Uranium from seawater

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Note

In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

Contents

Summary and conclusion

1 Introduction

2 Extraction from seawater, some aspects
  Warm sea currents
  Volumes
  Mixing entropy of uranium in seawater

3 Uranium recovery from seawater, technical outline
  System
  Recovery yield
  Volumes to be processed

4 Adsorption from seawater
  Titanium hydroxide method
  Polymer adsorption method
  Mooring the adsorbent at sea

5 Hypothetical uranium extraction plant
  Uncertainties

6 Costs

7 Upscaling

8 Energy requirements
  Titanium hydroxide adsorption method
  Polymer adsorption method

9 Comparison
  Uranium from seawater
  Uranium from a conventional mine

References

TABLES

Table 1 Basic parameters of one adsorption bed
Table 2 Parameters of a hypothetical extraction plant
Table 3 Parameters of three mooring methods
Table 4 Parameters per Mg uranium (theoretical)
Table 5 Estimates of costs and energy consumption
Table 6 Theoretical energy production per Mg U in reference LWR

FIGURES

Figure 1 Schematic outline of the extraction process of uranium from seawater

Summary and conclusions

Technically it is possible to extract uranium from seawater. The first stage of the extraction process is the adsorption of the complex uranium ions dissolved in seawater on solid adsorption beds. The extremely low concentration of uranium and the relatively high concentrations of a great number of other dissolved chemical species in seawater have important consequences for the technical system that would be able to recover uranium from seawater on a scale significant for the nuclear energy generation:

- highly selective adsorbents are required; highly selective means a highly energy-intensive production
- exceedingly large volumes of seawater have to processed, measured in hundreds of cubic kilometers
- the dimensions of an extraction facility would have to measured in tens of kilometers
- extraction facilities could only be located in warm sea currents
- exceedingly large masses of ordered materials (e.g. stainless steel, adsorbent) have to be produced, transported and processed: more than 13000 tons for every ton of uranium
- generation of a massive stream of radioactive and chemically contaminated waste.

Broadly two adsorption methods have been investigated, one is based on titanium hydroxide, the other is based on a special polymer. The first method has been studied in the 1970s, leading to the conclusion in 1980 that it was not viable. The polymer-based method has been investigated in the 1990s and 2000s by Japanese groups.

The adsorbent of the Japanese method is selective not only to uranium ions, some other ions are adsorbed even more selectively, particularly vanadium and iron. Besides relatively large amounts of calcium and magnesium are adsorbed. This may necessitate a differentiated and complicated elution process.

It should be noted that the conclusions of these studies are highly hypothetical and are based on just a few laboratory-scale experiments, unproven extrapolations, untried technology and a hypothetical one-step ten billion-fold upscaling of the sequence of processes.

The Japanese studies are based on gram-scale experiments with the adsorbent. No trials with a pilot system under realistic conditions have been reported, not even regarding a part of the required system, let alone with an integrated system. In addition, some crucial parameters have been 'upgraded' apparently without a solid empirical base.

History shows that we should be prudent with technical optimism, especially regarding very large and very complicated systems of unproved technology.

The huge uranium resource in seawater is known and assured, but could it be a net energy source?

It would be wise to first calculate the theoretical extraction work based on a thermodynamic assessment before embarking on a large R&D effort aimed at extraction of uranium from seawater, and before publishing statements on uranium from the oceans as an almost limitless energy resource.

1 Introduction

Seawater contains dissolved uranium, mainly as uranyltricarbonato ions $[UO_2(CO_3)_3]^{4-}$(aq), at an average concentration of 3.34 mg uranium per cubic meter seawater. Since the total volume of seawater of the world is about 1.37 billion km^3, the total amount of uranium in the oceans is nearly 4600 Tg (1 Tg = 1 teragram = 1 million metric tons).

In the past a limited number of studies have been published on the extraction of uranium from seawater. Some of the studies go into detail, e.g. [ORNL 1974] Q133, [Burnham et al. 1974] Q136, [Mortimer 1977] Q98, [Sugo et al. 2001] Q298 and [Sugo 2005] Q303. Other studies are confined to only a part of the process, e.g. [Koske 1979] Q223, [Saito 1980] Q224, [Burk 1989] Q73, [Nobukawa et al. 1994] Q72 and [Seko et al. 2003] Q312]. [Brin 1975] Q225 gives a concise bibliography. The comprehensive and leading international study [INFCE-1 1980] Q226, based on an unspecified study by the US Department of Energy in 1978, concludes:

> "Therefore it would be unrealistic to expect uranium from seawater to contribute significant amounts of the world's uranium demand for thermal reactors on an acceptable time scale."

Though uranium from seawater is still cited as an energy resource option for the future, e.g. MIT 2003 [Q280], few feasibility studies have been published after 1980, which is not surprising after the conclusions of INFCE in 1980.
In Japan still some interest in extraction of uranium from seawater appears to exist, judging by the publications of [Nobukawa et al. 1994] Q72, [Sugo et al. 2001] 298, [Seko et al. 2003] Q312, [Sugo 2005] Q303 and [JAERI 2005] Q304.
Report [IAEA 2001] Q149 states:

> "Research in Japan indicates that uranium could potentially be extracted from sea water at a cost of approximately US$ 300/kg U, more than 10 times the spot market price at year end 1999."

This statement has a weak scientific base.

NEA/IAEA [Red Book 2014] Q90 reports:

> "Seawater has long been regarded as a possible source of uranium due to the large amount of contained uranium, over 4 Tg U. However, because of the low concentration of uranium in seawater (3-4 parts per billion), developing a cost-effective method of extraction remains a challenge.
> Research on uranium recovery from seawater was carried out in Germany, Italy, Japan, the United Kingdom and the United States from the 1950s through the 1980s and more recently in Japan. In 2012, researchers at the US Department of Energy's Oak Ridge National Laboratory and Pacific Northwest National Laboratory reported encouraging results through the use of innovative improvements to Japanese technology tested in the late 1990s (Ferguson, 2012)*. Although not commercially oriented, the goal of the research is to determine the minimum cost of a virtually limitless supply of uranium in order to guide future fuel cycle decisions. Many Chinese research groups in universities and institutions have also shown interest in uranium extraction from seawater."

The huge uranium resource in seawater is known and assured, but would it be economically recoverable and, more importantly, could it be a net energy source? This report assesses the technical and thermodynamic aspects of the recovery of uranium from seawater in order to find an answer to these questions.

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* Ferguson, W. (2012), "Record haul of uranium harvested from seawater", *New Scientist*, online article dated 29 August 2012, Magazine issue 2880.

2 Extraction from seawater, some aspects

Warm sea currents

Extraction of uranium is only possible from relatively warm seawater with temperatures of, say, 20 °C or higher, for chemical and other reasons. If the adsorption phase would rely on natural seawater refreshment, only a few sea currents would be suitable for the Japanese concept (e.g., the Black Current in the Pacific and the Gulfstream in the Atlantic). The size of the required installations would be measured in tens to hundreds of kilometers.

Part D10 assesses the recovery of uranium from seawater, based on the Japanese studies (adsorption on special polymers) and other studies (adsorption on titaniumhydroxide).

Volumes

The volumes of seawater to be processed in obtaining useful quantities of uranium are huge. The reference reactor of this study, corresponding with the best reactors currently operating, needs 162 Mg natural uranium per year per GW.

With an assumed overall system extraction yield of $Y = 17\%$ (this will be explained later in this report), 285 km^3 seawater per year per GW has to be processed, or 9040 m^3 per second per GW. This is about 3-4 times the outflow of the river Rhine into the North Sea.

To fuel a world nuclear power plant fleet of 370 GW a volume of about 105000 km^3 seawater per year should be processed, or 3.3 million m^3 per second.

Mixing entropy of uranium in seawater

An estimate based on the scarce data available points to a strongly negative energy balance of the nuclear system feeded by uranium from seawater. An unfavourable energy balance could be expected, given the very high mixing entropy of uranium ions in seawater.

The mixing entropy of uranium ions in seawater is extremely high, due to the very low concentration of uranium ions ($1.4 \bullet 10^{-8}$ mol/L) and the relatively high concentrations of a large number of other dissolved species, such as sodium, magnesium, sulphate and chloride ions. To separate uranium from all other chemical species in seawater, in the exceedingly pure form needed for nuclear fuel, large quantities of work (high-quality useful energy) and ordered materials are needed.

The work needed to bring uranium from a state of very high entropy (in seawater) into a state of the lowest possible entropy (in nuclear fuel) has a thermodynamic minimum, that cannot be circumvented by advanced technical means. In practice the thermodynamic minimum work can only be approached but never reached. A practical amount of work about three times the thermodynamic minimum may be seen as a good achievement.

The thermodynamic separation work of the recovery of one kilogram of uranium from seawater might be higher than the useful energy which can be generated from the extracted 1 kg uranium. If so, any research of extraction techniques of uranium from seawater would be futile beforehand.

3 Uranium recovery from seawater, technical outline

System

The first stage of the extraction process is the adsorption of the dissolved complex uranium ions from the seawater on solid adsorption beds. Because of the extremely low concentration of uranium and the relatively high concentrations of many other kinds of ions, very selective adsorbents are required.

After the first stage, the adsorption at sea, a series of additional processes is needed to recover the uranium (see Figure 1):

- cleansing of the adsorption beds to remove organic materials and organisms.
- desorption: elution of the adsorbed uranium ions from the adsorption beds with a suitable solution; depending on the type of adsorbent, this process may be a two-stage process in itself,
- purification of the eluent: removal of other desorbed compounds, which are present in far higher concentrations than uranium ions,
- concentrating the solution,
- solvent extraction of uranium from the solution with a mixture of an organic solvent and a specific complexing agent (an organophosphorus compound),
- concentrating and purification of the extracted uranium compound and conversion into yellowcake or uraniumoxide U_3O_8.

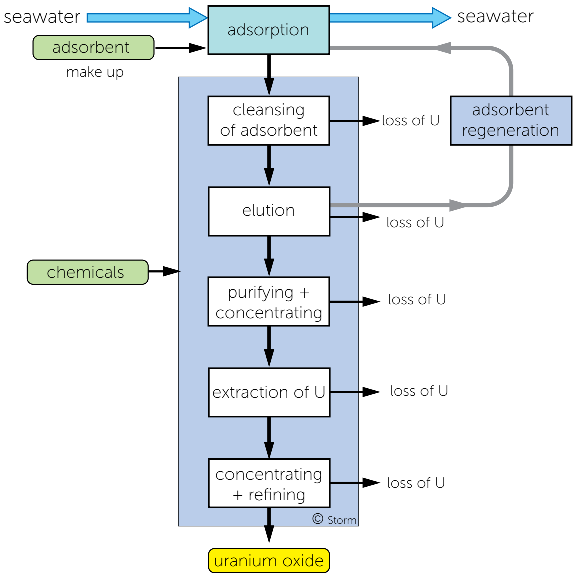

Figure 1

Schematic outline of the extraction process of uranium from seawater

Recovery yield

After the elution (desorption) phase, the adsorbent has to be regenerated. A significant part of the adsorbent will be lost in the first stages of the process chain, so that it has to be replenished by fresh material in the restoration of the adsorption beds for the next cycle.

All processes have their unavoidable losses, this is an inherent feature of chemical equilibria involved in the extraction process. A five-stage process with an assumed recovery yield of 80% of each stage, would have an overall yield of 33%. If each stage has a individual yield of 70%, the overall yield would be 17%. A rough estimate of the overall yield of a five-stage extraction process, excluding the first stage (adsorption from seawater), may be in the range of 20-30%. If more stages are needed, the total yield may be lower.

Volumes to be processed

The volumes of seawater to be processed in obtaining useful quantities of uranium are huge. The reference reactor of this study (see report m19 *Advanced reference reactor and EPR*), corresponding with the best reactors currently operating, needs 162 Mg natural uranium per year per GW.
With an assumed overall system extraction yield of Y = 17%, 285 km^3 seawater per year per GW has to be processed, or 9040 m^3 per second per GW. This is about 3-4 times the outflow of the river Rhine into the North Sea.
To fuel a nuclear power plant fleet (370 GW) a volume of about 105000 km^3 seawater per year should be processed, or 3.3 million m^3 per second.

4 Adsorption from seawater

Due to the extremely low concentration of uranium, very large volumes of seawater have to pass through the adsorption beds. With an assumed adsorption efficiency of about 0.3, 1 gram of uranium would be adsorbed from 1000 m^3 seawater. The contact time of the adsorption bed with seawater, the time needed to attain a reasonable load of uranium on the adsorption beds, may vary from several days to several months. The adsorption stage therefore requires very large facilities, with dimensions measured in tens of kilometers.

The adsorption rate strongly depends on the water temperature. Only locations in warm sea currents with water temperatures of 20 °C or more (e.g. the Gulf Stream in the Atlantic and the Black Current along Japan) are appropriate to adsorption facilities, if the contact time of the adsorbent beds in seawater is to be kept within reasonable limits. This because the establishment of the chemical equilibrium between the complex uranium ions in seawater and the bound uranium ions on the solid adsorbent phase, which is slow, is speeded up by higher temperatures. On the other hand, if the adsorption is an exothermic process, and probably it is, the ratio of adsorbed uranium/dissolved uranium becomes less favourable the higher the temperature, because the equilibrium shifts to the endothermic reaction (desorption) at higher temperatures. So an optimum between adsorption rate and shifting equilibrium has to be found.

Two adsorption methods are here described in some detail: the titaniumhydroxide adsorption method and the polymer adsorption method. Neither of these have actually been tested other than in small-scale experiments.

Titanium hydroxide adsorption method

This method, introduced by British studies in the 1960s and reviewed by [ORNL 1974] Q133, is based on adsorption of the dissolved uranium-complex ions using hydrous titaniumhydroxide gel, $Ti(OH)_4$, on small titania spheres. The adsorbent is packed in large horizontal beds. The seawater is refreshed either by pumps in a facility on the shore, or by tidal currents in a facility on a dam in a large estuary. The pump-fed facility seemed more economical than a tidal facility.
According to ORNL, very few parameters of the British studies were backed by solid experimental data. The

loading of uranium, for instance, was assumed to reach 240 mg U/kg adsorbent after 4 days immersion time, but laboratory experiments showed values no higher than about 130-150 mg U/kg adsorbent after 9 days contact time. Dependent on the production process of the adsorbent, the load values may be much lower. Considerable amounts of adsorbent are lost in the processing of the adsorbent: at least 15-65 kg titanium per kg uranium.

If an adsorption yield of 30% can be achieved, about 1 km^3 seawater has to pass the adsorbent beds to get 1 Mg uranium adsorbed. Because of the low yield of the subsequent processes to recover the uranium from the adsorbent, the required amount of seawater has to be a multiple of 1 km^3, to recover 1 Mg uranium.

There are many unsolved problems, such as clogging of the adsorption beds by organic materials from the sea. By the large uncertaintities in a number of parameters, such as the recovery yield of the system, the feasibility of the concept will be speculative.

Polymer adsorption method

The adsorbent of the Japanese method is a fibrous polymer with amidoxime groups, which act as a chelating agent for a number of metal ions from seawater. The adsorbent is selective not only to uranium ions, some other ions are adsobed even more selectively, particularly vanadium and iron. Besides relatively large amounts of calcium and magnesium are adsorbed. This may necessitate a differentiated and complicated elution process. No data are reported regarding the adsorption of other radioactive elements from the sea: the decay daughters of uranium and thorium and its decay daughters.

The polymer fibers are packed in a special way into beds which are placed into stainless steel cages. The cages are transported to open sea and are moored in a warm sea current, hanging from anchored buoys. After some 60 days at sea the cages are hoisted aboard crane ships and brought to an on-shore processing facility. After processing the adsorption beds and cages are refurbished and returned to sea.
Of note is that the adsorbent units have to be moored in a warm sea current. The temperature of the seawater should be at least 20 °C. There are two candidates: the Black Current near Japan and the Gulfstream in the Atlantic.

Each cage, with a total mass of 1 Mg, contains 125 kg adsorbent. After an immersion time of 60 days some 250 g uranium would have been adsorbed (2 g U per kg adsorbent). If so, theoretically 4000 cages would be sufficient to recover 1 Mg uranium from seawater. However, the overall extraction yield of the processing of the adsorbent and subsequent uranium recovery from the eluent will be considerably lower than 100%: 30% might be a high estimate. Besides a part of the cages will get lost at sea due to heavy waves, high winds and during handling. This loss fraction x is unknown. The total number of cages N with adsorbent beds to be handled and processed to obtain 1 Mg uranium is:

$$N = \{4000 \bullet (1+x)\}/Y$$

Assumed an overall extraction yield of 30%, the net number of adsorbent cages to be processed per Mg uranium is $N = 13000$. Further we assume an average transport distance of 100 km from the processing facility to the mooring area at open sea. This is a guess, for it is unknown where to locate the mooring area, outside the shipping lanes. The area occupied at sea would be some 10000 km^2 (100 x 100 km) for a plant with a capacity of 10000 Mg uranium per year

A Japanese concept [Sugo et al. 2001] Q298, [Seko et al. 2003] Q312 and [Sugo 2005] Q303 is based on adsorption on a fibrous polymer. This material is called a graft polymer because the active agent, consisting of amidoxime groups, is chemically bound to it via a special chemical process involving electron beams. The adsorbent sheets are packed in stainless steel cages which are moored in a warm sea current, hanging from anchored buoys. The plant to recover the uranium from the adsorbent is situated on the shore.

[Seko et al. 2003] Q312 describe adsorption experiments during the years 1999-2001 with three stainless steel cages containing 350 kg adsorbent. The calculated mass of uranium adsorbed during 12 immersion experiments was 1048 gram, involving 1800 adsorption stacks with a total dry mass of 1458 kg. This would correspond with an ideal (dry) 'uranium ore from sea' with a grade of 0.07% U. The actual 'ore grade', worked out on basis of the wet adsorbent, as it is processed by the extraction plant on the shore, would be much lower.

The authors did not mention the mass of the cages to be transported to the shore and back to the sea again in each cycle, nor the extraction yield of the uranium from the adsorbent, nor the way they calculated the mass of the adsorbed uranium.

The publication of [Sugo et al. 2001] Q298 may be the most detailed one on this subject and gives hold for some practical insight. The following analysis is based on this publication.

Mooring the adsorbent at sea

In two mooring methods the cages with the adsorption beds are connected in units of 100 beds, spaced at 0.5 meter intervals, and hung under buoys (one unit per buoy) or large platforms (540 units per platform). Special crane ships hoist the beds aboard after a residence time of 60 days at sea, and bring them to the shore for processing.

In a third approach, the adsorption beds (cages) are connected in units of 10 beds, and are hung from a long horizontal line connecting anchored buoys. The line is 23 kilometers long and forms a loop. Both ends are connected with a processing plant at the coast. Recovery of the beds is done in the same manner as a ski lift: winching up one end of the rope and easing the other. At the plant the exposed beds are removed and fresh ones are attached on the outgoing line.

Table 1

Basic parameters of one adsorption bed, from [Sugo et al. 2001] Q298

mass adsorbent	125 kg
mass spacer	104 kg
mass stainless steel mesh container	685 kg
total mass (cage + adsorbent)	1 Mg (average dry and wet)
adsorbed uranium	2 g uranium per kg adsorbent
immersion time (= 1 cycle)	60 days
adsobent loss replenishment	1/4 of total mass of adsorbent per annnum
diameter	4 m
height	0.4 m

5 Hypothetical uranium extraction plant

Based on the data from [Sugo et al. 2001] Q298 some parameters of a hypothetical uranium extraction plant can be approximated, see Tables 2, 3 and 4. The production capacity of this example is 10 Gg U/a. The current (2012) world uranium consumption is some 62 Gg/a.

Table 2

Parameters of a hypothetical extraction plant. Theoretical base case: without any process losses. Data from [Sugo et al. 2001] Q298

annual uranium production	10000 Mg/a
annual operating time	300 days
number of cycles per annum	5
uranium production per cycle	2000 Mg
number of adsorption beds	8 million
total mass of adsorbent	1 million Mg
replenishment of adsorbent	250 000 Mg/a
daily number of beds to be processed	133333 each day
mass of beds to be processed	133333 Mg/day
loss of adsorption beds at sea	unknown, not mentioned in [Q298]
recovery yield uranium from adsorbent	unknown, not mentioned in [Q298]

Table 3

Parameters of three mooring methods (theoretical), based on data from [Sugo et al. 2001] Q298

parameter	buoys	floating bodies	chain loops
number	80000	148	350
area occupied at sea (km²)	3200	1926	4025
number of ships unloaded per day	133	27	–
occupied coast line (straight, km)	–	–	350

Table 4

Parameters per Mg uranium (theoretical)

effective uranium grade per bed	0.025%	
number of beds to be processed	4000	
mass of adsorption beds to be processed	4000 Mg	
number of ships to be unloaded	4 (method 1)	1 (method 2)
adsorbent loss	25 Mg adsorbent/Mg U	

Each adsorption bed (cage) has to go through the following processes during each cycle:

- hoisting mooring unit from the sea into the ship
- transport from sea to shore (tens to hundreds of kilometers), as a unit

- disassembling sea-going mooring unit of the adsorption beds
- disassembling the adsorption bed (cage)
- processing the adsorbent, a multi-stage process
- replenishing the adsorbent
- reassembling and repair of the cages
- reconnecting the cages to the mooring unit
- transport from shore to sea (tens to hundreds of kilometers)
- remooring the units in the sea.

Uncertainties

The figures of the hypothetical plant above are calculated ignoring the losses in the processes of the recovery of uranium from the adsorbent. As pointed out above the recovery yield will certainly be much less than 100%. If a yield of 50% is assumed (a high estimate) all dimensions in above tables have to be multiplied by 2. If the recovery is lower, e.g. 33% or 20%, the multiplier will be 3 to 5.

It is unknown which fraction of the adsorption beds will be lost and damaged during each cycle by heavy waves at sea and by other causes. The minimum number of adsorption beds to be handled during each cycle theoretically would be 8 million, and practically a lot more, say 16-40 million, depending on the multiplier mentioned above. As long as the multiplier is unknown, the project is characterized by very large uncertaintities, apart from the uncertainties posed by incorporating untested technology.

6 Costs

Some figures from the literature are listed in Table 5. All figures except the last two [Nobukawa et al. 1994] Q72 and [Sugo et al. 2001] Q298 refer to the titaniumhydroxide adsorption method.
Estimates of the cost of deriving uranium from seawater range between approximately $1000 and $25000 per kg uranium. To put this into context, note that a nuclear reactor requires about 180 tonnes of uranium per full-power year, and the present (2006) average cost of uranium from conventional ores is around 40-80 $/kg.

The authors of ORNL 1974 emphasize that the cost figures they found are based on very optimistic assumptions, so the real values will probably be several times higher.

The figures of Sugo et al. are based on apparently unrealistic assumptions:

- The processes following the adsorption stage, required to recover the uranium from the adsorbent, and their inherent losses are ignored.
- Sugo et al. assumed an uranium load of 6 grams uranium per kilogram adsorbent under operational conditions, expecting that this could rise to 10 g U per kg adsorbent. Their own experiments showed that a load of about 2 grams uranium per kilogram adsorbent could be reached after a residence time of 60 days and about 3 g U per kg adsorbent after 240 days immersion in seawater. Apparently the adsorbed uranium load then approaches an equilibrium value. The calculations of Sugo et al. are based on a contact time of about 60 days.

Taking above two factors into account, the cost estimates by Sugo et al. may be low by a factor of at least 10.

Table 5

Estmates of costs and energy consumption of uranium from seawater

reference	energy consumption TJ/Mg (U)	costs $(2000)/kgU
Burnham et al. 1974 [Q136]	26 (1)	–
ORNL 1974 [Q133]	90 (2)	›› 2766
	1,2 (3)	›› 2766
Brin 1975 [Q225]	~390 (1)	289-8280
Mortimer 1977 [Q98]	20-600	728-2210
Koske 1980 [Q223]	5-10 (4)	–
INFCE 1 1980 [Q226]	–	18400-23700
Burk 1989 [Q73]	–	–
Nobukawa et al. 1994 [Q72]	–	370
Sugo et al. 2001 [Q298]	–	280-560
Seko et al. 2003 [Q312]	–	–

(1) only pumping energy, deduced from data in publication
(2) only pumps, pump-fed plant, pump head 20 m
(3) pumps in tidal plant
(4) deduced from data in publication; only pumps in first stage, pump head 0.5 m

7 Upscaling

The cost figures in Table 5 should be regarded as highly speculative, as no practical experience of uranium extraction from seawater exists with an integrated system, not even on a pilot plant scale. The sole empirical data known are the results of a few adsorption experiments at gram scale.

As every chemical engineer knows, the upscaling of complex chemical processes is not a simple task, even with a factor of ten. For a meaningful contribution to the world uranium supply, an extraction plant with an annual production capacity of at least 10 Gg uranium would be needed (uranium consumption in 2012 was 62 Gg/a). That would mean an upscaling of the adsorption process, coupled with the subsequent chemical processes, with a factor of *ten billion*.

Large cost escalations are intrinsic to new technology projects, as [RAND 1981] Q126 reports:

- Severe underestimation of capital costs is the norm for all advanced technologies; the underestimation for energy process technologies mirrored that seen in major weapon systems acquisition, very large advanced construction projects, and major public work activities. A number of advanced technologies brought to project completion had problems with reliability and performance.
- Capital costs are repeatedly underestimated for advanced chemical process facilities, just as they are for advanced energy process plants. Furthermore, the performance of advanced energy process plants constantly falls short of what was predicted by designers and assumed in financial analyses.
- Greater than expected capital costs and performance shortfalls not anticipated by conventional estimating techniques can be explained in terms of the characteristics of the particular technology and the amount of information incorporated into estimates at various points in project develop.

According to [RAND 1979] Q127, escalations in cost estimates of energy process plants by factors of 2-5 are not uncommon. The nuclear industry itself provides many examples of these observations and those of [RAND 1981].

There are no indications that the mechanisms described in the RAND studies would not apply to new large technology projects in 2006, including the extraction of uranium from seawater. On the contrary, a number of factors leading to underestimation of the costs of uranium from seawater are clearly demonstrated in the publication of Sugo et al.:

- the assumed adsorption rate of uranium from seawater is far higher than experimentally demonstrated
- the unavoidable losses of materials and adsorption beds at sea by heavy waves and by corrosion and other causes are ignored
- the unavoidable extraction losses in the chemical processes needed to recover the uranium from the adsorbent are ignored
- maintenance and refurbishment are not accounted for
- starting from an ideal situation and disregarding technical imperfections
- estimating costs on theoretical grounds, without practical experiences (e.g. in a pilot plant)
- the components of the system are considered separately, not as an integrated system
- potential problems posed by the sheer size of the facilities at sea and on the coast are not evaluated.

In addition a number of problems are unsolved, including:

- dynamic behaviour of the mooring equipment at sea under stress of high waves and strong winds; violent movements and collisions may cause losses at sea of adsorption beds or even whole units of beds.s
- recovery of the adsorption beds under adverse conditions.
- problems for shipping posed by the buoys and floating platforms.
- pollution of the adsorber beds by organic materials from the sea.

The evaluation by ORNL [Q133] is critical of the cost estimates as done by the reviewed studies, for similar reasons.

8 Energy requirements

Titanium hydroxide adsorption method

[Mortimer 1977] Q98 concludes that most of the techniques he reviewed have an energy consumption equalling the energy content of the uranium.

A minimum value of the specific energy consumption for the extraction of uranium from seawater may be:

$$J_{sea} = 100 \text{ TJ/Mg} \quad \text{(mainly electricity)}$$

This figure is based on the comprehensive study of [ORNL 1974] Q133, and includes the energy costs of plant construction, chemicals and operation and maintenance of a pump-fed plant at sea, as large-scale tidal plants do not seem feasible. The process needs powerful pumps and consumes large amounts of electricity. Regeneration of the eluant by steam stripping is very energy-intensive and may alone consume thermal energy in the order of 200 TJ/Mg U.

The authors of ORNL 1974 emphasize that the values they found are based on very optimistic assumptions, so the real values can be expected to be several times higher.

A rough estimate of the specific energy requirements including plant construction, chemicals, operation and maintenance, can also be made using the costs in dollars and e, the energy/GNP ratio. Using the cost estimates quoted in [INFCE-1 1980] Q226 (taken from an undisclosed 1978 US Department of Energy study) of 18400-23700 \$(2000)/kg and e = 10.6 MJ/\$(2000), we find:

$$J_{sea} = 195\text{-}250 \text{ TJ/Mg}$$

The above values are underestimates, because the chemical industry is more energy-intensive than average economic activity. The figures agree fairly well with the estimates of Mortimer 1977 and ORNL 1974.
In all studies, to our knowledge, extraction losses (see above) are not taken into account, so the cited figures are low estimates.

Table 6
Theoretical gross energy production from 1 Mg natural uranium in the reference LWR (representative of current design), operational lifetime 30 years at mean load factor of 0.82 (see report m19 *Advanced eference nuclear reactor and EPR*)

Heat production, per Mg natural U	TJ/Mg	465
Gross electricity production per Mg natural U	TJ/Mg	149

Table D.30 does not include the physical process losses of uranium, nor the energy requirements of the processes needed to convert uranium ore into reactor fuel, to operate, maintain and refurbish the nuclear power plant and to sequester the nuclear waste safely.
The net energy production of an LWR nuclear power system is much lower than the theoretical maximum of 149 TJ/Mg U and may be in the range of about 70-100 TJ/Mg natural uranium. Equation above shows that the energy requirements of the complete process might be much higher than even the theoretical energy production possible using uranium recovered from seawater.

From an energetic point of view, uranium from seawater using the titaniumhydroxide method cannot be considered an option for the global energy supply.
This is confirmed by the conclusion of [INFCE-1 1980]Q226:

“Therefore it would be unrealistic to expect uranium from seawater to contribute significant amounts of the world’s uranium demand for thermal reactors on an acceptabele time scale.”

Polymer adsorption method

Based on the concept of Sugo et al. some parameters of a hypothetical uranium extraction plant can be deduced (see Tables 1 – 4). The plant has an assumed annual production capacity of 10000 Mg uranium from seawater.

The effective ‘ore grade’ of the adsorbent beds is G = 0.025% U (250 ppm = 250 g U per bed of 1000 kg). This value is quite near the energy cliff of about 0.02% U of conventional ores. If the yield of the recovery of uranium from the adsorbent is lower than the recovery yield from conventional ore of the same grade, the effective grade of the adsorbent may be significantly lower than 0.025% U. If, for instance, a recovery yield from conventional ore $Y = 60\%$ is assumed, and from the adsorbent $Y = 30\%$, which is not urealistic, twice as much adsorbent has to be processed as conventional ore, to recover the same mass of uranium.

Although the adsorption process itself requires no energy input because the seawater is continuously refreshed by the sea current, handling of the adsorbent units and processing the materials to recover the uranium requires huge quantities of energy, equipment and materials.

The transport of the adsorbent to the shore and back to sea – in contrast with the transport required for ore, using trucks and belts – requires cranes, ships and other equipment over long distances, maybe hundreds of kilometers. Moreover, the energy requirements of all the processes which each adsorbent cage has to undergo, cited under Table 4, should also be taken into account. The replenishment of adsorbent beds requires energy-intensive materials, such as stainless steel and the amidoxime polymer.

The specific energy consumption of the production of the adsorbent, a polymer with the amidoxime groups, may be high, because of its special chemical composition and the need for electron beams to bind the active groups to the polymer. For each Mg uranium recovered at least 25 Mg polymer adsorbent is consumed.

Given the above considerations, it seems extremely unlikely that the specific energy consumption of the method of Sugo et al. will be less than the specific energy content of the recovered uranium.

9 Comparison

Uranium from seawater

Starting from the production of 13000 cages and their transport to the harbour, the cycle to obtain 1 Mg natural uranium encompass the following quantities and activities, starting at the adsorbent beds at sea.

1. Retrieval of 130 adsorbent units from the sea by special crane ships. Each unit consists of a string of 100 cages, totalling 100 Mg, hung from one buoy.
2. Transport (100 km) to the on-shore processing facility.
3. Unloading of the 130 units (13 000 Mg) at the harbour and transport to the facility.
4. Defauling of the cages.
5. Disassembling of the 13 000 cages.
6. Elution of the adsorbent
7. Regeneration of the adsorbent
8. Processing of the eluent: extraction, concentration and refining of the uranium compound, product 1 Mg U (as U_3O_8)
9. Reassembing of the cages,
10. Make up of adsorbent lost during processing (25 Mg)
11. Make up of the lost cages (1 Mg each)
12. Loading of the refurbished 13000 + x cages aboard the crane ships
13. Transport to the mooring area (100 km)
14. Remooring the the adsorbent units.

In addition to the processing facility a large-capacity fresh water supply is required and a facility to safely handle and store permanently the waste chemicals.

The chemical waste is radioactive due to uranium losses of the processing en due to the desorption of other radioactive elements (decay daughters of uranium) from the adsorbent. The studies this report is based on do not mention this issue. No data are published on the adsorption of other radioactive elements from seawater.

The energy input of the full system comprises the energy consumed by the construction, operation and maintenance of the ships and on-shore facilities, plus the embodied energy of the used materials and chemicals. The adsorption stage at sea is the sole part of the process chain that does not need human-supplied energy.

Of note are, among other, the following energy inputs per Mg uranium:

- The total transport input is: 13000•100•2 = 2 600 000 Mg•km by ship, from sea to shore and back from shore to sea (ignoring the lost fraction *x*). In addition the crane ships are to be unloaded and reloaded.
- Hoisting 13 000 Mg two times: from and into the open sea.
- Energy embodied in materials consumed per Mg U:
  - *x* complete cages (stainless steel and other high-quality materials), to replace lost ones
  - adsorbent polymer make up: 25/0.30 = 83 Mg adsorbent polymer per Mg uranium,
  - extraction chemicals, chemicals for regeneration of the adsorbent polymer.
- Energy required for construction and maintenance of the equipment and facilities.
- Fresh water supply.
- Construction and operation of the waste storage facility.

To fuel one 1 GW reactor for one year, above figures are to by multiplied by a factor 162 in case of the reference reactor of this study. That would mean 2.1 + x million cages per year or more than 7000 cages a day (1 operational year corresponds with 300 working days).

A loaded adsorption cage, as recovered from the sea – containing 250 gram uranium per Mg materials – could in some aspects be compared with 1 Mg of a conventional ore at a grade of 0.025% U. From this viewpoint we compare the recovery of 1 Mg U from the sea with the recovery from conventional ores.

The data used for the conventional mine are from report m26 *Uranium mining + milling*. Recovery of uranium under these conditions would be near the verge of the energy cliff.

Uranium from a conventional mine

Assumed:

- overburden ratio $L = 3$: for each Mg of ore 3 Mg of waste rock has to be removed
- extraction ratio $Y = 0.50$ (may be a high estimate, see report m26 *Uranium mining + milling*
- hauling distance $d = 10$ km.

To extract 1 Mg U, 8000 Mg of ore has to be milled and chemically processed and 24000 Mg of overburden has to be removed.

1 drilling and blasting of 32000 Mg rock
2 excavating of 32000 Mg rock
3 sorting ore
4 transport of 32000 Mg rock with dump trucks: 24000 Mg of waste rock to the rock dump (10 km) and 8000 Mg of ore to the mill (10 km).
5 milling of 8000 Mg of ore
6 chemical treatment of 8000 Mg of ore,
7 extraction, concentration and refining of the uranium compound, product 1 Mg U (as U_3O_8).
8 transport of 8000 + *x* Mg tailings to the tailings pond (10 km)

Energy input:

- Embodied energy in explosives, extraction chemicals (10 Mg/Mg U), materials.
- Total transport input = 400 000 Mg•km by dump trucks.
- Energy required for construction and maintenance of the equipment and facilities.
- Fresh water supply.
- Isolation of the radioactive mill tailings from the environment (see report L21p22 *Mine rehabilitation*)

In addition to the processing facility a large-capacity fresh water supply is required and a facility to safely handle and store permanently the mill tailings and the waste chemicals.

Judging by the involved transport and material requirements of the recovery from seawater compared to uranium recovery from a conventional ore, it seems questionable if uranium from seawater could be a net energy resource. Unfortunately, even a rough energy analysis of the Japanese concept turned out to be unfeasible, due to the lack of usable data.

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