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Review

Uranium from seawater – Infinite resource or improbable aspiration?

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ABSTRACT

The availability of uranium drives the future of the nuclear energy industry; an upper limit on uranium prices will determine whether it is economically viable to continue utilising the present generation of light water reactors (LWRs). The alternative is a move towards fast reactors, which use less uranium than LWRs, however require substantial investment and development, and might never become economically viable unless uranium prices rise considerably. While terrestrial uranium resources are seen to be limited, there are approximately 4 billion tonnes of uranium in seawater and although uranium only exists at concentrations of around 3.3 ppb, selective extraction has been achieved. Even though several thorough cost estimates of the extraction process have been undertaken, the practicality of the process and the scale on which it would need to be deployed to sustain the nuclear industry is still questionable. This review aims to examine some of the limitations of the current favourite amidoxime braid system, as well as examining possible interactions with existing legal frameworks which have been put in place; in particular those protecting the marine environment. The potential for uranium extraction from seawater is clearly vast, together with the consequences for nuclear technology choices - but the implications of deploying the technology on such a large scale must be considered.

1. Introduction

One of the key drivers affecting the development of nuclear power is the long term price of fuel, which in turn is a function of uranium availability. In order to know whether more uranium-efficient reactors such as fast breeder or thorium reactors will become economically viable in the future, the forecast for uranium supply and demand must be assessed. The nuclear industry continues to grow despite events such as at the Fukushima Daiichi plant in Japan, partly due to the push for decarbonisation and reduced emissions by many nations. With 60 new, uranium-fuelled, reactors under construction (World Nuclear Association, 2017) and over 300 at the proposal stage (IAEA PRIS, 2017) the growing industry requires large quantities of uranium fuel and demand is predicted to continue rising for the foreseeable future (Uranium, 2014).

2. Background

The majority of the world's current nuclear capacity utilises light water reactors (LWRs) in which the fuel is used once then stored for disposal (open cycle). This consumes uranium at a rate of around 180 te per 1 GWe reactor per year[1], (Cerullo et al., 2012), however other systems such as fast breeder reactors recycle their fuel in a closed cycle and are able to generate a factor of over 60 times more energy from uranium (Van Goethem and Pioro, 2016). Though fuel is a relatively small component of the overall costs of nuclear power generation, a large rise in uranium price could begin to tip the economic balance towards fast breeder reactors, or bring into play systems using thorium as a fuel. Thorium based reactors require uranium and/or plutonium to start the system but can then take advantage of the relative abundance of thorium, which is approximately three times that of uranium (Thorium fuel utilization, 2002; Introduction of Thorium to the Nuclear Fuel Cycle, 2015;

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[1] Typical calculation: 1,000 MWe reactor at 34.1% efficiency requires 2,993 MWth, and at 90% load factor the reactor produces 963,343 MWd per annum. At a fuel burnup of 50,000 MWd/teHM this requires 19.28 teLEU (low enriched uranium), which for a 4.9% enriched fuel and an enrichment feed factor of 9.33 (0.208% U-235 tails) gives a uranium requirement of 180 teU per annum.

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Kademani et al., 2006).

Regardless of the proposed fuel, a new generation of reactors will be expensive to develop to full commercialisation. A closed cycle system with reprocessing and materials recycling is more complex than a once-through system, and is likely to be more expensive unless uranium (and/or fuel disposal) costs rise enough to compensate for the greater capital and operational costs. As a result of this, there is a doubt as to whether (largely state-funded) research and development into new generations of reactors can be continued forward across the developmental 'valley of death' to allow (largely private-funded) commercial deployment. Sixty years of experience with a range of advanced reactor systems has not been encouraging.

One of the biggest influences in this debate is the approximately 4 billion tonnes of naturally occurring uranium (Uranium, 2014) present in solution in seawater. At a concentration of 3.3 ppb oceanic uranium is far less concentrated than the lowest grade of ore yet utilised, but in total it represents over 1000 times the total uranium that can feasibly be extracted from terrestrial ores (Linfeng, 2011). Provided that uranium could be extracted from seawater on an industrial scale, this would put a ceiling price on uranium. If this upper limit was a small multiple of current uranium prices, as asserted by several studies (Lindner and Schneider, 2015; Kim et al., 2014), then reactor systems relying on uranium scarcity/expensiveness as economic drivers would be fatally compromised. Thus the economic extraction of uranium from seawater could have a profound effect on the development and deployment of many of the advanced nuclear fission technologies. There are a range of economic assertions in the literature, but several foresee a price low enough to supply once-through systems economically and essentially indefinitely.

Though seawater contains an average of 3.3 ppb dissolved uranium (3.3 μg/L) (Ku et al., 1977), it actually exists in a steady state, with additions and losses occurring naturally by a variety of pathways (Swarzenski et al., 1999). The greatest contributor to oceanic uranium is from rivers in particulate form (Morris et al., 2002), along with a smaller quantity of dissolved riverine uranium. Other key contributors include glacial particulates and uranium from coastal erosion, altogether contributing around 76,000 tonnes of uranium per year. It is more difficult to estimate a figure for the removal rate of uranium because little is known about the full effect of some deep sea processes. Though few data have been collected, it is known that significant uranium sinks include reducing sediments, the hydrothermal activities in the ocean crust and microbial reduction (Klinkhammer and Palmer, 1991). Together, these oceanic uranium removal processes are estimated to be of the order of 1000 tonnes per year, much smaller than the inputs (Morris et al., 2002) and when put in perspective of the total 4 billion tonnes, these quantities become insignificant. Nevertheless it is not actually known whether the uranium concentration in the oceans is truly in a steady state or what the effects of removing large amounts of uranium from the ocean might be (Barnes and Cochran, 1990).

3. Uranium price tipping point

Rising demand for uranium and diminishing availability of high grade ores will inevitably cause a rise in U_3O_8 prices. If uranium prices rose high enough, it would push up the running costs of LWRs to the point where a closed fuel cycle and/or thorium fuel may be able to compete economically. The Levelised Cost of Energy (LCOE) is the cost per unit energy at which a particular power station will break even over its entire lifetime. There have been many studies and reports on the potential LCOE of fast reactors, with conclusions ranging from total uncertainty (Vernhet, 2013) to claims of electricity costs comparable to those of LWR or fossil fuel power plants (Assessment of Nuclear Energy Systems Based on a Closed Nuclear Fuel Cycle with Fast Reactors, 2012). It is nevertheless widely accepted that fast breeder reactors will be more expensive to run than the existing LWRs and until they are commercially deployed, it is not unreasonable to expect a premium of at least 20% over current LWR power on fast reactor power.

As a contribution to LCOE, the price of uranium is relatively small when compared with the fuel cost of other power plants such as coal or gas. Therefore to change the LCOE dramatically in an LWR to a point where fast breeder or thorium reactors become competitively priced will necessitate a very large, long term increase in U_3O_8 prices. It has been estimated that to push the cost of LWRs up to 120% of their current LCOE requires a rise of around five times the current U_3O_8 price (McGlynn et al., 2014), from $35–50/lb to $175–250/lb U_3O_8 (see Fig. 1). This means prices consistently greater than that of the price spike in 2007, when uranium prices rose to $135/lb U_3O_8 (UxC, 2016).

4. Amidoxime technology

Although there are many potential sorbents for uranium from seawater reported in the literature (Sodaye et al., 2009) including biopolymers, synthetic polymers and inorganic materials, at present the most successful uranium capturing system comes in the form of polyethylene with amidoxime functional groups grafted onto the surface (Lindner and Schneider, 2015; Kim et al., 2013). This method has been more thoroughly tested than other adsorbents both in the lab and field, including multiple scaled up ocean trials, from which several cost analyses have been derived. Consisting of a plastic 'braid' core surrounded by adsorbent fibres, it is moored to rows of chains on the seabed, floating vertically (see Fig. 2). Diffusion and oceanic currents bring aqueous uranium species to the polymer surface where they become bound to the amidoxime groups until elution.

The braids are synthesised via radiation grafting, using a beam of accelerated electrons to irradiate HDPE (high density polyethylene) under a nitrogen atmosphere. This generates free radical sites on to which acrylonitrile can be bound, and is subsequently chemically reacted to produce amidoxime groups. Once the braid has adsorbed aqueous uranium species, they can then be recovered by washing with hydrochloric acid and nitric acid to elute the alkaline earth metals (primarily Mg, Ca (Suzuki et al., 2000)) and uranium respectively, and then replenished with a potassium hydroxide solution so the braid may be reused. This particular amidoxime system has demonstrated an average adsorbency of 1.5 g of uranium per kilogram of adsorbent after 30 days soaking in 30 °C seawater off the coast of Japan (Tamada et al., 2006; Tamada, 2009).

A 1 GWe LWR requires around 180 te of uranium per year (at 90% load factor). To collect this mass in one year, a minimum of 22,000 te of amidoxime braiding is required, assuming an average maximum adsorption capability of 1.3 kgU/te adsorber. This allows for losses in adsorbent efficiency as well as the replacement of the braid after 6 monthly cycles, and equates to adsorbing all the uranium in 54 km^3 of seawater. To be a secure supply for the world's current uranium demands, it would be necessary to collect at least 70,000 te uranium per year, requiring at least 5.8 x 10^5 te of adsorber. This would equate to collecting all the uranium in 21,212 km^3 of seawater per year, which is roughly the volume of all the North American Great Lakes (see Table 1). If recovery was only 1%, then the 70,000 teU would require 2.1 million cubic kilometres of seawater, or close to the volume of the Black Sea. This would also be equivalent to approximately 7% of the annual flow of the Gulf Stream (Hogg and Johns, 1995).