ENGINEERING COMMITTEE ON OCEANIC RESOURCES

Report of Working Group on Marine Geothermal Energy

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Introduction

Beneath the world's oceans there are ~60,000 km of mid-oceanic ridges (MORs) where tectonic plates are pulling apart. Wherever these have been explored hydrothermal vents (HTVs) have been found. It has been estimated that HTVs collectively dissipate tens of terawatts of geothermal energy none of which is presently utilized by mankind (Reves-Sohn, private communication, 2007). In addition to MORs, HTVs are also found along volcanic arcs. Perhaps 10 percent of all HTVs are found along volcanic arcs, (de Ronde, private communication, 2008).

This must surely represent one of the world's last great untapped energy resources?

Before this resource can be harnessed, a number of issues must be addressed. These are:

- Can useful energy be extracted from HTVs?
- If so, how can this energy be utilized?
- What technical, commercial, legal, political and environmental issues need to be addressed in developing this new technology?

Feasibility

At a physical level, extracting energy from HTVs closely resembles the extraction of geothermal energy on land. However, rather than drilling bore holes, an insulated conduit is used to bring a hot water / steam mixture to a point where it can be used to drive a turbine or some other heat-engine. We use the term offshore geothermal to distinguish it from on-land geothermal. Offshore geothermal has one definite advantage over on-land geothermal in that it is always self-flowing and pumps do not need to be used. Cavitation in pumps is the *bete noir* of on-land hydrothermal and limits its applicability to self-flowing systems or those with temperatures of less than 190^o C. (Sanyal, *et al*, 2007).

On the other hand deployment costs at oceanic sites involves the charter of specialist vessels, remotely operated vehicles (ROVs) and the like. These costs will always be large and strongly site dependent. Deployment costs for some sites could well exceed manufacturing costs.

Remoteness from markets is another disadvantage of offshore geothermal and may limit its use to specialist applications, as discussed below. Nevertheless some countries such as Iceland, Japan, Indonesia, PNG, Tonga and New Zealand are likely to have useable HTVs sufficiently close to land to provide power to the national grid.

Much of the technology for offshore geothermal already exists in the form of insulated risers used by the offshore oil industry. Heat losses through the walls of the conduit are not an issue, although corrosion and fouling problems are likely to be more like the conditions the oil industry encounters in refinery pipelines than offshore.

Utilization

We envisage two ways in which energy extracted from HTVs by means of insulated risers can be used, viz:

- for the generation of electrical power, and
- for mixing deep nutrients into the upper layers of the ocean

Electrical Power Applications

The electrical power applications are not necessarily limited to HTVs which are situated close to land, as mentioned above. Only a small fraction of the world' HTVs would be suitably located. Just as offshore oil platforms operate at great distances from shore specialist industries requiring a cheap source of power could be similarly located. Industries which extract metals from salts by electrolysis come to mind. One such industry is the aluminium industry. Offshore electrolysis of alumina would have the additional advantage of releasing toxic fluorides many miles from land where they would be less of a hazard. Note that the entire smelting process does not need to be carried out offshore; only the electrolytic step.

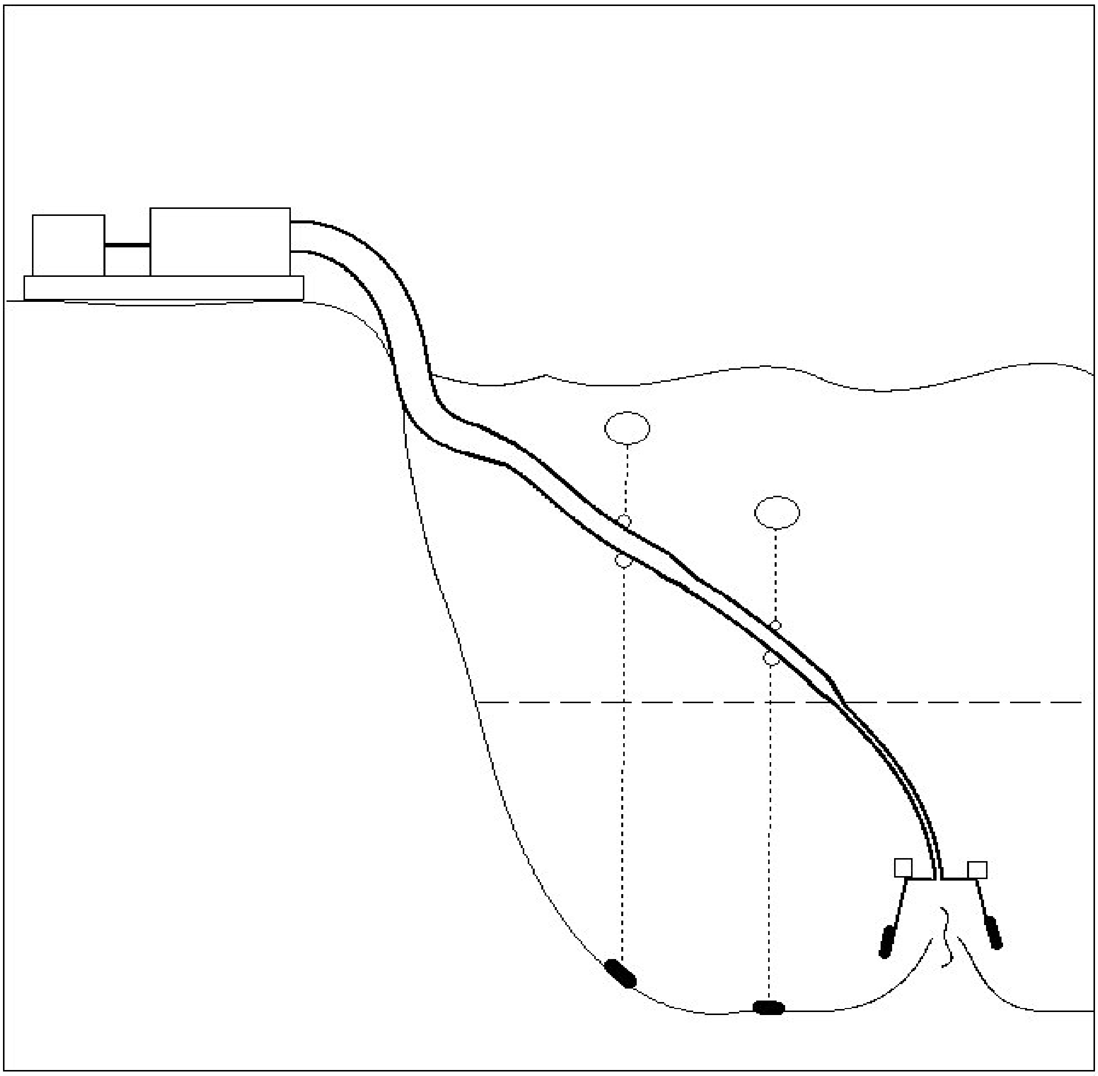

Figure 1. A schematic diagram showing the deployment of an offshore geothermal installation in a power generating application. The insulated conduit is flared to allow for expansion of the two phase fluid with decreasing depth. The dotted line shows the depth of vaporization, i.e. the depth at which the fluid starts to expand due to boiling.

The Nutrient Mixing Application

Mixing deep nutrients into the euphotic zone (i.e. the well-lit surface layer) of the ocean has been proposed by Kithill of Atmocean Inc and by Lovelock and Rapley (2007). In both cases wave power is proposed as the power source needed to raise the potential energy of the colder, denser water that is brought to the surface. We propose that offshore geothermal energy be considered in this application. It promises to be more plentiful and, in the long run, cheaper and more reliable than using wave power. Ecofluidics proposes using the upwardly thrusting action of steam bubbles generated when HTV effluent is brought to shallower depths to produce this mixing.

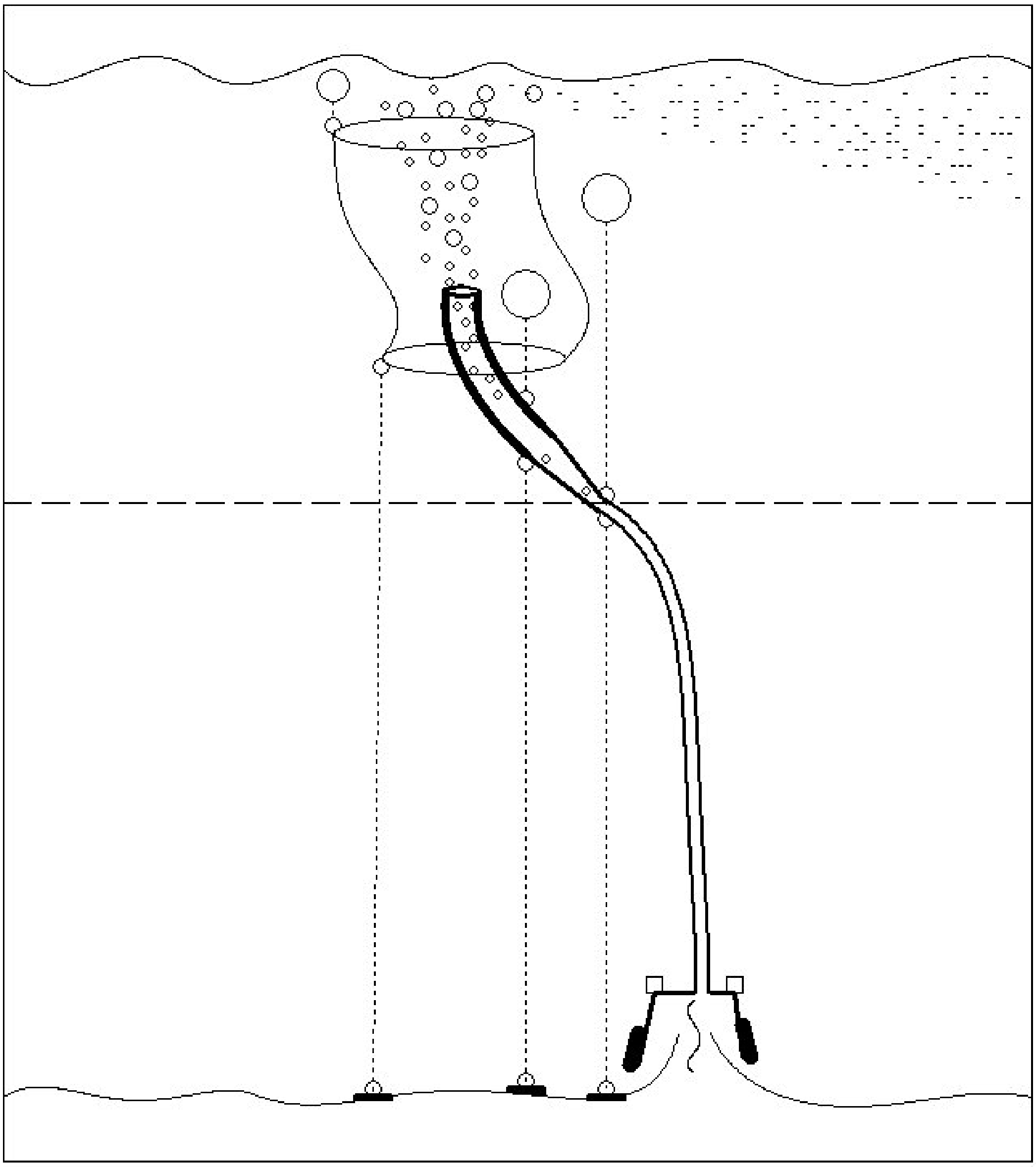

Figure 2. A schematic diagram showing the deployment of an offshore geothermal installation in the nutrient mixing application. The upper tube is made of light weight material such as plastic film and serves to inhibit entrainment of cold water into the rising plume.

The environmental and economic benefits (via enhanced fisheries and carbon sequestration) of nutrient mixing are discussed elsewhere (Reid and Nielsen, 2007). Lovelock and Rapley's paper was criticized by Shepherd *et al* (2007) but this and other such criticism seems to be a knee-jerk response to geo-engineering schemes in general. The standard objection from oceanographers is that such mixing will "always" bring up more CO_2 than is removed from the atmosphere.

However experimental data (WOCE) shows that this is clearly not the case for the entire North Pacific Ocean while there are certainly parts of the world oceans which are nutrient-poor at depth; the South East Pacific and North Atlantic for example (Reid 2008c).

Rough calculations indicate a likelihood that there is sufficient deep nutrient and sufficient offshore geothermal energy to reverse the current upward trend in CO_2 and to greatly enhance the world's fisheries, reduce ocean acidity and cool the ocean surface in the process.

Physics Issues

HTVs are found in two general locations, along (and immediately behind) volcanic arcs and along MORs. Volcanic arc HTVs are much shallower (~50% are < 500m) and tend to lie closer to land. They are also cooler (~150-300^o C) so that any heat engine driven by them will be inherently less efficient for thermodynamic reasons than a heat engine driven by MOR HTVs which are typically around 350^o C although at depths of ~2500m.

The thermodynamic behaviour of the two phase fluid delivered by the conduit in Figs 1 and 2 has been modeled both numerically and analytically (Reid 2008a, 2008b) for the case where the fluid is delivered to a heat engine at the surface for the generation of electricity. The modeling showed that while pressures in the conduit are very high, steam quality is very low. This implies that either a binary turbine system is required or specially designed turbines must be used. In general vent fluid can be expected to contain high concentrations of sulphides and other salts which precipitate out as the fluid cools. This could lead to rapid fouling of heat exchangers required by a binary system.

The analytical model showed that the thermodynamics of the ascending fluid is dominated by the gravity term.

In the nutrient mixing case the two-phase fluid is released directly into the sea some distance below the surface. The density of the fluid leaving the conduit is very low compared with the surrounding sea water and a steam bubble plume will be formed. Surrounding sea water will be entrained into the plume and be raised to the surface. Because the density difference between the plume and surrounding water masses is so large compared with the density differences between naturally occurring water masses, a small amount of vent fluid would raise a very large amount of sea water. This "buoyancy amplification" ratio is of the order of 10^3 to 10^5.

Unfortunately, the large buoyancy of the vent fluid is mitigated by the cooling and condensation which occurs when the hot two-phase vent fluid mixes with cold surrounding sea water. This cooling and condensation is difficult to model because mixing will always be imperfect and the water-steam mixture leaving the conduit will tend to cohere into blobs rather than mix uniformly.

Where these blobs come into contact with entrained cold water their steam component will condense. However, when this happens, heat will flow into the surrounding water and a surface layer of hotter water will be formed which will inhibit further cooling. Indeed, this heat flow may reverse due to the lowering of boiling point with pressure. This "halo effect" has been modeled numerically (Reid and Nielsen, 2007) and found to be strongly dependent on the scale size of the blobs.

Cooling by entrainment can be inhibited by containing the plume within a second much larger conduit to inhibit mixing (as shown in Figure 2) or by generating a single larger plume by adding the effluents from a number of separate HTVs at judiciously spaced intervals.

The behaviour of two phase plumes generated by HTVs is strongly dependent on scale size. This, together with the role of gravity in controlling the thermodynamics of the ascending fluid, means that it is impossible to construct a small scale prototype which would give meaningful results.

There is an urgent need for more and better quality survey data to be gathered if this technology is to go ahead. Detailed knowledge of vent temperatures and flow rates are required at every scale so that the extent of the resource can be assessed. Presently these data are estimated by examining plumes using CTD data collected by towed sensor arrays. This is painfully slow and some better method is needed. We suggest new types of instrumentation be developed for this purpose, e.g. higher frequency Doppler acoustic methods for measuring flow rates. It may be desirable to temporarily cover a candidate HTV with an instrumented cowling to make the precise measurements needed by design engineers prior to capping. Better instrumentation may lead, in turn, to empirical "rule of thumb" algorithms which allow flow rates to be estimated from video imagery.

Geological Issues

After reading the first draft of this report, retired geologist, Ray Binns, made the following comments:

My experience is with arc- and back-arc-related vents in PNG and NZ, not with mid-ocean ridges, including recent commercial (mining-related) activities. A few points to consider

1. A lot of the heat output, some say the majority, of vent sites is as low-T diffusely venting fluids just 10 degrees or less above ambient and way below 'boiling point'

2. Maximum vent temperatures are in effect buffered by phase separation and the latent heat involved, at depth-related temperatures, but in fact a lot of the 'boiling', and cooling by admixture with down-drawn seawater happens well below the sea floor. Ocean Drilling Program Leg 193 results in the Manus Basin demonstrate this, as does the fact most 'smokers' expel fluids 100 degrees or more below the nominal BP for their depth

3 'Flashing' chimneys emitting vapour (at the nominal BP, but which condenses within centimeters) are very rare at any particular site

4. Hi-T chimneys at a particular site tend to be scattered over fairly large areas - 100s of metres in the case of significant fields. You would need a very large umbrella, well sealed to the sea floor, to trap their combined output, and even then it will have been greatly diluted by the product of more numerous lower-T chimneys

5. Most popular concepts of 'black smoker' activity are biased by images taken shortly after chimneys have been broken off, releasing 'pent-up' pressures> from their upper plumbing systems. The venting slows down fairly quickly in the few cases where continued observations have been made (probably from rapid 'clogging up' of the conduits with mineral deposit.

These are certainly legitimate concerns. Our response is as follows:

The intention is to cap individual smokers not whole fields. From what Ray says, the temperature would be seriously degraded to the point where the conduit would not work if the fields he described were to be capped with a single large capture cowling. High quality smokers will need to be sought out within a field emphasizing need for better evaluation tools and specialized ROVs. Where necessary, effluent from a number of high quality smokers could be brought together by a "manifold" to drive a single turbine.

A single flashing chimney such as he describes could form the basis of a prototype ocean mixing experiment so that we can get a handle on the thermodynamics, mixing and cold water flux which would occur in such a device.

Capture cowlings do not need to be sealed to the ocean floor. Instead the flow in the conduit is limited so that excess vent fluid spills out from under the skirts of the capture cowling. This means that no cold sea water will be entrained. Even a small amount of entrained cold water would seriously degrade the thermodynamic performance of the device.

Commercial Issues

As with all new technology the key commercial issue is whether development costs can be justified by the expected return. Costs of deployment are likely to be large, particularly for vent depths in excess of ~500m when expensive ROVs are required. It seems likely that the first commercial offshore geothermal plant will be used to generate electricity from a shallow HTV close to land. As the technology matures, installations will be built further from shore until ultimately MOR HTVs are tapped.

Apart from the cost considerations mentioned above, there is another divide between shallow and deep HTVs, and that is temperature. HTV effluent is likely to be highly corrosive and the conduit and cowling will need to be protected with an inert coating such as Teflon. Deeper HTVs have temperatures well above the melting point of Teflon so that other measures will need to be adopted such as constructing components which operate in these higher temperatures from high-chromium stainless steel.

Legal and Political Issues

The key legal issue is that of jurisdiction. Most of the HTVs situated on volcanic arcs lie within the territorial waters of one or other nation states (e.g. Kermadec Arc: New Zealand, Mariana Arc and Aleutian Arc: United States) so that jurisdiction is clearly defined. This is not the case for HTVs which lie along MORs. By their nature these are far from land and almost all of them lie outside any national jurisdiction.

This has intellectual property implications - apparatus claims apply to the country in which the apparatus is manufactured while method claims apply to where the method is carried out so that the method of nutrient mixing to enhance fishery production described above cannot presently be protected on the high seas where MOR HTVs are found.

Likewise, the associated fishery itself cannot be protected from the depredations of poachers except by force of arms. Offshore manufacturers utilizing cheap power from MOR HTVs will also be vulnerable.

Any commercial enterprise or nation state seeking to exploit high seas HTVs may find the additional risk due to this lack of jurisdiction unacceptably high. International agreement may need to be negotiated before this resource can be utilized. The United Nations Convention on the Law of the Sea could provide a suitable vehicle for these negotiations.

Environmental Issues

On a global scale, the environmental consequences of bringing effluent from HTVs to the surface range from benign to beneficial. The nutrient mixing application will reduce atmospheric carbon dioxide, increase surface alkalinity and cool the mixed layer of the ocean to a small degree because of the cold water which is brought to the surface from depth. The fertility of the ocean will generally be enhanced.

On a local scale, there may be some undesirable consequences. The release of HTV gases to the atmosphere may lead to sulphurous smells and local increases in acidity similar to those found near natural hot springs and geysers. Heavy metals and other poisonous compounds which may present will rapidly become diluted to non-toxic levels. HTVs have been pumping these same chemicals into the ocean for billions of years and living organisms are well adapted to tolerate low concentrations.

On the ocean floor, vent communities will be affected. While these bizarre life-forms have only recently been discovered, there is no evidence that any species can be considered "threatened". To the author's knowledge, no vent species have been discovered to date which are unique to a particular vent location and almost all are found across entire ocean basins. The environmental effects of offshore geothermal installations will be no worse than the destruction of trees and grass near a mineshaft or quarry.

This is not to say that no objections will be raised. Some of the more extreme environmental activists are opposed to any form of "technological fix" or geo-engineering. To some degree this is understandable. Some geo-engineering solutions to the present climate crisis that have been proposed leave one feeling distinctly uneasy. (The prospect of firing canisters of sulphur dioxide into the stratosphere comes to mind.) The geo-engineering solutions based on ocean fertilization such as those proposed here and by Jones (2006) and others are amongst the most benign of all such proposals. Not only can they be closely monitored but they can easily be switched off should any adverse effects become evident.

Conclusions

The harvesting of energy from hydrothermal vents on the ocean floor is now technically feasible although there are still a number of issues which must be dealt with.

Declaration of Interest

As Chair of this Working Group I should declare my financial interest. In 2007 I became interested in this topic and, with others, filed a patent for a device for harnessing hydrothermal vent energy. We formed a company called Ecofluidics Pty Ltd which holds this patent. This topic is so new that much of the analysis and discussion has not yet appeared in the open literature but can be found in Ecofluidics reports which are referenced below.

Literature References

Jones, I.S.F. (2006) "Report of the Ocean Sequestration Working Group". ECOR.

Lovelock J.E. and C.G. Rapley (2007)."Ocean Pipes could help the Earth cure itself", *Nature*, **449**, p403.

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Wichers, S. (2005) "Verification of Numerical Models for Hydrothermal Plume Water through Field Measurements at TAG" M. Sc. Thesis presented to M.I.T and Woods Hole Oceanographic Institution.

Ecofluidics References

Reid, J. and P. Nielsen (2007), "Using Geothermal Energy to Mix the Ocean".

Reid, J. (2008a), "Harnessing Ocean Geothermal Energy using an Insulated Pipe".

Reid, J. (2008b), "Analytical Modeling of an Underwater Steam Horn", Ecofluidics Report Number 4.

Reid, J. (2008c), "Unpublished Letter to Nature", Ecofluidics Report Number 6.

These reports may be downloaded from www.ecofluidics.com

Other Web References

Kithill and Atmocean Inc: http://atmocean.com/