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Mining the Oceans: Can We Extract Minerals from Seawater?

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Figure: Japanese researchers testing uranium extraction from seawater using a braided adsorbent fiber (JAEA 2006). Is this the way of mining of the future?

After a couple of centuries of mining, the best and most concentrated mineral ores are on their way to disappearance. In the future, we'll have to extract from less concentrated deposits and that will be more expensive. It is not just a question of money; mining low concentration deposits costs more energy and, with fossil fuels being rapidly depleted, that is a serious problem. Our society cannot survive without a cheap supply of minerals; so, it may not be too early to look for new sources.

If mines on land are gradually becoming depleted, could the oceans become our new mines? There have been several proposals for mining the oceans' floor, but that is just an extension of conventional mining and, besides, the task has proved to be complex and expensive. The real change of paradigm, instead, is in extracting ions dissolved in seawater.

The oceans are vast and contain immense amounts of minerals which, in principle, could be recovered without the need of digging, crushing, processing, and all the other complex and energy expensive procedures that we need for mining on land. Indeed, the extraction of minerals from seawater is a concept that periodically reappears in times of energy crisis. It had become popular with the first oil crisis of the 1970s, only to disappear during the phase of relatively low oil prices that followed. Nowadays, with the new crisis ongoing, recovering minerals from seawater is looking attractive again. For instance, over the web it is often stated as an obvious fact that any uranium supply problems that could occur in the future will be easily solved extracting uranium from seawater. Occasionally, we read that the same method could be used to solve all mineral shortages.

However, things are not so simple and we'll see in the following that extracting low concentration minerals from seawater is a huge, expensive and complex task. We are not going to see minerals produced from seawater taking the market anytime soon and the dream of fishing uranium from the sea is destined to remain just that: a dream. But let's go into the details.

1. Minerals in seawater

Open ocean water contains dissolved salts in a range of 33 to 37 grams per liter, corresponding to a total mass of some 5E+16 tons, (in the "E-notation", E+16 means 10 elevated to the power of 16). In other words, the oceans contain some fifty quadrillion tons of dissolved material. It is a huge amount compared to the total mass of minerals extracted today in the world: of the order of "just" a hundred billion tons per year (OPOCE 2000). However, most of the mass dissolved in the oceans is in the form of just a few ions and these are not the most important ones for industry.

The four most concentrated metal ions, Na+, Mg2+, Ca2+, and K+, are the only ones commercially extractable today, with the the least concentrated of the four being potassium (K) at 400 parts per million (ppm). Below potassium, we go down to lithium, which has never been extracted in commercial amounts from seawater, with a concentration of 0.17 ppm. Other dissolved metal ions exist at lower concentrations, sometimes several orders of magnitude lower. None has ever been commercially extracted.

But let's see exactly how we stand. In the table below I have listed the seawater concentrations and total amounts of some metal ions. The table excludes those already being extracted (Na, Mg, Ca and K) and those which exist only in traces so minute that extraction is simply unthinkable. The amounts available in seawater are compared with the reserves listed by the United States geological survey (USGS). The concept of "reserves" may be conservative but the results of a recent work (Bardi and Pagani 2007) show that it may be the most realistic estimate of what we can actually extract from land mines.

Element	Concentration in seawater (ppm)	Total oceanic abundance (tons)	Mineral reserves (tons)
Li	0.178000	2.31E+011	4.10E+006
Ba	0.021000	2.73E+010	1.90E+008
Mo	0.010000	1.30E+010	8.60E+006
Ni	0.006600	8.58E+009	6.70E+007
Zn	0.005000	6.50E+009	1.80E+008
Fe	0.003400	4.42E+009	1.50E+011
U	0.003300	4.29E+009	2.60E+006
V	0.001900	2.47E+009	1.30E+007
Ti	0.001000	1.30E+009	7.30E+008
Al	0.001000	1.30E+009	2.50E+010
Cu	0.000900	1.17E+009	4.90E+008
Mn	0.000400	5.20E+008	4.60E+008
Co	0.000390	5.07E+008	7.00E+009
Sn	0.000280	3.64E+008	6.10E+006
Cr	0.000200	2.60E+008	4.75E+008
Cd	0.000110	1.43E+008	4.90E+005
Pb	0.000030	3.90E+007	7.90E+007
Au	0.000011	1.43E+007	4.20E+004

For data sources, see note (1) at the end of the text

As we see, there are huge metal resources in the sea. The question is how to extract them. The most general method consists in passing seawater through a membrane that contains functional groups that selectively bind to the species of interest. No known membrane is 100% selective for a single species, but it is possible to create membranes that can retain a small number of selected low concentration species. The adsorbates can be extracted from the membrane by flushing it with appropriate chemicals; a process called "elution". After this stage, the metal ions can be separated and recovered by precipitation or electrodeposition.

In practice, it is very difficult to extract low concentration ions at reasonable costs. Lithium extraction was tried in the 1970s (Schwochau 1984) but the tests were soon abandoned. The idea of extracting uranium has been around for a long time, at least from the 1960s (see Nebbia 2007 for a review). But just a few grams were extracted in Japan in the late 1990s (Seko 2003). Then, there is the old dream of getting gold from the sea. The German chemist Fritz Haber tried that in the 1920s but the task of extracting gold ions at concentrations of a few parts per *trillion* (ppt) was nearly desperate and, indeed, the attempt was a total failure.

Evidently, we have big problems here. That is not surprising: there is a lot of water in the ocean and, in comparison, very small amounts of useful metals. So, we have to process huge amounts of water. Huge, in this context, means really *huge* , as you can see in the following table. Consider, as a comparison, that the total volume of water desalinated today is 1.6E+10 tons.

Element	Total mass in oceans (tons)	Production in 2007 (tons)	Mass of water to be processed (tons)
Li	2.31E+011	2.50E+004	1.40E+011
Mo	1.30E+010	1.87E+005	1.87E+013
U	4.29E+009	6.65E+004	2.02E+013
V	2.47E+009	5.86E+004	3.08E+013
Cd	1.43E+008	1.99E+004	1.81E+014
Au	1.43E+007	2.50E+003	2.27E+014
Sn	3.64E+008	3.00E+005	1.07E+015
Ni	8.23E+008	1.78E+006	2.81E+015
Cu	1.17E+009	1.56E+007	1.73E+016
Mn	5.20E+008	1.18E+007	2.90E+016
Zn	6.50E+009	1.80E+008	3.60E+016
Al	1.30E+009	3.80E+007	3.80E+016
Cr	2.60E+008	2.00E+007	1.00E+017
Pb	3.90E+007	3.55E+006	1.18E+017
Fe	4.42E+009	2.26E+009	6.65E+017
Ti	1.17E+006	6.10E+006	6.78E+018
Co	8.84E+006	8.23E+007	9.18E+018

Table 2. Elements are ordered as a function of the mass of seawater that would need to be filtered in order to obtain the same amount of materials that we obtain today from traditional mining. That value is calculated in the optimistic assumption of 100% efficiency of the filtering membrane. For data sources, see note (1) at the end of the text

The table shows that, even for the best case listed, lithium, in order to recover the same amount we get today from conventional mining we would need to set gigantic facilities. We'd need to process at least ten times as much water as it is processed by desalination plants today. All the other metals would require to process amounts of water orders of magnitude larger.

Moving these gigantic amounts of water is not just a practical problem: it involves energy; a critical parameter especially if we consider the extraction of two elements that are to be used as energy sources: lithium and uranium. Uranium, in the form of the 235 isotope, is the fuel of the present generation of nuclear fission plants, whereas lithium, in the form of the 6-Li isotope could be the source of tritium to be used as fuel for a future generation of fusion power plants. In both cases, the feasibility of extraction is determined by the energy needed according to the well known concept of "EROEI" (energy returned for energy investment) (Hall 2008).

In the next section, we'll see in detail the case of uranium, perhaps the most important for practical applications and the one for which we have the best data available. It will serve as a benchmark for evaluating the feasibility of extraction of all the other elements.

2. Uranium extraction from seawater

At present, the mining industry can provide only about 60% of the uranium needed for the currently operating reactors which produce about 16% of the world's electricity. The gap is filled with stockpiled reserves, in large part obtained from dismantling old nuclear warheads. Raising mineral production to the level needed to satisfy demand is a huge and expensive task; even more if it were to occur together with the construction of new reactors. Whether we'll develop a serious uranium shortage in the near future is hotly debated, but the problem cannot be ignored (see, e.g. EWG 2007).

So, extracting uranium from seawater is a subject often discussed and, as we saw in the previous section, the amounts theoretically available in the oceans are more than sufficient to stave off all worries of shortages for a long time. Indeed, already in the 1960s, the idea had started to be evaluated (Nebbia 2007). The development of a membrane able to recover uranium from seawater (Vernon and Shah, 1983) was an important step forward and it led to experimental tests performed in the 1990s by researchers of the Japanese Atomic Energy Agency (JAEA). In these tests, a few grams of uranium oxide were actually recovered from the sea. From a web page dated 1998 (JAEA 1998), we see that these tests were performed in 1996 and 1997 and the results are reported in detail in a paper in English by Seko et al. (Seko 2003). Some results with braided fiber used as adsorbent are reported in a web page (JAEA 2006).

However, JAEA seems to have stopped all activity in this field, at least from what can learned from the examination of their site in English . There are no reports of further experiments, demonstration plants or of scaling up tests being planned. Something went wrong here, clearly, but exactly what? The question is complex, but we can try to answer it using the concept of energy return of the energy invested, EROEI.

From table 2 we see that we would need to process 2E+13 tons of water every year in order to produce enough fuel for the present fleet of nuclear reactors. Considering that the present worldwide production of nuclear energy is about 2.5E+3 TWh (terawatt-hour) per year (WNA 2007), we arrive to determine that the "energy density" of seawater exploitable by the present nuclear technology is about 1E-1 kWh/ton (one tenth of a kWh per ton). It doesn't look large but it is still much larger than the kinetic energy of the same mass of water moved by average strength currents (See note 2).

Now, in order to extract this uranium, there are two possible strategies: one is of actively pumping the water through the membrane, the other simply dropping the membrane in the sea and wait for the metal ions to migrate to the active sites. In both cases, energy is needed for a variety of operations: pumping, infrastructure building, moving the membranes, manufacturing them, etc. We don't have enough data for a step-by-step evaluation of the energy necessary but we can try an order of magnitude estimate by comparing with known processes.

Let's start with the first strategy: actively pumping water through a membrane. The process requires energy mainly because of the viscosity of water. This effect is described by Darcy's law which says that the energy required is inversely proportional to a parameter called "permeability". A finer membrane (e.g. sand) has a lower permeability than a coarse membrane (e.g. gravel). The permeability of a uranium extraction membrane is not reported in the available studies and it is probably not even known at the present stage. However, we can estimate the energy involved by comparing with a similar, known, process: desalination by reverse osmosis.

In reverse osmosis, seawater is pumped through a membrane that retains the dissolved ions; just as it would be done for uranium extraction. The energy involved in desalination by reverse osmosis is of the order of 2-4 kWh/ton; a value that includes all the energy used by the plant. For uranium, we would use membranes with a higher permeability, but the energy needed cannot change too much. If we take a value of 1 kWh/ton as a reasonable "order of magnitude" estimate, we immediately see that it can't be done. If what we can recover from the uranium contained in a ton of water is about 1E-1 kWh, it makes no sense to spend 1kWh/ton for the extraction, even if we could do that at 100% efficiency. This result is nothing new and there are other kinds of calculations that lead to the same conclusion (Schwochau 1984). Pumping water through membranes is so energy expensive that it can't be considered as a practical strategy for uranium extraction.

So, we are left with the second strategy: dropping the membrane into the sea and wait until currents or diffusion brings the uranium to the adsorbing sites. This method avoids the energy cost of pumping. Yet, it is also a less efficient way to use the membrane. As a consequence, we need larger amounts of membranes, a larger infrastructure, and we need to move the membranes in and out of the sea. All these are energy costs. We are looking at a complex and largely unknown process which is difficult to analyze in all its details. Nevertheless, we can try.

First of all, we can gain some idea of the size of the task. Dittmar (2007) has already noted that the task is huge, but exactly how much space would the adsorbing membranes occupy? We saw (see table 2) that we need to process at least 2E+13 tons of water per year. We also need a relatively shallow body of water, so that the infrastructure that carries the membranes can be anchored to the sea bottom at a reasonable cost. Now, consider the North Sea as a suitable area. It is a shallow sea (average depth less than 100 m) and it contains about 5E+13 tons of water. Assuming a recovery efficiency of 50% (which is probably optimistic), it means that we would have to appropriate the whole North Sea with adsorption structures in order to get enough uranium for just 16% of the present world's electric power production. For powering the whole world, we'd need the equivalent of at least six North Seas.

But it is unlikely that the North Sea would have sufficiently strong currents for sustaining uranium extraction for a long time. That is a problem which has not been studied in detail: where can we find currents strong enough to move the huge amounts of water we need?

Current strength is sometimes measured in "Sverdrups", a unit that corresponds to one million tons of water per second, or 3E+13 tons of water per year. So, one Sverdrup is almost exactly the flow of seawater that carries enough uranium for the present needs of nuclear plants. Some currents are reported to be much stronger than one Sverdrup. For instance, perhaps the strongest current in the world is the Antarctic Circumpolar Current (ACC) which carries about 135 Sverdrups. There is plenty of uranium being transported there. But the average depth of the Southern (Antarctic) Ocean is around 3000-4000 meters and the area is highly hostile to human activities. Anchoring there millions of tons of adsorbing membranes, together with all the processing facilities, is simply unthinkable.

Perhaps we could consider the Strait of Gibraltar as a more friendly environment where to find strong currents. Damming the strait in order to produce energy had already been proposed by Herman Sorgel in the 1920s with his concept of the "Atlantropa" dam. The dam was supposed to provide about 50 GW of hydroelectric power, a little more than 10% of the power presently provided by the nuclear industry today. The dam was never built; of course: it would have been a disaster for the Mediterranean sea.

Today, we seem to be a little more careful with these megaprojects, but still the Strait's current is very strong and we could appropriate a fraction of it for uranium extraction. The flow of seawater through the strait is about one Sverdrup , enough to satisfy our current uranium needs. Let's say that we could intercept 10% of it (and even that could have huge negative effects on the Mediterranean environment). In this case we'd need the equivalent of 10 Straits of Gibraltar just for satisfying the current needs of the nuclear fission industry and some 60 equivalent straits for raising production to match the present world's demand. Do we have the equivalent of 60 Straits of Gibraltar in the world? We can't say for sure that we don't; but of one thing we may be sure: the task would be colossal, devastating for the environment, and expensive beyond imagination.

All this doesn't mean that it is impossible to extract uranium from seawater in amounts comparable to our needs. But it gives us a certain perspective that we can use for the evaluation of the really critical parameter of the process: EROEI. The huge areas that we calculated to be needed bring us to compare uranium extraction to another industrial activity where large masses of materials are transported over the sea: oceanic fishing.

We have some data about the energy expenditure of the fishing industry (Mitchell and Cleveland (1993)) and we can estimate that the industry uses fuel for an energy of about 7 kWh for each kg of fish recovered. Another estimate derives from knowing that the total fish catch today is around 90 million tons (9E+10 kg) per year (FAO 2005) while the total amount of fuel used by the world's fishing fleet in 2005 is of some 14 million tons of diesel fuel (FAO 2008) (2E+11 kWh, considering that the energy content of diesel fuel is 43 GJ/ton). The result is about 2 kWh of energy per kg of fish landed. These are rough estimates that only take into account the fuel cost.

Yet, it seems that fuel is the main energy expenditure involved in ocean fishing. So, if we take a midrange value of 5 kWh/kg, we can't be too far off in terms of the energy cost of extracting something from the open sea and bringing it back to land.

Now, if we want to use membranes for uranium extraction, it means that we have to carry the membrane at sea, submerge it for a while, raise it, bring it to land for processing, then back to sea, and so on. From the paper by Seko et al (2003) we see that we need about 300 Kg of membrane per kg of uranium extracted per year. We also read in the paper that the membranes were "pulled out of seawater using a crane ship every 20 to 40 days". In other words, the membranes have to be brought back to the elution facility every month or so. Recovering one kg of uranium, therefore, would require processing at least 3 tons of membranes per year. For the present worldwide uranium demand (6.5E+4 tons/year) we'd need to move 2E+8 tons of membrane every year. That is about ten times larger than the weight of the total catch of today's fishing industry. This is another indication of the colossal size of the task.

But the real problem is the energy involved. Using the ratio of 5kWh/kg that we calculated before for fishing, and assuming the yield and the conditions reported by Seko (2003) we can calculate a total energy expenditure of about 1E+3 TWh/year for the present needs of the nuclear industry. This is about the same as the total produced, ca. 2.5e+3 TWh/year. So, the energy gain (EROEI) is too low to be interesting.

Of course, there is a high level of uncertainty in this calculation. On the one hand, we need to consider that is possible to improve the efficiency of extraction process using braided membranes and working at higher sea temperatures (JAEA 1998, 2008). We might also build floating processing facilities in order to reduce the transportation costs. On the other hand, the calculation refers only to the fuel expenditures. To that, we need to all the costs for the infrastructure, for the chemicals used in elution, for the energy needed for recovering the species of interest and so on. We need also to consider that the membranes are synthesized starting from crude oil. Since there are no data available for how long a membrane could last in operation, we can't calculate how much oil would be needed, but surely it would not be negligible (see note 3 for an attempt of calculating this value).

We can conclude that there is a high risk that uranium extraction from seawater in these conditions would have an EROEI smaller than one. Very likely, it would be too low to be interesting. In practice, nobody will provide the huge financial resources needed to embark in such a task while that uncertainty remains. Moreover, investors are not likely to appear when they can't ignore that, at any moment, the development of an efficient fast breeder reactor would make their huge investments worthless. So, we don't know for sure whether the nuclear industry will be facing a fuel shortage in the near future but, if it does, the best bet to concentrate on conventional land mining and on developing more efficient reactors. Extracting uranium from the sea is not a practical possibility.

4. Lithium and the others

The case of uranium gave us the tools that we need for the evaluation of the perspective of extraction of all the other elements. First of all, we should consider lithium, which is more abundant than uranium in the sea and that could also be used as an energy source. The 6-Li isotope can be transformed into an isotope of hydrogen, tritium, which could be the fuel of a future generation of fusion reactors.

Fasel and Tran (2005) estimate that a water-cooled lithium–lead breeder blanket reactor of 1.5 GWe power will need 787 tonnes of lithium per year. This reactor could produce 12 TWh of energy per year. From the data of table 2, we see that for producing 800 tons of lithium we need to process 4E+9 tons of seawater. In other words the "energy density" of seawater in terms of fusion plants would be about 3 kWh/ton, more than an order of magnitude larger than that of uranium (1E-1 kWh/ton).

If efficient selective membranes for lithium adsorption can be developed, the energies involved in extraction would likely be about the same as for uranium, but we would need ten times less water for the same amount of lithium, hence ten times less energy. Extraction by active pumping would still be very uncertain in terms of EROEI, but with submerged membranes the task appears possible without destroying the North Sea or damming the equivalent of dozens of Straits of Gibraltar. Still, it would be a huge task and its feasibility remains uncertain. However, Fasel and Tran (2005) also mention the possibility of more efficient ways of using lithium in fusion reactors. So, we can conclude that the extraction of lithium as nuclear fuel from seawater cannot be proven to be feasible in terms of energy return, but it is nevertheless a process worth investigating.

Lithium is also an essential element for the new generation of batteries used in road vehicles. Tahil (2006) studied the availability of mineral lithium if we were to substitute the present vehicle fleet with vehicles based on lithium batteries. He concluded that we would face a lithium shortage. This is not a problem for the near term future, nevertheless it could become serious one day. From a look to table 2 we see if we were to get the present lithium mineral production by filtering ocean water through a membrane, we'd need around 1.5E+3 TWh which is 10% or the present world production of electric power. It is a very large amount but not an unconceivable one. Using submerged membranes, we would be able to substantially reduce that amount of energy, perhaps of one order of magnitude. However, according to Tahil (2006), we would need to step up lithium production of approximately a factor of ten if we were to keep up with the present trends of growth. That is clearly impossible using lithium extracted from seawater, at least as long as we rely on the present energy sources. Nevertheless, it is not impossible that seawater could be one day a significant source of lithium for vehicle batteries, provided that lithium is recycled and vehicles are built in such a way to be lighter and more efficient.

For all the other elements listed in table 1, extraction from seawater seems to be impossible or, at least, extremely difficult. Consider copper as an example. The total amount that exists in the oceans is about 50 times the current yearly production (see table 2). So, in 50 years we would run out of copper from seawater, even if we were able to filter all the water in the planet's oceans. But that is unthinkable, of course. Similar considerations hold for most metals of technological interest. The old dream of fishing gold from the sea remains just that: a dream.

5. Conclusion

Perhaps, one day, we might develop futuristic robotic facilities anchored to the deep sea floor. These machines would be powered by uranium extracted from seawater and would use marine plankton to manufacture organic "tentacles" for adsorbing mineral ions. Processing would be made in place and the recovered metals would be shipped to the surface in neat packages. But that looks like a dream of the 1950s, on a par with atomic planes and weekends on the Moon for the whole family. With the possible exception of lithium, the best we can conceive today is that mining the oceans could produce only truly "homeopathic" amounts of minerals, thousands of times lower than the presently produced amounts. In today's industrial system, such amounts would be useless. This result is true also for uranium, where extraction from seawater can't be seen as a solution for the present shortage of mineral uranium.

Adding together very large volumes of low concentration mineral resources easily leads to optimistic estimates of availability "when the market price will be right". But this optimism is misplaced. Eventually, it is the paradigm of the "universal mining machine" (Bardi 2008) that rules. It is not the absolute amount of a mineral resource that counts but, rather, its concentration. Extracting from low concentration resources, no matter whether dissolved in seawater or in the earth's crust, is so expensive in terms of the energy needed that it is beyond our possibilities for the present and for the foreseeable future.

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- Notes

(1) *data sources for the tables* : seawater elements concentration from J Floor Anthoni (2000, 2006) www.seafriends.org.nz/oceano/seawater.htm. Oceanic abundance calculated assuming a total ocean volume of 1.3E9 cubic km. Mineral reserves are from USGS 2007 mineral commodities summary (http://minerals.usgs.gov/minerals/pubs/mcs/) except for uranium reserves which are from Energy Watch Group (www.lbst.de/publications/studies__e/2006/EWG-paper_1-06_Uranium-Resource...). All reserves are in terms of the pure element, except for Aluminium, iron, and titanium, given in terms of oxides.

(2) *Comparison of the energy density of seawater in terms of fissionable uranium and as source of energy for underwater turbines* . A strong sea current may move at speed of a few m/sec. Let's consider a representative speed of 4 m/sec and calculate the energy as 1/2mv^2. In this case, one ton of water would carry about 2E-3kWh, much smaller than the value calculated before in terms of uranium content (ca. 1E-1 kWh/ton). However, an underwater turbine could well have a better EROEI than the complex process of uranium extraction from seawater and utilization in a fission power plant.

(3) *Tentative calculation of the energy involved in manufacturing membranes for uranium extraction* . From the only work published in the international scientific literature (Seko 2003) we can infer that we need about 300 Kg of membrane per kg of uranium extracted per year. Trying an educated guess on the basis of the paper by Vernon and Shah (1983) we might assume that repeated immersions of the membrane would degrade its performance and generate the need for replacing it approximately every year. A Russian site http://npc.sarov.ru/english/digest/132004/appendix8.html says that the membrane can be "assumed" to be usable 20 times before it has to be discarded. If this is the case, it can be used for about one year and a half. Taking one year as the lifetime of the membrane, we would need to synthesize about 300 kg of activated fiber per year. Assuming an overall yield of 30% (again, an educated guess) for the synthesis process, we see that we need about one ton of crude oil in order to extract 1 kg of uranium per year. Since crude oil has an energy content of about 12 kWh/kg, we would be using some 12 MWh that, used in a high efficiency combined cycle gas turbine would produce about 6 MWh of electric power. One kg of uranium in a nuclear fission plant can generate about 40 MWh of electric power and, therefore, the process could have a reasonable EROEI of about 7. However, note also that, in order to obtain sufficient fiber for supplying enough uranium for the production of the total of the electric energy today, we'd need about 2-3 billion barrels of oil per year. This is a small amount compared to the present production (more than 30 billion barrels per year) but not negligible and would become more and more important as oil production dwindles down because of depletion.

References

Bardi U., Pagani, M., 2007, "Peak Minerals" http://europe.theoildrum.com/node/3086

Bardi U., 2008 "The Universal Mining Machine" http://europe.theoildrum.com/node/3451

Busch, M. Mickols, B, "Economics of desalination— reducing costs by lowering energy use" Water and wastewater international, http://www.pennnet.com/display_article/208957/20/ARTCL/none/none/1/Econo...

Dittmar M., 2007, "The Nuclear Energy Option facts and fantasies", Proceedings of the ASPO-6

conference, Cork, Ireland.
www.aspo-ireland.org/contentfiles/ASPO6/3-2_APSO6_MDittmar.pdf

FAO 2005 http://www.earth-policy.org/Indicators/Fish/2005.htm

FAO 2008, http://www.fao.org/docrep/009/a0699e/A0699E08.htm.

Fasel, D., Tran. M.Q., 2005, Availability of lithium in the context of future D–T fusion reactors. Fusion Engineering and Design 75–79 pp. 1163–1168

Floor Anthoni, J., (2000, 2006) Oceanic abundance of elements, www.seafriends.org.nz/oceano/seawater.htm.

JAEA 1998 Development of the Adsorbent at the Takasaki Research Laboratory http://www.jaea.go.jp/jaeri/english/press/980526/ref01.html

JAEA, 2006 "Confirming Cost Estimations of Uranium Collection from Seawater" JAEA R&D Review, http://jolisfukyu.tokai-sc.jaea.go.jp/fukyu/mirai-en/2006/4_5.html

Mitchell, C. and Cleveland C.J., 1993. "Resource scarcity, energy use and environmental impact: A case study of the New Bedford, Massachusetts, USA, fisheries. Journalof Environmental Management, volume 17, Number 3 / May, 1993, p. 305

Nebbia, G., 1970, "L'estrazione di Uranio dall'acqua di mare"
http://www.aspoitalia.net/index.php?option=com_content&task=view&id=192&...

OPOCE (Office for official publications of the european communities) 2000. Environmental signals, http://reports.eea.europa.eu/signals-2000/en/page017.html

Schwochau, K., 1984, "Extraction of Metals from Sea Water", Springer series "Topics in Current Chemistry" vol 124. http://www.springerlink.com/content/y621101m3567jku1/

Seko N., Katakai A., Hasegawa H., Tamada M., Kasai N., Takeda H., Sugo T., Saito K. 2003, "Aquaculture of Uranium in Seawater by a Fabric-Adsorbent Submerged System" Nuclear Energy
Volume 144 · Number 2 · November 2003 · Pages 274-278

Tamada, M.; Seko, N.; Kasai, N.; Shimizu, T., 2005
Synthesis and practical scale system of braid adsorbent for uranium recovery from seawater
FAPIG (169), p.3-12(2005) ; (JAEA-J 00045)

Tahil, W, 2006, "The Trouble with Lithium Implications of Future PHEV Production for Lithium demand" http://tyler.blogware.com/lithium_shortage.pdf

Vernon, F., and Shah T., 1983, "The extraction of uranium from seawater by poly(amidoxime)/poly(hydroxamic acid) resins and fibre Reactive Polymers, Ion Exchangers, Sorbents Volume 1, Issue 4, October 1983, Pages 301-308

WNA, World Nuclear Association, 2007, http://www.world-nuclear.org/info/inf16.html.

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