as opposed to a static barrage. This would enable the new tidal regime to be adjusted from tide to tide in order to meet the specific needs of the various interests, be it navigation or wildlife. The large enclosed area of water and the low operating head makes it much easier to 'bias' the generation period towards periods of high consumer demand. If it was combined with a much smaller 'Inner Reef' at the Shoots, continuous generation would be possible and a greater degree of control over water levels would be possible.

1.3 **The alignment** of the outer reef from Minehead to Aberthaw has been chosen to maximise power generation, ease navigation and provide as much flood protection for the low-lying areas of Somerset as possible, and all without damaging the environment. The cost should be no higher than competing schemes because of the simplified construction and better utilisation.

1 BACKGROUND

2.1 For over 100 years engineers have discussed how to harness the enormous tides of the Severn Estuary to produce electricity. This debate has once again come to the fore with the Government announcement of proposals to build additional nuclear plants and/or support renewable energy generation including that from the tides. But within the pro-tidal camp a major split has opened up with the promoters of conventional barrages (including the Severn Tidal Power Group, STPG) on the one hand, and the wildlife interests (WWF, RSPB, WWT, FOE, GWT and local councils) on the other. Fear of increased flood risks, damage to wildlife habitats and compromised navigation are but some of the many and complex issues.

2.2 The Cardiff and Weston Barrage (Brean and Lavernock), as with most 'conventional tidal barrages', has been designed to provide the necessary hydraulic head for low-head water turbines, and this involves delaying the tides by many hours to produce this head difference. It is this long delay in the tidal cycle that causes most of the potential problems. Massive disruption to the levels and flow patterns within the estuary will result from the highly localised discharges from the 40MW turbines. The impacts of such disruption are many, complex and may be very detrimental to the environment as well as navigation. The S.T.P.G barrage comprises a lot of 'hard engineering structures' in the form of powerhouses, sluices and ship locks which will have a significant visual impact. It is also designed with an adequate freeboard to protect the powerhouse and roadway from flooding and damage. Such a structure is very expensive on account of the head differential and wave action that it is required to withstand and the quantity of material require for its construction is also very large.

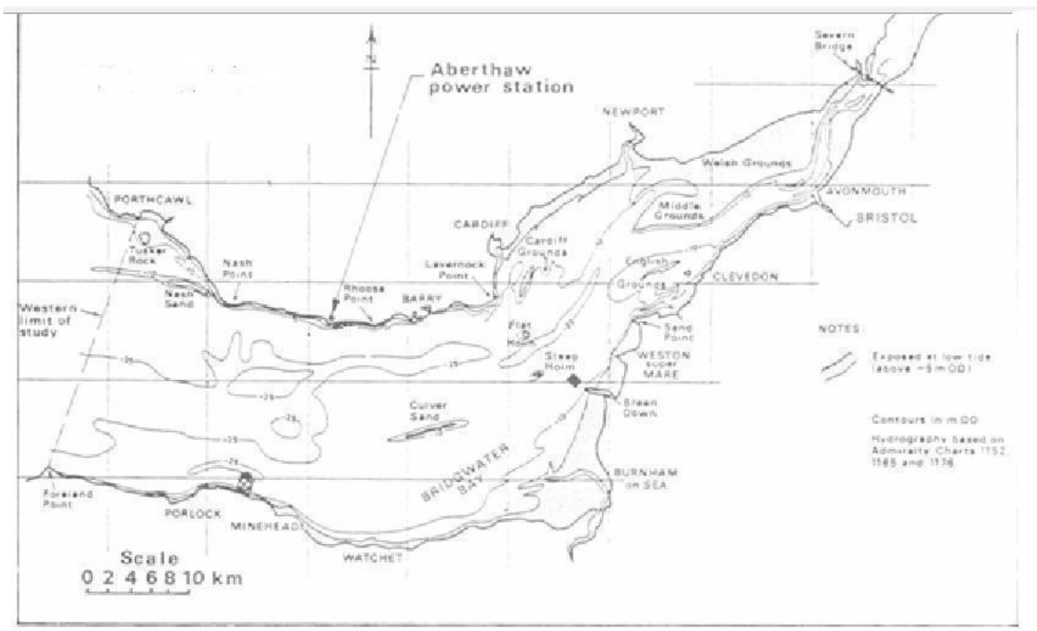


This type of monolithic engineering structure is very inflexible in operation. Energy is also wasted by restricting the water flow through sluice gates, and the environment is damaged by the long delays imposed on the natural tidal cycle.

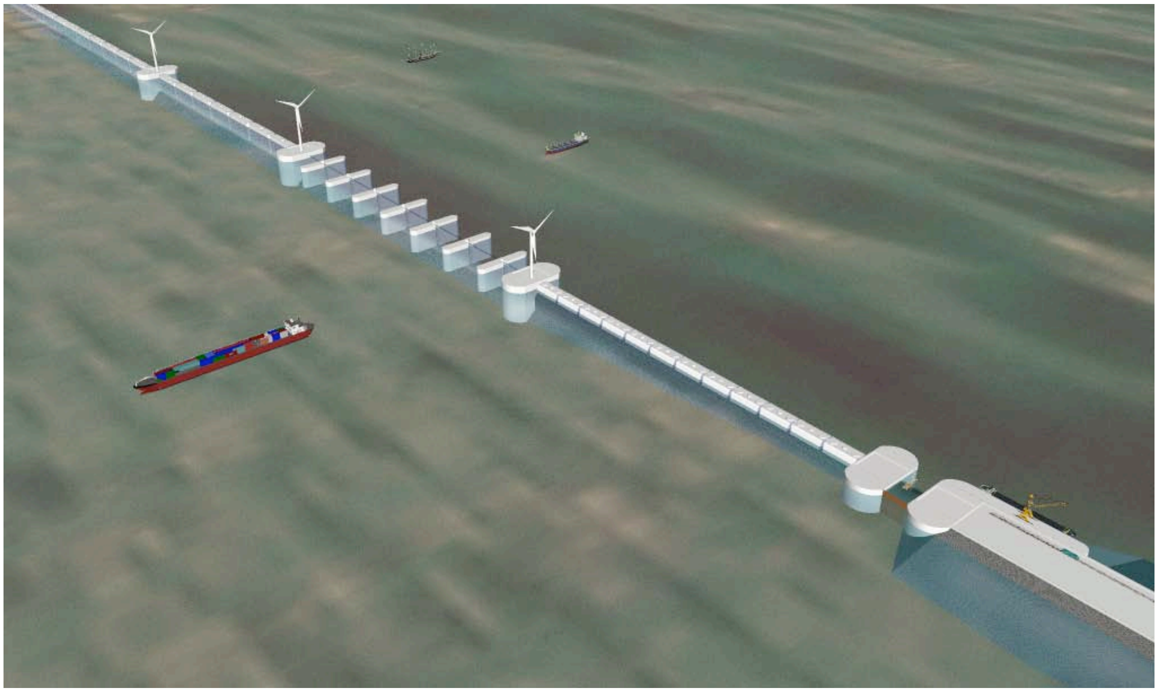
2.3 The 'Tidal Reef Concept' is a dramatically different approach to the environmental conflicts that may severely limit or even destroy the prospect of ever harnessing the power of the Severn Estuary. The starting point for this design is to obtain a consensus of informed opinion on how to satisfy the environmental criteria and around which all the engineering should be designed. These criteria include, but are not confined to, minimising damage to migrating fish, preservation of inter-tidal feeding grounds used by wading birds, salt marshes and related habitats. The avoidance of increased flood risk from building the 'Reef' and preferably an increased security against storm surges and sea-level rise is considered. The impact on shipping should be no more than a minor increase in transit time and no significant increase in navigation hazards and the ability to meet future increases in the size of ships.

2.4 Simple fixed flow turbines working on a very low constant head difference (around two metres) across the barrage are contained within a relatively light structure of caissons and/or gates that reach to the surface of the water and follow the tide level so as to maintain the small head difference irrespective of the stage of the tide. Instead of the power being generated in one big drop, it is generated in what is best described (metaphorically) as a cascade, the low-head turbines producing a lower power output but for a much longer period during each tide. The turbines and civil structures do not have to be designed to meet the higher stresses resulting from the higher heads (used by the other proposed designs). In addition, the grid system sees a much more 'friendly' power supply (smaller peaks) and a higher output because of the larger area of estuary enclosed.

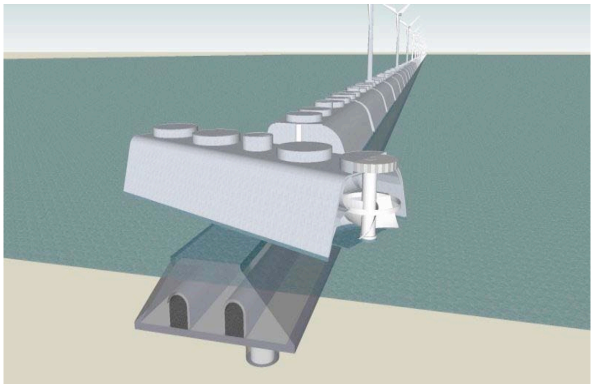
2.5 The length of the 'Reef' would be just under 20 km (12 miles) and stretch from Minehead in Somerset to Aberthaw in South Wales, a line usually referred to as the outer barrage. This route encloses an area of estuary that is almost double that enclosed by the Cardiff – Weston route. This larger volume of water can generate significantly more power despite the tidal range being smaller and the hydraulic efficiency of the turbines lower to accommodate the passage of fish without causing injury.



2.6 The 'Tidal Power Reef' comes someway between 'Tidal Stream Turbines' and the 'Big Barrage' projects in terms of impact and generation potential. The tidal stream turbine, for which I built the first UK prototype, is more suited to single point remote applications, but even when deployed as an array, the cost of maintenance and very low output are a major disadvantage. Linking them into a 'fence' structure where there is little or no hydraulic head, simply won't work hydraulically, because it is necessary to reduce the velocity to extract energy and this is not possible in a confined estuary situation. The conventional high head barrage (5 to 10 metres as opposed to less than 2 metres) is, I suggest, driven by the requirements of the water turbine manufacturers who do not want to stray far from the conventional hydroelectric approach. This leads logically to a wish to obtain the maximum differential head across the turbines and an exceedingly low plant/load factor. This fact coupled with the low load factor for the associated grid connection, and the very poor matching to the consumer load, makes for a very expensive and environmentally damaging option.

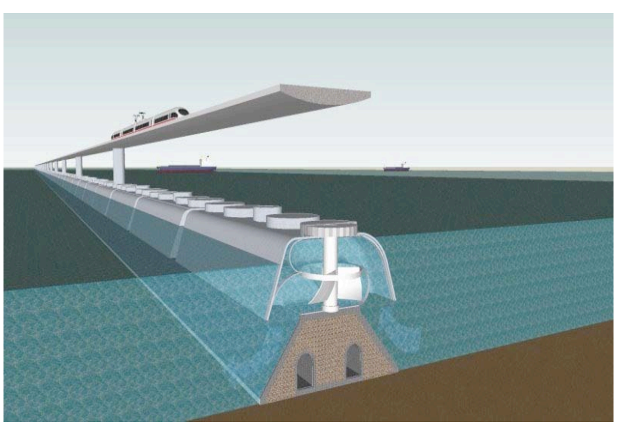


2.7 The 'Reef' turbines could be installed in groups within a rotatable structure. This structure can be rotated through 180 degrees about the vertical piles so that the water flows the same way through the turbines whether the tide is ebbing or flowing. The ability to open the barrage and offer minimal resistance to the incoming tide is critical to the 'active control' of the barrage. Extracting energy from the flood tide will reduce the high tide levels up the estuary but with 'active tide control' it would still be possible to achieve an almost full tide without any pumping when it was required to meet navigation depths and maintain sensitive habitats. In order to capture the energy but maintain only a small head differential the barrage must extend upwards to the maximum height of the tide. A slender structure could be used on account of the modest differential pressure or a 'bascule' or crest gate fixed to the turbine caissons could be used to achieve the same thing but with the added advantage of being able to bypass water flow over the structure. A barrage comprised of floating turbine caisson could be used, or a combination of these and other features could be developed to produce the necessary head and water control.



Illustrated is a rotatable group of turbines that allow unidirectional turbine operation, screen cleaning and water to bypass the 'Reef'

2.8 A twin barrage project encompassing both an outer 'Reef' between Aberthaw and Minehead, with an inner 'Reef' higher up the estuary has some significant advantages in terms of water level regulation and the ability to generate continuously. The modelling is very complex and it would be a major part of a detailed study to look at the interrelationship between generation and the environmental impact. Generation from the main 'Reef' will be at reduced efficiency when the differential head is reduced below 2 metres and will all but cease when the head is about one metre unless an electronic variable speed drive system is used. With a single barrage the 'dead band' at high and low water would last at least an hour each side of high and low water. If a second barrage were incorporated further up the estuary, it would be possible to hold the high pond level several metres above low water when the tide is close to low water. The outer barrage would be closed off until the next incoming tide reached two metres above the middle pond and started to generate. The generation gap would be covered by generation from the top pond to the middle pond. A similar scenario would exist at high water where the upper barrage would be closed off several metres below high water, so that when generation stopped on the outer barrage, there would still be a working head differential between the middle pond and the top pond.



The main vertical piles of the 'Reef' structure could be extended upwards to provide support for a railway bridge, but provision would have to be made for shipping.

3.0 ACTIVE TIDAL CONTROL

3.1 This system allows the characteristics of the whole project to be altered from tide to tide, giving preference to generation, navigation, the environment and even the Severn Bore, at the most appropriate times. As the time of high water advances each day it becomes more and more difficult for a 'conventional barrage' to match the peaks in consumer demand. The lower head turbines and much larger area of lagoon allow the generation period to be biased to meet the peaks in demand. A small increase in working head caused by a delay in opening or by back pumping will allow a very significant change in the available power, without any environmental conflict. To obtain the same power on the smaller lagoons would almost certainly cause increased flooding upstream.

3.2 Having control over the opening and closing times of the barrage as well as the turbine running times, you can tailor make the tide to the needs and modify them from tide to tide. The predictability of the tide makes it possible to increase a tide to accommodate ship movements or modify the tide height and timing to maintain salt marshes, land drainage and recreational interests. It is a very complex system to model but 'active tide control' will allow the many and diverse interests to preserve their unique requirements alongside the need for power generation.

3.3 Active control may also be used to control silting and micro management of the marine environment. Careful study of the impacts of various operating regimes could lead to modifications of the system to minimise problems, something that is completely impossible with a fixed barrage.

3.4 The controlling system for the 'Active Tidal Reef' will need inputs from:

1. The Estuary model.
2. Tide information.
3. The wind direction and strength.
4. River inflows.
5. Optimisation criteria.

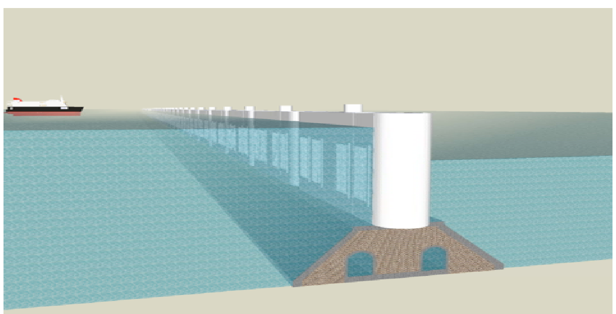
The Estuary model has to take into account the existing natural topographic features of the estuary as well as the proposed Reef structures. The location of the structures in the estuary and the distribution of the flow/resistance to the flow across those structures for all states of the tide have to be determined.

The Tide Information is also a known input but is modified by real time measurements of wind direction and strength, and in the long term, by changes in sea level.

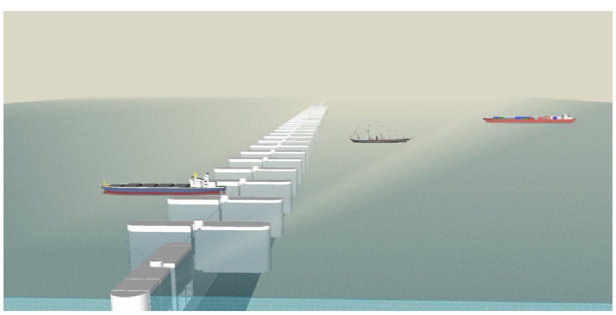
Inflows from the rivers can be based on historic data for planning or in real time from the EA for flood control.

The Optimisation criteria will be categorized by time, importance, so that some criteria relating to the preservation of habitat will carry a weighting that indicates that a particular area should be inundated by the tide x times per month (the importance increasing with time). At the other extreme, the likely peak electricity demand can be predicted in relation to the state of the tide at that precise time and the Reef operated in advance of that peak to best cope with it. In a similar way, the predicted arrivals of large ships could be coordinated with the rest of the barrage operations to minimise loss of generation whilst facilitating and possibly enhancing the passage of the ship by artificially raising water levels at the appropriate time.

Post construction study will certainly reveal changes in the sedimentation patterns within the estuary, and it may be possible to fine-tune the operating system to mitigate any undesirable effects and possibly enhance beneficial effects such as reducing the need for maintenance dredging in certain areas. A key point is that the Active Reef system can be modified as the operating data becomes available and the modelling becomes more sophisticated. Whereas filling the estuary with passive immovable structures commits everyone involved with the estuary to whatever consequences are inbuilt at the initial design stage and any that develop later.



The navigation gates not only provide the access for deep draught ships but for the unimpeded flow of water when high upstream levels must be achieved.



The large navigation gates that are shown in their open position, are floated into position during construction and floated to dry-dock for maintenance work.

4.0 THE DESIGN PROCESS

4.1 It is my opinion that the community has yet to agree what the objectives of this project should be and I think the structures and processes that are necessary to address this type of project are in danger of disappearing in a sea of proposals and reports. Underlying this project is a 'tug of war' between the environment and the economics, both of which are somewhat subjective sciences. Three discrete stages are looked at here, the overall concept, the main structures and the water turbines. Much work has been carried out into the details of the different proposals, but it is my opinion that unless the overall concept of a tidal project embraces the environmental constraints, the end result will be unsatisfactory.

OBJECTIVES

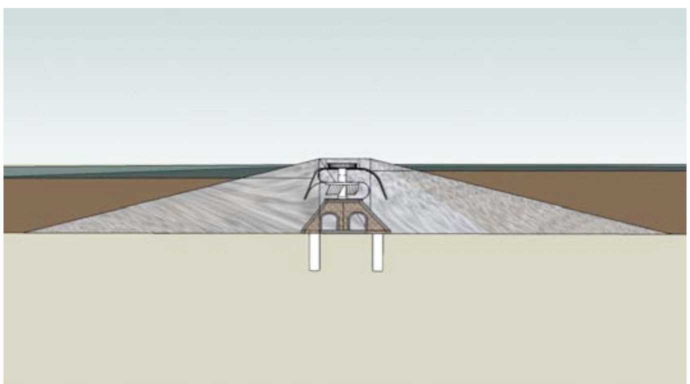
ENVIRONMENT a ECONONICS

CONCEPT x STRUCTURE x TURBINES

PROJECT

4.2 The main feature of the reef system, and from which all other things are derived is the low differential pressure/head across the barrage at any one time. In simplistic terms there is an input of energy into the Severn Estuary in the form of a body of water and a velocity (MV^2). As the estuary narrows the tide increases in height. The energy available is reduced by friction and turbulence but the higher tide means that a greater power output can be obtained from a given turbine diameter over a shorter period. I argue that this is not an advantage because the turbines are under utilised and produce short intense bursts of power that are not easily absorbed by the Grid network. There is as much energy available even lower down the estuary where the height of the tide is lower, it is simply more difficult to capture this energy because the volume of water that has to be passed through the turbines is much greater because of the lower differential head. More turbines are required, but they are simpler in construction and each one will have an output of around 3 MW instead of 40 MW each for the STPG proposal. With the 'Reef System' the generating period is increased substantially, and because the basin size is larger, the available energy is also increased, though the turbine efficiency may be lower because the design is also able to pass fish without injury.

4.3 The 'Reef' system should be cheaper to build per MW of installed capacity because of its modular structure and lower materials cost per kilometre. It is still a very large project but considerable thought has been put into reducing the risk by allowing modifications to the structures and operating system after completion, something that is quite impossible with most of the competing proposals. The output should be high because of its location to the extreme west of the estuary and the maintenance is medium because the modules can be floated to dry-dock for heavy repairs. The flood risks associated with the Reef are low or negative, since it should reduce the risk of flooding in the low-lying areas of North Somerset. The inconvenience to navigation is reduced by its position to the west and by the ability of the 'Butterfly gate sections' of the 'Reef' to open for shipping. The impact on wildlife including wading birds, sea mammals and fish should be minimal because this is the starting point for the whole endeavour. The visual impact is not minimal but can be reduced towards the shore by using low-profile turbine caissons that are almost completely submerged above the mean tide level.



A section of the 'Reef' superimposed on the outline of a typical rock and sand embankment. The difference in material content can clearly be seen.

5.0 THE DESIGN CRITERIA

To move the impounding structure as far west as possible, to maximise the electricity generation, make navigation as easy as possible and reduce the impact on local communities and wildlife.

To limit the head across the 'Reef' structure to minimise environmental impact caused by major modification to the natural tidal regime and currents within the estuary.

To reduce the materials required for the construction, by aiming for a low aspect ratio (minimum width to height ratio) possible because of the low differential pressure and extensive use of pre-cast caissons, comprised mainly of open voids and passages.

To extend the period that generation takes place and to more nearly match the periods of high demand by using the much larger area of water storage afforded by the outer barrage location.

To reduce the impact on local communities during the construction phase by relying on existing rail links, grid infrastructure and remote construction of the concrete caissons.

6.0 CIVIL ENGINEERING

6.1 A simple causeway structure is at the core of the reef system, and is low enough that it can be overtopped by storm surges and exposed at low tides without sustaining damage. Turbine modules are then floated into position and installed along pre-cast foundation modules. A 'crest gate' may be incorporated into some of the turbine modules to prevent the tidal flow from passing over when the tide is high. It will be more economic to build than a conventional barrage that is designed to counter the waves and support a higher differential pressure of at least 8 metres. The reef is almost entirely made up of turbine modules, which are comprised largely of water passages and voids, so in addition to the low aspect ratio of a caisson when compared to an embankment, much less material required. The height of the barrage is also reduced by not having to protect a roadway, having to counter storm surge levels or to take the higher operating head necessary for the 'big barrage's Kaplan turbines. Over 10 million tons of rock fill would be saved by not having to dredge a new shipping channel and further dredging would be saved by not having a relatively small number of very large turbine caissons that need a greater installation depth.

6.2 Much of the construction can be achieved using land based construction machinery such as tracked cranes, as opposed to floating crane barges that are considerably more expensive to operate. By providing a series of intermediate 'island refuges' it will not be necessary to remove construction equipment to the shore at high tide. Reducing the amount of offshore work by prefabrication. The construction period for the large barrage is estimated at 15 years, whereas Mulberry Harbour the pre-fabricated floating dock built for the D-day landing in Normandy took only six months to build in secret around the UK before being installed in Normandy under enemy fire. It comprised 9km of cast concrete caissons, not dissimilar to my current proposal. A time scale of 15 years before revenue earning would make the big project uneconomic from the start.

6.3 Rock armoured embankments about 2 km in length will lead from the shoreline to artificial islands which would be used as construction bases and later landscaped into environmental and/or leisure areas. These islands are simply the seaward ends of the embankments that are broadened to accommodate the railway sidings for transferring armour stone, aggregate and other supplies to tramways and road vehicles for transport on to the areas of operation. A causeway built from pre-cast concrete foundation units would continue along the seabed at the low tide level and would support the large water turbine caissons. The causeway foundation units have two access tunnels cast into their structure, these will subsequently be made water tight and used as cable and access routes to service islands located every mile or so along the 'Reef'.

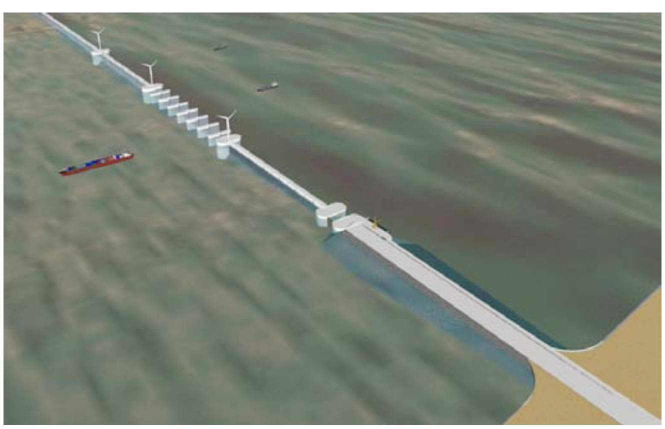
6.4 The service islands will be built higher than the rest of the structure and provide a refuge for construction plant and equipment between tides. A dock will be provided on each island for the transfer by water of heavy construction materials and subsequently for the transfer of maintenance staff and materials. A lift shaft will connect each island to the sub-sea access tunnels for the transport of maintenance staff and light materials at any stage of the tide. Each island may be provided with one or possibly two wind turbines of several MW (depending on the layout of the island). The islands will also be the location for the step-up transformers to 400,000 volts.

6.5 The turbine caissons would be built in shipyards and floated to the site and installed on the foundation causeway. Several types of caisson and turbine could be used but all would have to be designed to operate with a low differential head. The preferred design incorporates a siphon arrangement and vertical turbines. This allows the turbines to be stopped and started by introducing or removing air from the water passages around the turbines. A mechanical brake would be provided on each turbine to lock it in the event of a mechanical problem. The turbines would be installed in groups of four within a rotatable structure. This structure can be rotated through 180 degrees about the vertical piles so that the water flows the same way through the turbines whether the tide is ebbing or flowing. The rotation of the assembly could be used to clear any screens installed by reversing the flow for a short time. When the gates are rotated to 90 degrees, there is a considerable gap between adjacent units allowing the water and smaller vessels to pass. The ability to open the barrage and offer minimal resistance to the incoming tide is critical to the 'active control' of the barrage. This system allows the characteristics of the whole project to be altered from tide to tide, giving preference to generation, navigation, the environment and even the Severn Bore, at the most appropriate times. Maintenance of the turbines would be relatively straight forward, since all the components could be lifted vertically by means of a mobile gantry crane and transported to the nearest service island.

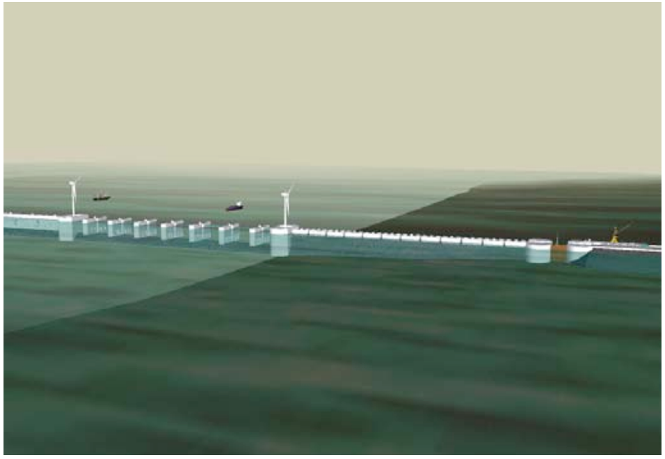
6.6 The deepwater sections, where the depth at low water is around 20 metres, would in part be developed with very large navigation gates, again rotating about vertical piles (the size of a lighthouse) sunk into the seabed. These gates would be of considerable size to safely accommodate large container ships up to 120,000 tons and having a beam up to 43 metres. In total 1000 water turbines of around 10 metres diameter would be required to produce 3 to 4000MW. The operating period at the rated head (of two metres) would be around eight hours and reduced head for another four hours. The longer generation period offered by this design will give a flatter generation curve and considerably better utilization of the plant and grid connection. It will much easier to match the generation with the consumer load

6.7 Standard and proven engineering systems have been proposed as a starting point wherever possible, though more 'advantageous' designs are introduced for further detailed investigation. I therefore started by gathering information on the environmental impacts in order to create a 'design envelope' in which the engineering is constrained, in much the same way that the 'North Sea operating environment' defined the new technology for building oil platforms 40 years ago. Environmental impact has in the past been seen more as a series of mitigating measures rather than an integral part of the engineering design. A reasonable balance has to be struck is between the local environmental impact and the wider benefits of 'green energy' generation.

6.8 The structure of the proposed 'Reef' is more modest and less intrusive to the environment than conventional 'big barrage' designs. It is much smaller than a conventional barrage but it still has the potential to generate as much electricity as a fixed full height barrage on the same site and significantly more than one located along the Cardiff-Weston route. The 'Reef' will require significantly smaller quantities of material per kilometre for its construction, so the cost and environmental impacts on land or through dredging operations will also be much reduced. The operation of the 'Reef' will require only a modest alteration to the tidal cycle amounting to a phase delay of around two hours as opposed to six hours for the large barrages. The 'Reef' will be comprised of several different types of structure, each optimised for the depth of water, the function and environmental impact. Ease of construction and maintenance will be a high priority in the engineering designs. I propose the use of caissons containing turbines with or without additional gates, being floated into position over a 'causeway structure' in the shallow water sections of the route. Deepwater sections have to open to allow the passage of large container ships with a draught that could in the future be as great as 20 metres and with a beam that could be almost 50 metres. Although the present navigation can accommodate ships up to 14.5 metres, future plans cannot be sterilised even if deepening of the channels does not take place for a number of years. I will cover this in more detail under navigation issues.



The 'Reef' would be made up from a number of different types of structure, each optimised for its particular function or selected by competing power generating companies keen to promote their particular devices.



The small craft lock is shown to the right at the end of the embankment section. For illustrative purposes a section of turbine caissons is shown leading up to an island with an optional wind turbine before a section of navigation gates.

7.0 HYDRAULIC ENGINEERING

7.1 The turbines for these very low heads are large, but need not be expensive per MW, as the materials required for their construction can be significantly cheaper than the single regulated Kaplan turbines proposed for several of the other barrage projects. The extensive use of concrete and 'resin bonded aggregates' is feasible because the water velocities are very low. Bidirectional generation is essential to minimise environmental damage and maximise the utilisation of the plant. Several different turbine types and layouts are feasible and include ducted tidal stream turbines, conventional propeller, low specific speed Francis, Darrious. cross-flow and Schneider. Each has particular advantages and disadvantages but this does not impinge on the validity of the 'Concept' or the 'Structure'. The detailed design will address not only the hydraulics but also the need for migratory fish to pass unharmed through the turbines.

7.2 A barrage located to the West of Minehead would offer, according to the study carried out in 2007, around 20Twh/annum, which is about a 50% more electricity production than the proposed Cardiff-Weston barrage. The lower mean tidal range at this location of around 9 metres, as opposed to 11 metres at Cardiff, should not in itself be a disadvantage with the proposed 'Reef' system. The longer generation period means that the probability of being able to synchronise generation with peak demand are much greater. Furthermore, a relatively small increase of head of around half a metre over the nominal operating head of 2 metres, will enable the scheme to operate at an overload capacity to meet peaks for short periods without causing environmental problems. The considerably greater storage capacity offered by the outer barrage further enhances this feature of the project because the percentage change in water level/tidal phase is much less significant and within the range variations that you would expect from factors such wind direction.

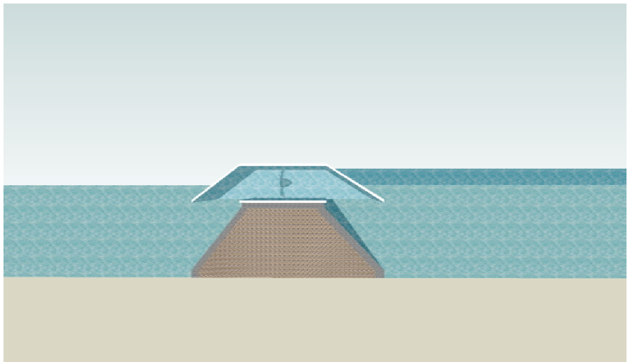
7.3 The water turbines can be one of several different designs and layouts and each has their own merits. Later on I suggest that Government provides the basic infrastructure while competing commercial companies provide whatever turbines they consider will give the best return, while meeting the necessary environmental operating parameters. The concept is based on a near environmentally benign starting point to which the engineering is applied and not vice versa. The concept of pumping live fish on fish farms is not new, neither is the passage of live fish through large low head water turbines. This is an important feature that has to be incorporated into any project because fish screening on this scale would be totally impractical. From discussions with many parties in my own capacity as a fish-screening consultant, it is thought that sudden pressure changes of more than a few meters can rupture or damage the swim bladders of some species of fish. This information needs to be collated and considered.

7.4 Large Kaplan turbines of high specific speed, have good full flow efficiency at rated head and R.P.M. but these ideal conditions are only met twice in every tidal cycle, so all other stages of the tide are a compromise, giving lower efficiency and output. By contrast the 'reef' system uses many smaller turbines that will have slightly lower full flow efficiency but which run under 'ideal design conditions' for almost the whole of the operating period. The water turbines used in a barrage such as the Rance scheme, are usually unidirectional, so a significant portion of the civil engineering cost is associated with sluices and by-pass channels to let the tide in. Bi-directional turbines, whilst requiring a more ingenious hydraulic design, save on these associated structures such as sluices.

7.5 The Simple fixed-flow turbines can be built by many more sub-contractors around the country, so the price per kW will probably be the same or even lower than the large turbines that can only be built by a handful of international companies. The use of smaller and more innovative turbine designs is possible because of the modular design and more companies have the physical capability to build them. By limiting the operating head of the turbines to less than two metres, the differential pressure exerted on the structure in much lower than for a barrage, making the construction easier and less sophisticated so pre-cast unanchored concrete caissons similar to those used in the construction of Mulberry Harbour for the D-day landing, would allow the construction to proceed rapidly during the 'windows of opportunity' when the tides and weather are favourable.

7.6 Significant engineering design challenges exist, including the size, number, type and layout of the turbines. The effect and method of controlling marine growth, the systems for installing and maintaining the turbine modules and the behaviour of the caissons under storm conditions. The routing of service and power cabling through the foundation causeway to the islands and the flexible umbilical connections will all need a considerable amount of development. The grid connection at Aberthaw power station is made to the 400,000volt super-grid. Since the coal station is no longer in use, this capacity is already available at the end of the north barrage. The closest point of the super-grid on the south side is at Hinkley Point. If capacity were available here, it would have to be connected to Minehead, probably by underground cable.

Part of the route for this 10 mile connection could be adjacent to the West Somerset Railway.



The turbine caissons could be of a horizontal duct form with 'Darrius' 'Crossflow' or 'Propeller' turbines, provided they could meet with the overall environmental criteria and in particular, being 'fish friendly'.

8.0 ENGINEERING

8.1 This proposal does not set out to define structures, turbines or operating systems but to present a logical direction for the design process and novel concepts and designs that could be developed to takes into account the wide spectrum of environmental concerns. Limiting the operating head of the turbines to less than two metres reduces the pressure exerted on the structure. The construction is then easier, less sophisticated and cheaper. The construction can also proceed more quickly during the 'windows of opportunity' when the tides and weather are favourable.

Navigation requires a depth of over 20 metres to accommodate the existing generation of cargo ships. Dredging operations would be far more modest for the 'Reef System' as ships could pass through 'Butterfly Gates' or a low lift ship lock for only two metres of differential head.

Large Kaplan turbines of high specific speed have good full flow efficiency at rated head and R.P.M. By contrast the 'Reef' system uses many smaller output turbines that will have slightly lower full flow efficiency but which run under 'ideal design conditions' for almost the whole of the operating period.

9.0 NAVIGATION

9.1 Navigation in the estuary requires a depth of over 16 metres to accommodate the existing generation of post-panamax cargo ships and this may well have to increase to accommodate the next generation of container ships up to 120,000 tons. The proposed Cardiff-Weston barrage requires the dredging of a new channel to Avonmouth, and the removal of around 10 million cubic metres of material. The ship locks are only designed to pass the current post panamax ships. The prime considerations for the existing and planned ports, is maintaining the high water levels, the depth of the channels and minimising the disruption to shipping traffic.

9.2 The 'Reef Project' with its small head differential can be designed with locks that need to withstand only one third of the hydrostatic pressure, and are therefore cheaper to build. The low lift lock could be a completely pre-cast structure that is floated into place like a floating dry dock. It is also intended that wide sections of the barrage structure can be opened at all or some stages of the tide so that ships that can safely navigate a twelve knot current can pass straight through without being delayed. This will result in a loss of generation in the immediate vicinity of the opening, but it would be for a relatively short time. This type of 'flashing' system was extensively uses on early river navigations, and a detailed investigation into the practical operating conditions, savings on the civil engineering and cost/benefits of lost generation versus delays to ship transit time, would have to be carried out. Structures similar to the Thames Barrier or that proposed to protect the Venice lagoon from storm surges may be considered, but I propose a novel 'Butterfly Gate' which may also incorporate ducted tidal stream turbines.

9.3 The 'Butterfly Gates' would have a vertical axis of rotation about a seabed implanted concrete pile. The pile itself would measure some 10 metres in diameter and extend above sea level to accommodate a platform with navigation aids and possibly a large wind turbine. The pile would extend below seabed and be grouted into the rock and possible intersect a sub-sea service tunnel. A structure in the form of a pre-cast sill would be installed between adjacent piles and form a close fit with the 'Butterfly Gate'. The gates themselves, weighing in at around 10,000 tons, would comprise a cast concrete hull through which the turbine ducts would pass. The turbines, if installed, would be hydraulically asymmetric in that the flows would always be in the same direction but the complete gate would rotate by 180^0 to face the water flow. While rotated to 90^0 ships would be free to pass through unhindered. To achieve this the clearance between a pair of pile would be over 150 metres and the depth around 20 metres. Installation and maintenance would be achieved by floating the complete gate away from the locating pile and towing it to a suitable dry-dock. Rotation of the gate could be achieved by means of thrusters or motoring one of the turbines once the locking mechanism has been released.

9.4 Navigating the outer 'Reef' should be less hazardous because simply because the water is deeper and there is more room for ships to manoeuvre. Once inside the 'Reef' the navigation would be unaltered all the way upstream, whereas the Cardiff – Weston scheme requires ships to manoeuvre into a lock, with a consequent delay and to navigate an estuary that will be much altered.

10.0 FLOODING

In the event of a storm surge, controlling the opening of the barrage could regulate the maximum upstream levels, while land drainage outfalls at a number of locations compromised by the Cardiff-Weston barrage 'holding' the high water for several hours, would be unaffected.. The 'Reef Project' requires only a short dwell period, which could be as little as one hour, to allow a fall of around 1500mm before generation can start. Near high water when the head is no longer adequate for power generation, the 'butterfly gate' sections of the barrage could be opened to allow the remaining water to continue up the estuary. The reduction in the peak tide level would thus the minimised (and even the Severn Bore might continue under certain conditions). Energy lost before high water can in part be recaptured by allowing generation to start earlier on the falling tide. The degree that storm surges can be attenuated by such a structure will depend on many factors and require extensive computer modelling. The technology of installing large concrete piles was pioneered by Seacore in the UK and used (on a smaller scale) to install navigation lights in the Severn Estuary and also the Tidal Stream Turbine off Lynmouth for which I designed and built the prototype.

11.0 ENVIRONMENTAL

11.1 The 'Reef System' is designed with the environmental constraints such as Natura 2000 to the fore, as opposed to mitigation measures after the engineering has been designed. The phase change in the tides and the alteration of the natural regime will be significantly less than for a conventional barrage, resulting in minimal disruption to migrating fish, bird life and the mudflat ecology. The 'Reef' is in effect one continuous line of small turbines, typically 5MW each, so the tidal flow is not diverted across to a smaller number of large turbines of over 40 MW each that would radically alter the water flow patterns within the estuary, with the possible consequences of erosion or silting. The local flows are further increased by virtue of the short generation period to give a local flow at least six times the natural flow.

11.2 Migratory fish can pass safely through the 'Reef' by incorporating slower running, low specific speed turbines of fixed geometry. This type of turbine need not be more expensive to build on account of the simplicity of design, the lighter construction and the use of lower cost materials, all made possible because the operating head is both low and constant. For fish to pass through the turbines without injury it is necessary to have wide clearances, smooth surface finishes and the lack of pinch points. A differential operating head of around two metres will not adversely affect fish by rupturing their swim bladders, which might occur if the head difference was greater. The choice of low specific speed turbines with a small number of blades with wide openings is feasible on this very low head, which should allow the safe passage of salmon and sea mammals.

11.3 Loss or altered habitat resulting from the altered tidal range is largely avoided with the 'Reef System' simply because the working head is so much less and the resulting changes very much smaller. Flooding and peak tides should be reduced upstream of the reef and only marginally altered on the seaward side because the delay in the tide cycle is so short. Difficulties with land drainage outfalls should also be reduced, simply because the deviation from the natural tidal range will fall within what is experienced naturally, even if the pattern is altered marginally. Almost all the environmental and navigation concerns are as a direct result of the high differential head resulting from the long 'dwell' at high water. The first objective of my proposal is to reduce this 'dwell' period to around two hours or sufficient to produce a head differential of around two meters.

11.4 Dredging and quarrying will be much reduced with the 'Reef Project' when compared to the 18 million mt^3 required for the big barrage. On-shore infrastructure environmental impact will be lower for the 'Reef' because the more constant generation will make better use of the electrical infrastructure and 'hard engineering' structures will be physically smaller. Distributing the construction of caissons between several shipyards around the country will cause less disruption to the sensitive local environment and possibly improve employment in locations that do not have the capability to build the large 'big barrage' caissons'.

11.5 The aesthetics of the estuary and surrounding landscape, while being altered by the 'Reef' project, will not be altered as much as that required by any of the 'big barrage' proposals. Parts of the 'Reef' close to shore will be almost totally submerged at most stages of the tide, while the 'Butterfly Gates' will be well out in the estuary. The other 'big barrage schemes' will tower fifteen or even twenty metres above low water level, and four or five above average high water levels.

12.0 ECONOMICS

12.1 The material required for construction the 'Reef Project' will be significantly less than that required for a 'big barrage' because it is lower and only has to withstand two metres of head difference, and there is no need to have expensive 'non-revenue generating' technology such as sluice gates. No road is incorporated, because the cost of providing the extra height and protection from waves is not the most economic way of providing a road crossing. For each metre increase in height you have to provide about five metres of width. So a structure half the height of the 'big barrage' uses about a quarter of the material. No conventional ship lock would be needed as a single or double gate flush lock will allow ships to pass through at any stage of the tide, and dredging a new shipping channel would also be avoided.

12.2 The generation profile of the 'Reef Scheme' would be flatter, generating less power but for a longer period. This requires smaller generator and electrical transmission capacity, and a corresponding reduction in the intrusion on the landscape as well as improved electrical efficiency and utilization. Returns from the electricity generated will be seen well before completion of the project using the 'Reef System' improving the early economic returns significantly.

12.3 The simple fixed-flow turbines for a 'Reef System' can be built by many more sub-contractors around the country allowing local manufacture, so the price per kW will probably be the same or even lower than the large turbines that can only be built by a handful of international companies. For maintenance the complete sealed turbine units could be lifted out and replaced with a serviced unit. Unlike the 'big barrage' turbines that are far too heavy to lift out once installed and require conventional dry powerhouses with personnel inside them to be protected from the elements.

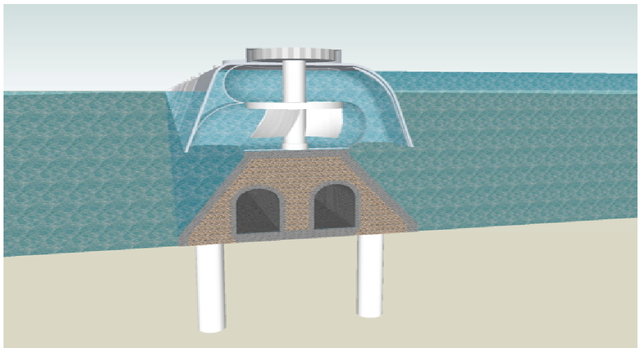
12.4 A mixed public/private partnership would be much easier to implement with the 'Reef', because the main infrastructure including the underwater foundations could be public funded, with secondary power developers bidding for space to install a range of competing turbine devices along the barrage (similar to the planned 'Wave Power Hub' off the North Cornwall coast)

12.5 The Risks during installation of a 'Reef' are reduced because the technology is kept simple and 'mammoth' operations are kept to a minimum or eliminated all together. Because of the nature of the working environment with strong tides and poor weather, the installation of the huge caissons for the 'big barrage' would be very risky. Building the scheme in smaller steps reduces risk. The long-term performance of the project will be more secure if several technologies and competing developers install many turbines. The chances of catastrophic failure are much reduced with the 'Reef Concept'. The Unknowns relate mainly to the environmental impacts and large scale marine operations, such as placing the caissons. The smaller the barrage and alteration of the tidal regime the lower the environmental risks and the cost of mitigation measures. The smaller the caissons are, the less the risk there is of an expensive accident.

12.6 The number of man-hours required for offshore operations will have to be kept to a minimum if the cost are to be contained, reducing the risks of engineering failures and environmental disturbance if the concept is kept simple and the turbine modules are relatively small, though numerous.

12.7 Revenue earning could start within a couple of years of work commencing on the 'Reef Project' and well before the barrage is completed. This is possible because of the low differential head. So although the water will tend to flow around the completed sections, generation should be possible at reduced efficiency. A total construction period of five or six years would make the project much more attractive financially.

12.8 The 'Shoots Reef' could incorporate a rail connection within the 'causeway' structure which would be prefabricated and sunk to the bed of the estuary.



An alternative method of construction at the 'Shoots Location' might employ a 'Causeway' that included railway tunnels as part of the base structure.

13.0 THE PROJECT SUMMARY

13.1 The route for the proposed 'Tidal Power Reef Project' (a low differential head barrage) would run from Warren Point just east of Minehead in Somerset, to Breaksea Point near Aberthaw power station in South Wales. This route is proposed in order to obtain much energy as possible from the tides but without encroaching on the Exmoor or Glamorgan Heritage Coasts. This route can take advantage of an excellent rail link to Aberthaw, existing industrial and National Grid facilities at the old power station and existing cement works. On the Somerset side, the West Somerset Railway passes within a mile of the landfall and has recently been engaged in transporting large quantities of armour-stone from Merehead Quarry for sea defence work at Minehead. Whilst disruption in the immediate area of the landfall would be inevitable, the town of Minehead itself would be bypassed by all construction traffic, and could benefit from the project because of extra visitors. A route further west between Nash point and Hurlstone Point would be slightly shorter and enclose a further 120 km^2 but the depth is greater and the access is more difficult put it should be considered in outline.

13.2 Remote construction depots would be required to receive materials and construction personnel, and trains would run to a forward depot located at the seaward end of a rock causeway about a mile offshore. The Minehead rail connection would be made from a point near Dunster station and cross the low-lying land to the coast just east of Warren Point. A rock armoured peninsular would stretch about a mile out to sea and carry the standard gauge line to transfer sidings and a dock on the lagoon side of the peninsular. The dock would be for the transfer of heavy materials including rock armour stone to barges for placing offshore. The transfer area would allow materials including the long lengths of insulated high-voltage cable to be lifted onto special narrow gauge wagons for transport down into the sub-sea cable tunnel, a process almost identical to that used during the construction of the Dinorwig pump-storage scheme in North Wales. A travelling gantry would also be used to lift heavy items such as transformers from low-loading railway wagons. This peninsular could later be reclaimed and established as a marine park or leisure facility, allowing visitors to walk, cycle or travel by tram, out to the start of the 'Reef'.

13.3 Artificial islands, would be built about a mile off-shore to store and transfer construction materials, and be connected to the shore by rock armoured embankments, which would also carry railway sidings. A dock for ship borne materials would be provided on the lagoon side of these main islands. Electrical sub-stations may also be located on these islands. Suitably designed and landscaped to hide the engineering facilities and underground high voltage electrical connection to the shore, these features could be an environmental asset.

13.4 The construction period for the project should be considerably shorter than the 15 years being mooted for the Cardiff-Weston scheme. The high 'front end cost' of this type of projects makes it exceedingly desirable to get some revenue as early on as possible. The low operating head makes this possible because even a partly completed barrage will produce enough head to run the turbines, be it at reduced output. The modular nature of the design allows many of the components to be built in parallel and remote from the main site.

13.5 The impounding 'Reef' structure would be comprised of several different types of construction, each optimised to its particular function. An approach embankment would carry the railway siding from the West Somerset Railway, underground power cables and also make the connection with the coast. It would be designed with the environment and aesthetics as the prime consideration because of its close proximity to a nature reserve, golf course and leisure facilities.

13.6 The sub-sea spine or Causeway (exposed at low-water spring tides) is intended to provide land access for construction machinery and avoid costly use of jack-up and lifting barges for many operations. The pre-cast concrete caissons that would be constructed at other industrial locations, would be floated into place, located and filled with rock-armour and possibly suitable salvaged building rubble and concrete. A light contractors railway would be required to transport the fill during the short windows of suitable weather and tide. The Main island depot would be used to accumulate material brought in by rail, so that it could be deployed rapidly when the conditions were right. The causeway would be constructed by drilling into the seabed from a jack-up barge in the same manner as the navigation lights were installed for the second Severn crossing. The connecting foundation units would be floated into place and armour stone placed to fill the void between the foundation unit and the irregular seabed. The pile installation is a well proven technology even in these difficult waters and establishes a secure datum from which all subsequent activities are related.

13.7 Service Islands would be built at intervals of about a mile as refuges for plant and equipment and later for the location of electrical services and sub-stations. Additional wind turbines might be erected on these islands as appropriate, because of their exposed position and proximity to electrical services. An additional 30MW of capacity might be added in this way. Each island refuge would communicate by means of small diameter tunnels (three metres) passing through the 'Causeway' caissons. One tunnel would carry the high voltage cables back to shore, and the other would be provided with a road tram or light railway for moving maintenance crews and light materials between the islands and the Main depot. Mooring facilities would be provided on each island for unloading heavy items of plant.

13.8 Work on the Causeway that could be the publicly owned part of the 'Reef' project, could progress relatively independently of work on the turbine caissons and navigation gates that would be built and probably privately owned and financed. The caissons being relatively modest low-tech structures could be constructed by a large number of sub-contractors around the UK, further reducing the need to concentrate a large workforce in a small area.

14.0 THE TURBINES

The working portion of the 'Reef' would comprise a large number of turbine modules, floated into position astride the 'Causeway' and secured. Several different types and layout of turbine are feasible, and it would be for individual developers to select what they considered to be the best option. These options include the more unusual bi-directional designs or conventional propeller and Francis designs with methods for diverting the flow in the same direction through the turbine during both ebb and flood. My own preference for a very low speed 'fish friendly' mixed flow turbine. Such a turbine would have to be installed vertically and be built in the form of a siphon, so that the application of a vacuum or air pressure can start or stop individual turbines.

15.0 THE NAVIGATION

15.1 A conventional barrage with a head differential of 8 or 10 metres requires a ship lock that takes some time to negotiate and delays ship movements, something that is important when turnaround times in dock are very short. Manoeuvring into a lock where the channel width is limited and part way up a difficult estuary also gives cause for concern. The delay caused by locking through could well pose additional difficulties if a ship for any reason has to wait upstream of the barrage for the next tide.

15.2 The 'Reef' proposal for shipping is based on an inbound vessel being able to pass through the barrage at low water with no significant current, and in an area much further west where there is more room to manoeuvre and the water is deeper. Transit through the 'Reef' should result in only a short delay, as there is only one gate like the Thames Barrier. From low water the velocity through the gate when open, will increase to a maximum after two hours of about 2 knots. It should be possible to limit the current through the gates to about 5 knots and still have only one gate. The proposed opening would be two or three times the beam of the largest container ships afloat (120,000 tons post-panamax).

15.3 For small craft and if the above proposal is not considered practical, a large rock embanked pound provided with two gates could be constructed and which would introduce only a short delay. Sluices in the sides of the pound would keep the ship central in the pound, a system that is used with very large barge strings on the Mississippi navigation.

15.4Progress up the estuary to Avonmouth and beyond would then be similar to the present navigation but the rising tide would be delayed by up to two hours. Because the 'Reef' is a long way down stream and the currents within the estuary will be little changed because the flows through the 'Reef' are evenly distributed along its length. The alteration to high water levels can to some extent be modified from tide to tide to accommodate large ship movements.

16.0 ACTIVE TIDAL CONTROL

16.1 Only limited flexibility to accommodate specific environmental changes that may occur after commissioning can be achieved with conventional barrage, but because the tidal 'Reef' system operates on a very small head difference, it is possible to modify the operating regime to take account of the predicted height of the tide, the time of day or year. This means that if there is a particular requirement for navigation, power generation or salt marsh ecology, it would be possible to change the point at which generation, barrage opening and barrage closing take place. If an upper estuary scheme (Shoots) of a similar design were included, even more precise control would be possible.

16.2 The 'Reef' operating concept could potentially remove almost all the conflicts with the inter-tidal habitat, but at spring tides it may be desirable to allow the full height of the tide to wet the upper areas of salt marshes. The frequency of these events and even the preservation of the 'bore' will depend on many factors, including the value of the power generation lost and the needs of the particular habitat. Achieving the necessary height but for a shorter duration may also be a compromise but requires a considerable amount of computer modelling.

17.0 COMMUNITY IMPACTS

17.1 The period of disruption for Minehead would mainly be confined to the construction of the landfall and causeway connection to Warren Point. If the majority of the workforce is brought in by train from suitable assembly points, the number of extra cars on the roads in the area should not increase dramatically. There will undoubtedly be an increase in the number of people visiting the area to see the construction.

17.2 Employment prospects during the years of construction will be considerable, and be spread over a wide range of manufacturing and service industries. Locations with specific marine expertise will obviously be in a good position to secure major tenders. Shipyards and marine contractors will be well placed for the construction and later for the maintenance work on the 'Reef'.

Appendix 1

	COST per KILOWATT	POWER OUTPUT	MAINTENANCE	FLOOD DANGER	NAVIGATION IMPACT	WILDLIFE IMPACT	VISUAL IMPACT
LARGE BARRAGES	Med	High	Med	High	High	High	High
TIDAL LAGOONS	Med	High	Med	Low	Low	Med	Med
TIDAL 'REEF' PROJECT	Low	High	Med	Low	Med	Low	Med
TIDAL FENCES	Med	Low	Med	Low	Med	Low	Med
TIDAL CURRENT	High	Low	High	Low	Low	Low	Low

The above table has been included to give an indication of the relative merits and impacts of the competing systems in the opinion of the author.

Appendix 2
THE CASE FOR THE 'REEF'

Argument 1. (The water levels)
It will be legally impossible to employ a conventional fixed barrage that delays the tide significantly to produce a substantial hydraulic head of water to run the turbines. This is because it would damage protected habitats, kill a significant percentage of migrating fish and disrupt commercial navigation.

Argument 2. (Grid connection)
Generating a lot of electricity for short periods during the day causes major problems for the grid system and reduces the 'load factor' on the cables. With the increase in wind power it is essential that the Severn Tidal Project can closely match demand and buffer variations from the wind power installations.

Argument 3. (Siltation and erosion)
Releasing all the stored water from a barrage or lagoon over a short generation period will cause major changes to the sedimentation and currents within the estuary. Being inflexible in nature, any adverse consequences will be almost impossible to mitigate.

Argument 4. (Problems after construction)
All large civil engineering projects have unforeseen problems. The 'Reef' project is the only one where the operation can be altered significantly to take account of these problems and take account of future changes in environmental and commercial needs.

Argument 5. (Scale of project)
Small projects can take as long to execute as larger ones and have disproportionate costs associated with planning, so if we are serious about tidal power we should go for the largest feasible project so there is enough capacity to allow for environmental mitigation measures.

Argument 6. (Local disruption)
All big projects cause some local disruption. The choice of Minehead to Aberthaw with its rail connections allows the construction facilities to be located back from the coast along the railway or out to sea on the approach embankment and away from the town.

Argument 7. (Flood alleviation)
Placing any form of resistance to the incoming tide or escaping river flows will increase the danger of flooding. The 'Reef' is designed to have three times the opening area of the Cardiff-Weston barrage and being an 'Active Structure' like the Thames Barrier, and located to the west, it should reduce the risk of flooding from the sea and the river.

Argument 8. (Practicality)
Only a few of the ten schemes being investigated have active proposers and of those that have, some are not hydraulically practical. The 'Reef' uses many established offshore engineering techniques and traditional turbine designs, but put together in a novel and flexible way.

Argument 9. (Local employment)
Large projects usually require large companies who favour large items of equipment including the turbines. Since only a handful of international companies can build these turbines, there will be less local work. The 'Reef' is designed so that the turbines can be built in many small West Country shipyards.

Argument 10. (Cost & value)
Large inflexible projects invariably suffer from serious cost over-runs. The 'Reef Project' is divided into many smaller activities and components, which should promote more competitive pricing. The value of the 'Reef' in promoting local industry and integrating with the energy supply of the UK is as important as the first cost. The 'Reef' could save between 10 million and 15 million tons of CO^2 per annum.

Appendix 3

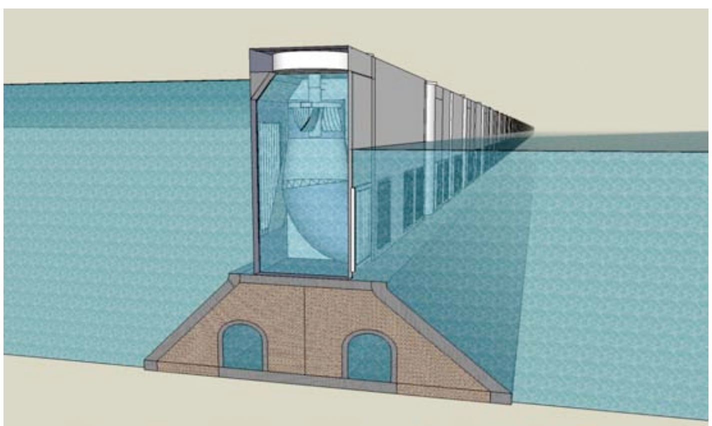
GENERAL OBJECTIVES

- To capture a significant percentage of the tidal energy available within the Severn Estuary but with minimal impact on the populations of wading birds, migratory fish and commercial shipping interests.
- Minimise the alteration to the natural tidal cycles, pollution and disruption during the construction and during operation, will minimise the negative impacts on wading bird populations.
- Installing water turbines with minimum head difference, maximum internal clearances and smoothest internal finish, will minimise mortality in migrant fish populations.
- Positioning the impounding structure so shipping can anchor safely outside or just inside the "Reef' and that a single line of 'navigation gates' with a clearance between adjacent fixed elements is at least 2.5 times the maximum beam of any ship, will minimise delays and disruption to traffic. That flexibility in the operation of the 'Reef' would minimise the reduction in navigation depths at Avonmouth and at critical times for the passage of any particular ship.
- There has to be a need for 'renewable energy' and it is my opinion that the alternatives will be very detrimental to the planet and that we will need conservation and small scale projects as well and not as a substitute to the large ones.
- The Severn Estuary is a very sensitive and highly protected environment and it is unrealistic to think that the various environmental groups will not come together to (quite rightly in my opinion) challenge any conventional 'barrage project' in the European Court, and will delay any project or extract such conditions as to make it impossible to build and operate.
- If a project is to be designed and built in the estuary, it must take the environmental constraints as the starting point, so if hydraulic engineering compromises have to be made (as they would) you have to have energy to spare (or you won't have anything left. The principal constraints are the inter-tidal feeding grounds, the migratory fish and the navigation.

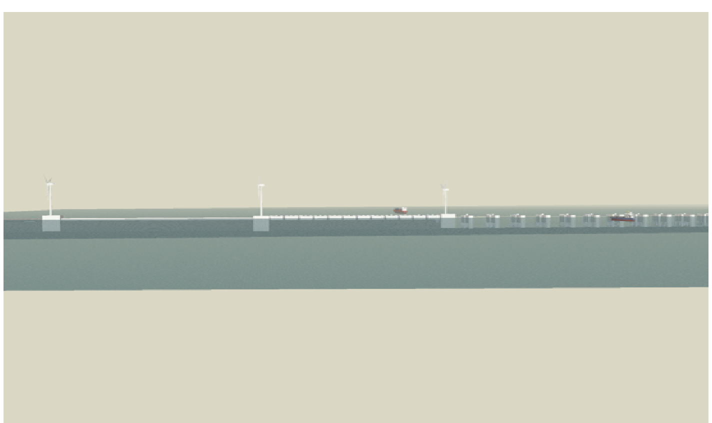
GENERAL ASSUMPTIONS

- That the flood risks will be reduced from both river and sea if the 'Reef Structure' can delay the tide and/or extract energy from it and so reduce its height.
- That it is possible to maintain a regime that does not result in the reduction or damage to sensitive habitats such as salt marshes but is dovetailed into the requirements that have a much shorter 'time constant'.
- That a project that release the water flow from a barrage or lagoon in a short time will cause a significant change in the circulation and probably the siltation regime of the estuary and should be avoided.
- Those structures with minimal visual and operational impact on local communities and businesses are favoured.

- That local labour and resources should be employed if desired by the local community.
- That integration of the project with the National Grid to improve the load balancing rather than introduce unmanageable surges in power generation that is unmatched to peaks in demand is important.
- That producing a project that is more cost effective than any of the other tidal projects being proposed and to compete directly with nuclear power when taking plant life and decommissioning into account is important.
- That being a power generation project within environmental constraints any reduction in flood risk is an advantage but that any major enhancement in flood protection capability would be considered and funded separately and compared with the cost of other mitigating measures.
- That if pump storage features were included in the project for the purpose of levelling the load on the National Grid, the value of the facility and the upgraded electrical interconnection costs would be fairly apportioned between the project and the National Grid.



The navigation gates could contain a number of different types of turbine. Illustrated are vertical shaft turbines with conventional screens.



Distant view showing some of the different types of caisson and optional wind turbines, that could be used as aids to navigation.

Appendix 4

HYDRAULIC ENGINEERING ASSUMPTIONS

- That a cyclic tidal system operates in a manner not dissimilar to an electrical capacitor network, in that energy may be extracted on either the ebb or flow or both tides, and that if sluices are employed in any part of the cycle, any head loss at the gates is expressed as resistance to the flow and results in a reduced tidal level upstream and a consequent loss of energy.
- That energy may be removed from the kinetic energy in the tidal flow over a long period with a 'Tidal Stream Turbine' or the water is stored behind a barrage and converted during a short period into kinetic, then to mechanical and then to electrical energy. Following from this it is assumed that producing a small head differential of two metres makes it easier and more efficient to convert the potential energy into mechanical power since the kinetic energy at entry and at exit of the turbines are constant (because there is no change in section of the estuary). So although the 'Reef' has a nominal head that is significantly less than for a fixed barrage, the energy capture can be as high because the generation period is longer.
- The inherent exit losses in such low head turbines (because the exit velocity cannot be reduced below the inlet velocity, because you are in a confined estuary and not operating from a storage reservoir) is in part off set by the reduced frictional losses expressed in terms of an increased tail water level down stream of a barrage that occurs when you release all the stored water in a reduced period of time.

EXCLUDED HYDRAULIC ENGINEERING OPTIONS

- Barrages that create a head difference of more than a few metres were excluded because fine screening to exclude migrating salmon smolts would become blocked in minutes and allowing them to pass through the turbines would possibly kill them because of the rapid change in pressure.
- Lagoons draw in and release vast volumes of water in order to produce significant amounts of power. They will therefore draw in a significant percentage of the migrating fish population, of which as much as 40% may be killed if conventional water turbines are used. There remains the problem associated with the rapid release of stored water in a confined area of the estuary that will undoubtedly have a significant effect on the circulation and deposition of silt.
- Tidal Stream Turbines have been excluded because, like wind turbines the energy extraction is subject to the Betz limit and can only the deployed in an array to avoid 'shadowing'. Installing such turbines in a 'Fence' configuration is not hydraulically feasible because, as with the 'Reef', the entry and exit velocities are identical (because there is no change in the cross-section of the estuary at the turbines) so the only energy available would be from a head differential, which is what the 'Reef' does. Below about two metres of head the

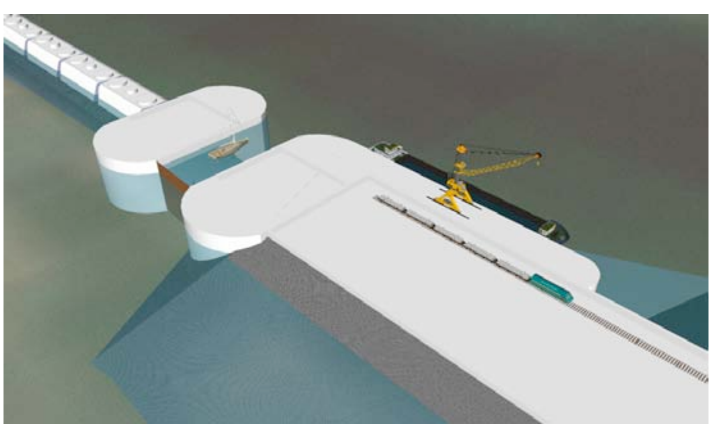
inherent loss are very significant and the required swept area of water turbine cannot physically be fitted between the shores of the estuary.

PROPOSED HYDRAULIC & CIVIL ENGINEERING DESIGNS

- The 'Reef' structure would be comprised of several different elements, each optimised for its particular function. The landfall sections of the 'Reef' across the beach and into shallow water are intended to provide the transfer areas during the construction period and visually attractive recreation and/wildlife areas after the construction period is completed. Looking similar to an undisturbed promontory and shoreline, the embankment would push the small craft locks and working parts of the 'Reef' at least 1km out from the shore. The embankment itself would be comprised of an outer armour stone facing and an inner core of selected landfill such as demolition rubble. Having rail connections, the material could economically be collected from a considerable area of the country as an alternative to paying landfill tax. A conventional reinforced concrete seawall would protect the seaward side of the crest out to the small craft lock and barge quay. It is proposed that these parts of the 'Reef' could be completed well in advance of the main project and before the final decisions on construction were made because the materials would comprise rock and land fill, and the end result if the project did not go ahead would simply be a promontory extending into the estuary.
- The shallow water sections of the 'Reef' extending from just below the low water level to the navigation gates at around 15 metres below low water, would comprise causeway base caissons located on piles and filled with rock armour on the outside and selected land-fill to the central core. Several different types and layout of turbine could be considered for these areas. I originally proposed floating turbines with or without bascule crest gates to minimise the visual impact but able to extend to the full height of the tide. While the system of floating the turbine modules into place during construction and removing them to a dry-dock for maintenance still holds true, the visual impact of the turbine modules offshore is considered less important than the simplicity of a fixed design that is set higher out of the water and uses a siphon arrangement to stop and start the turbines. Various types of turbine may be considered with reference to efficiency, fish friendliness, ease of maintenance and need to be rotated into the flow or not. I have illustrated rotatable modules of four 'fish-friendly' turbines with vertical shafts. The objective was to provide additional clear passage for the water flow through the 'Reef' when the conditions dictated and when the modules were rotated through 90 degrees. However, I now consider the advantages of shorter modules comprised of just two turbines, one on each side of the pivot, to be more advantageous. If rotation is still required because of the asymmetrical hydraulic passages and to clear debris from the guard-screens, it is better to allow the water to continue through the turbines even if there is too little head for

generation. This is because the open area is greater than for four turbines rotated through 90 degrees and the unit is structurally stronger.

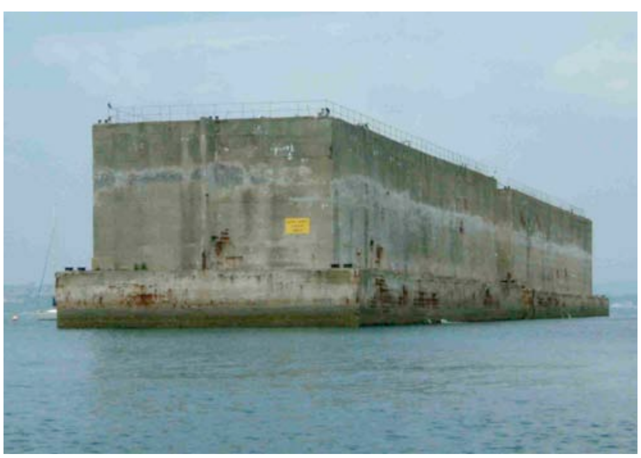
- My preferred design is a low specific speed mixed-flow turbine similar to that known as an 'Empire Turbine' manufactured by the Armfield Hydraulic Engineering Company from about 1880 and based on the 'Little Giant' turbines made in considerable numbers in North America during the latter part of the nineteenth century. With very low specific speed turbines there is no requirement for an expanding draft-tube, that is a great advantage in this situation, as a more conventional Kaplan turbine would require over 50 metres of draft-tube doubling the width of the structure. With an inlet volute and no guide vanes this design is well proven and ideal for the safe passage of migratory fish. Investigations into the design using modern computer modelling and novel composite materials should raise the efficiencies and reduce manufacturing costs.
- The deep water navigation gates present a significant engineering challenge, mainly on account of their size, but they have several features operating in their favour, not least of which is the relatively conventional vertical turbine layout. Considerably more flexibility is afforded by the greater height and a range of specific speed turbines, with or without screening, could be used.
- The gates themselves weighing around 15,000 tons each and made of reinforced concrete open to 90 degrees to provide an enormous opening for both ships and to pass water when there is no longer enough head for useful generation. The large opening is required to pass the full flow with minimal resistance when it is necessary to maintain the high tide levels at Avonmouth at neap tide to maintain navigation depths. The large openings are also required when swinging the generation period to coincide with peak demands periods. To install and maintain the gates and the turbines within the gates it is necessary for them to be buoyant while in transit to a dry-dock. It will also be necessary to empty ballast tanks so that the gate floats in a semi-flat attitude to reduce the draft from the 18 metres in an upright position.



Illustrated is the transition between the rock embankment with its railway transfer sidings and a turbine section with a small boat lock in between.

A completed section of one of the Mulberry Harbours, built in secret in six months and towed to France during the D-Day landings under enemy fire. If we are serious about renewable energy generation, why should it take over 10 years to build a not dissimilar scale of project.

Aberthaw, shown in this photograph, has a rail link, cement works and 400,000 volt super-grid connection to the coal fired power station.



A Phoenix caisson that has survived un-maintained for over 60 years, since being built for Mulberry Harbour during WW2.

Appendix 5

THE CONCEPT

- To limit the head differential to that which allows enough turbines to physically fit within the width of the estuary and yet doesn't result in a change in pressure across the turbine that will kill fish as they pass through. Limiting the head also minimises the loss of inter-tidal habitat for feeding birds and allows ships to pass through the opening sections of the 'Reef' at all stages of the tide (though slack-water is the easiest and results in no loss of generation. Despite the low head difference across the 'Reef' the same energy is captured because the generation period is longer and the water has time to flow away from the structure much as before, whereas the 'conventional barrage approach' necessitates higher flow rates during the generation period (to catch up with the falling tide). The hydraulic engineering consequence is the need for a larger number of lower powered turbines to pass the water at a lower pressure, This is therefore an engineering consequence of the environmental constraint.
- To design a turbine arrangement that will not injure fish as they pass through (it is not physically possible to screen out the fish on such a project and fish deflection systems have only a limited effectiveness). With very large inter-blade spaces, no guide vanes, no 'pinch-points' and smooth surfaces the % kill should be very small indeed. Meeting this benchmark would give the 'Reef' a considerable environmental advantage over all the other barrage options and the lagoons.
- To design a system that presents minimal disruption to the transit of shipping up to Avonmouth and beyond. Any conventional double lock system would be very expensive because of the 120,000 ton container ships that the Bristol Port Company are designing for, and introduce unacceptable delays. This feature would give a significant advantage over other barrage options.
- Power production from a 'Reef' located between Minehead and Aberthaw could produce between 11TWh and 14TWh of electricity per year depending on the level of hydraulic compromise necessary to achieve the three cardinal criteria.

Appendix 6

THE ECONOMICS OF THE REEF PROJECT

It is important when carrying out a cost benefit analysis for a tidal project such as the 'Reef', that all the costs and benefits are identified if not quantified. Conventional accounting procedures that write-off the capital cost of a large long term project such as this can underestimate the benefit by as much as 50% (The North of Scotland Hydro-electric Board on privatisation had enormous revenue assets with little or no book value). A simple internal rate of return or price over earnings ratio gives a good comparison between competing projects.

The costs/price has to include (but difficult to quantify in financial terms) any penalties that accrue to the environment and the benefits should include significant items such as the benefits to the operation of the national grid system. A conventional tidal barrage operating for short periods during each day imposes many additional costs on the electricity distribution network. Although the tides are predictable, generating high outputs for short periods results in significant losses and/or poor utilisation of the power lines.

The large low headwater storage capacity of the 'Reef' allows the generation periods to be biased towards the periods of maximum demand without imposing a risk of flooding upstream. This is because a small increase in operating head (less than one metre) would nominally double the power output of the project for a short time. The value of these peak half-hour periods is significant in that the marginal cost of generation from other sources is much greater than the average, to the extent that back pumping may at times be economic, despite introducing significant additional losses. Pumping may be advantageous when maintaining navigation depths at specific times of the day and lunar cycle.

The planned increase in wind power capacity brings with it the difficulty of matching generation to demand. Short-term transients in power generation, from a few minutes to an hour could be met provided it did not coincide with the 'dead bands' at high or low water. Introducing a second reef or lagoon would help to bridge this gap by allowing continuous generation. The control strategy and the cost/benefits are exceedingly complicated and dynamic but would appear to have a significant bearing on the economic case for building the 'Reef' project.

The 'Tidal Reef' is an 'Active System', in other words the operating system can be altered from tide to tide to take into account the height of the expected tide, wind conditions and the competing demands of power generation, navigation and wildlife. Unlike all the other proposed systems, the 'Reef' can be modified to take account of unexpected or planned changes in the future.

A significant contribution to the costs of building any large marine structure is undoubtedly the mitigation measures required during construction phase to minimise local disruption. By selecting a site that can be approached by sea and rail as well as road and does not come close to any particularly sensitive areas, the construction of the 'Reef' should be easier to manage. A large percentage of the total cost is for component constructed away from the site under controlled conditions in shipyards, this will reduce the risks, the build time and the costs.

The 'Reef' produces a lower peak output (unless peaking capacity is designed for), but over a longer and more flexible generation period. It is three km longer but encloses 50% more area of estuary than the Cardiff-Weston Barrage. Even with the compromise in the turbine design to accommodate the passage of fish, it will be almost twice as efficient as any tidal stream turbine.

The main structure is 'tall and narrow' as opposed to 'low and wide' This is only possible because of the small head differential and that it can be designed partly as a tension rather than gravity structure. The volume of concrete and rock-fill required per km will be considerable lower than a conventional barrage or lagoon.

- At a cost of £10bn and annual net revenues of £1bn based on an electricity value of £50 MWh the price over earnings ratio is around 10.
- It has been suggested that 'Desirable Public Works' may attract a price over earnings ratio as high as 20 or discount rate of 3 or 4%.
- The value of the electricity may be different from the nominal £50 per Mwh and a 50% contingency allowance on the construction costs would push the capital cost to £15bn.

Appendix 7 AREAS FOR FURTHER STUDY

Computer modelling of the estuarine flows with the outer 'Reef' only, the outer 'Reef' and an inner 'Reef' and with various combinations of opening and closing times and possibly pumping options. The object would be to establish a set of criteria to meet the environmental, the generation and the navigation requirements.

1. Detailed flow analysis of the proposed 'fish friendly' turbine.
2. Detailed analysis of the proposed low speed alternator.
3. Detailed analysis of the electrical inter-connections.
4. Detailed analysis of the marine structures.
5. Detailed investigation of suitable shipyards and sites for caisson construction.
6. Establishing the environmental constraints.
7. Establishing the cost.

PATENTS PENDING

- Tidal Reef Concept
- Floating Turbine Caissons
- Crest Gate System
- Butterfly Gate System
- Rotatable Turbine System
- Siphon tidal turbine
- Pile and caisson causeways
- Active Tide control system
- Twin barrage system

Version 7th November 2008
Author: Rupert Armstrong Evans

Armstrong Evans & Associates
Trecarrell Mill
Trebullett
Launceston
Cornwall PL15 9QE
www.evans-engineering.co.uk
01566 782285
re@eveng.com