Uranium extraction from seawater using adsorbent shell enclosures via a symbiotic offshore wind turbine device

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ABSTRACT

Seawater is estimated to contain 1000 times more uranium than conventional terrestrial resources, which are forecasted to be depleted within the century. Previous studies of harvesting uranium from seawater have focused on stand-alone, intermittent operation systems that have significant economic challenges due to the high cost of mooring and recovery of the uranium adsorbing polymer. This paper presents two new designs of a seawater uranium extraction system coupled to a floating offshore wind turbine to eliminate the need for additional mooring and increase the overall energy-gathering ability of the wind farm system. Both designs utilize adsorbent filament that is enclosed in a hard permeable shell to decouple the mechanical and chemical requirements of the system. One concept is prototyped at a 1:50-scale and pool tested.

KEY WORDS: Seawater uranium; offshore wind turbine; uranium adsorption; design.

INTRODUCTION

At present, electricity production relies primarily on fossil fuels and is responsible for a large share of the carbon dioxide released to the atmosphere by human activities. Given that one gram of uranium-235 can theoretically produce, through nuclear fission, as much energy as burning 1.5 million grams of coal (Emsley, 2001), nuclear fission has the potential to significantly reduce carbon dioxide emissions from power generation. However, terrestrial supplies of uranium are greatly limited. At the current consumption rate, the global conventional reserves of uranium, 7.6 million tonnes, could be depleted in a little over a century (OECD, 2014). Additionally, as reserves decrease, future uranium is expected to come from lower quality sites, resulting in higher extraction cost and even greater environmental impact.

Fortunately, uranium is present in the ocean as uranyl ions at low concentrations of 3 ppb (Oguma et al., 2011), which over the total volume of the oceans amounts to approximately 4.5 billion tonnes of uranium, which is nearly a thousand times that of conventional reserves (Tamada, 2009). Finding a sustainable way to harvest uranium from seawater will provide a source of uranium for generations to come. Furthermore, it gives all countries with ocean access a stable supply and eliminates the need to store spent fuel for potential future reprocessing, thereby also helping to address nuclear proliferation issues.

Extraction of uranium from seawater has been researched for decades, as early as post-World War II when the production of uranium was uncertain (Davies et al., 1964). In a recent review, Kim et al. (2013) identified uranium adsorption by chelating polymers to be the most promising uranium recovery technology in terms of cost, adsorption capacity, and environmental footprint (Zhang et al., 2003, Seko et al., 2003, Anirudhan et al., 2011). Other techniques including membrane filtration, coagulation, and precipitation were found to have issues such as high operating costs, durability, or toxicity (Kanno, 1984, van Reis and Zydney, 2007, Tularam and Ilahee, 2007).

Chelating polymers allow for the passive extraction of uranium from seawater by adsorption. The polymers are first deployed in seawater and remain submerged until the amount of captured uranium approaches the adsorbent capacity. At this point, elution is used to strip the uranium from the polymers. During this process, the adsorbent is immersed in acid solutions of increasing concentration to recover uranium and remove other elements that have bonded to the polymer. The adsorbent polymer may undergo a number of elution cycles before being regenerated by an alkali wash so that its functional groups are freed and the adsorbent can be reused. The output from the elution process can be transformed into yellowcake following purification and precipitation typical for mined uranium. Past work has focused on systems in which the adsorbent is brought back to shore for the elution process and redeployed afterward. However, these stand-alone intermittent operation systems have significant practical and economic deployment challenges (Seko et al., 2003) and to date none of these systems have become economically viable.

Several of the polymer adsorbent system concepts have been subject to marine tests to evaluate performance, feasibility and cost-effectiveness. The Japanese Atomic Energy Agency (JAEA) first developed a system of buoy floated stacks of adsorbent fabric. However, due to the large weight of the mooring equipment, mooring operations were found to account for more than 70% of the cost of this concept (Sugo et al., 2001,

Seko et al., 2003).

To address this problem, a buoyant braid adsorbent made of polyethylene fibers on a polypropylene trunk was proposed by Tamada et al. (2006). This design was found to achieve a reduction of 40% of the cost of uranium recovery compared to the adsorbent stack system, resulting in an estimated uranium production cost of $1000/kg-U (Tamada et al., 2006). An independent cost-analysis by Schneider and Sachde (2013) and later updated by Kim et al. (2014) of the system yielded a production cost of $610/kg-U. The difference in cost was due to the updates in the uranium uptake measurements and kinetic model. Further sensitivity studies confirmed that the major cost divers of such a system were the adsorbent capacity, number of recycles, and capacity degradation. For instance, if the capacity of the adsorbent was increased from 2 kg-U/t-ads to 6 kg-U/t-ads and the number of recycles was increased from 6 to 20, with no degradation and unchanged adsorbent production costs, the uranium production cost would drop to $299/kg-U (Schneider and Sachde, 2013). In comparison, the market price of uranium has ranged from a current low of $81/kg-U to a peak of $300/kg-U in 2007 when demand for nuclear power was higher.

Schneider and Sachde (2013) demonstrated that a major cost driver of harvesting uranium from seawater is the mooring and recovery of the adsorbent. Additionally, work by Picard et al. (2014) concluded that, due to the kinetics of the adsorbent, the recovery rate of uranium of the adsorbent can be increased by shortening the harvest period. Based on this observation, Picard et al. (2014) pursued the development of a system that continuously takes the adsorbent from the ocean through an elution process and then returns it to the ocean, allowing control over the harvest period. In this paper, we build upon the work of Picard et al. (2014) and the focus of integrating the design of a uranium harvesting system into a floating offshore wind turbine tower. The rationale is that the development of offshore wind or uranium harvesting by themselves bears a high capital cost for the structures, but if the mooring function can be shared, the overall cost for each will be lower. Fig. 1 shows the concept developed by Picard et al. (2014) in which a platform at the base of the wind tower supports a belt of adsorbent that loops in and out of the water. The belt slowly cycles through the seawater beneath the tower and through an elution plant located on the platform. The belt is weighted in the seawater by rollers which also space out the loops and prevent the belt from tangling. The proposed system was sized to collect 1.2 tonnes of uranium per year, a sufficient amount to supply a 5 MW nuclear power. Based on submerging the adsorbent for 38 days per use for a total of 18 uses, this would require 4 km of adsorbent belt for a total weight of 120 tonnes of adsorbent per wind turbine per year. To harvest enough uranium for a 1 GW nuclear power plant would require 214 wind turbines and a total of over 25000 tonnes of adsorbent per year. Preliminary analysis conducted by Picard et al. (2014) on the adsorbent belt and structural design to determine the first order scaling laws for this concept indicate that such a system is technically feasible.

Why offshore wind turbines? Given the low concentration of uranium in seawater, in order to harvest 240 tonnes of natural uranium required to power a 1 GW power plant requires an onshore plant that can pump 5100 m^3/s of seawater through the plant, or approximately 160 km^3 of seawater per year. If the seawater for the onshore harvesting system was also used to provide cooling water in addition to nuclear fuel for the 1 GW nuclear power pant, 5100 m^3/s of flow represents about 21 GW/C of cooling potential or enough cooling capacity for 315 GW of electric power generation, which is about 150 times what is needed for the power plant (Union of Concerned Scientists, 2011). Given the amount of water that would need to be pumped for an onshore system, far more than is required to cool a nuclear reactor, it is more cost-effective to forgo active pumping and instead locate the uranium harvesting system offshore using the ocean currents to flow water past the device.

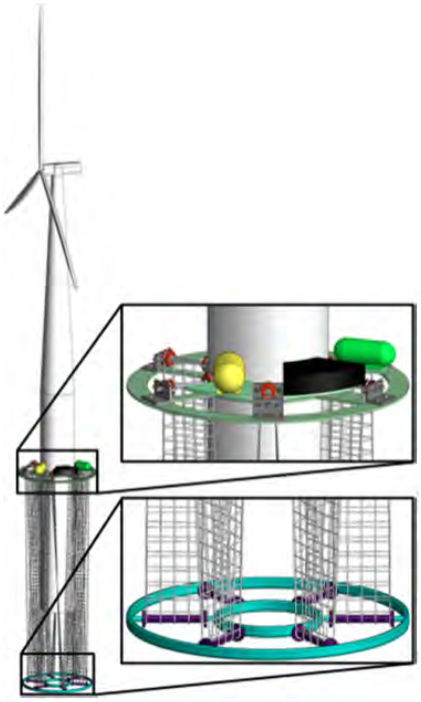

Fig. 1 Three-dimensional model of continuous uranium recovery system with adsorbent belt looped around the turbine mast proposed by Picard et al. (2014). The elution plant is housed on the upper platform out of the seawater.

A similar analysis demonstrates the unfeasibility of harvesting uranium from the brine outflow of desalination plants. Desalination plants routinely pump seawater onshore generating a supply of freshwater and a brine mixture that has a concentration three times that of seawater. To harvest 240 tonnes of uranium required to power a 1 GW power plant would require 53 km^3 of brine flow per year, which would be produced from a desalination plant that generates 77 billion gallons of freshwater per day. This plant would have to be able to generate 285 times more freshwater than the largest desalination plant in the world, Ras al-Khair in Saudi Arabia which produces 270 million gallons of freshwater per day. The sheer volume of water required for the case of harvesting uranium from brine further emphasizes an offshore uranium harvesting system is more cost-effective.

ADSORBENT BEHAVIOR

In order to design a suitable uranium extraction system, a good understanding of the adsorbent behavior is necessary. Using the AF1 adsorbent developed at Oak Ridge National Laboratory (Gill et al. 2016) as a reference, key characteristics of the adsorbent are presented here, namely the recovery rate of uranium, the adsorbent degradation from exposure to acid during the elution process, and the optimization of the main mechanical parameters of immersion time and number of reuses.

Recovery Rate

The rate at which uranium can be collected by the adsorbent depends on its capacity and adsorption kinetics. Using a one-site ligand-saturation model, the uranium uptake, C_0, after a certain exposure time in days, t,

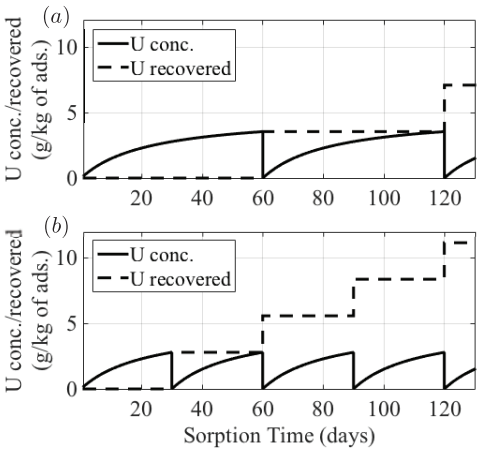

Fig. 2 Adsorption kinetics. Resulting uranium concentration and uranium recovering (g/kg-ads) for a harvest period of (*a*) 60 days and (*b*) 30 days for the AF1 adsorbent.

is given by

$$C_0 = \frac{\beta_{max} t}{K_D + t}, \tag{1}$$

where β_{max} is the saturation capacity in kg-U/t-ads, and K_D is the half-saturation time in days, both properties of the adsorbent used from Gill et al. (2016). After initial alkali conditioning, which is required for the adsorbent to be activated, the adsorbent capacity is degraded by a marginal amount. The ratio of adsorbent capacity after initial conditioning pre-deployment to theoretical capacity is taken to be $C_{ratio} = 90\%$ for this study. Therefore, the actual adsorbent capacity is

$$C = C_{ratio} C_0 = C_{ratio} \frac{\beta_{max} t}{K_D + t}. \tag{2}$$

Due to the kinetics of the adsorbent, the recovery rate of uranium of the adsorbent can be increased by shortening the harvest period. For instance, as shown in Fig. 2, when the period of uranium recovery from the adsorbent is reduced from 60 to 30 days, the amount of uranium collected over 120 days increases from 7 g-U/kg-ads to 11 g-U/kg-ads.

Taking $t = T_h$ be the harvest period, the rate of uranium recovery, R, is defined as follows,

$$R = \frac{C(T_h)}{T_h} = \frac{C_{ratio} \frac{\beta_{max} T_h}{K_D + T_h}}{T_h}. \tag{3}$$

The recovery rate reaches a maximum as the harvest period approaches zero:

$$\lim_{T_h \to 0} R = \frac{C_{ratio} \frac{\beta_{max} T_h}{K_D + T_h}}{T_h} = \frac{C_{ratio} \beta_{max}}{K_D}. \tag{4}$$

The variation of the uranium recovery rate with the harvest period for the AF1 adsorbent is shown in Fig. 3. The final choice of harvest period is a compromise between obtaining the highest recovery rate and minimizing damage to the adsorbent from more frequent elution.

Adsorbent Degradation

Experimental observation showed that adsorbents can lose as much as 20% of their initial capacity over five adsorption/elution cycles (Seko et al., 2004). It is believed that exposure to highly concentrated acid causes damage to the functional groups of chelating polymer adsorbent thus reducing their capacity. To model degradation during elution, it can be assumed that the time the adsorbent is exposed to the acid solution and the solution pH remain constant regardless of the recovery period. This is indeed necessary to make sure that all of the uranium is extracted from the adsorbent. Consequently, the relative loss of adsorbent capacity is assumed to be constant at each elution cycle since the damage to the adsorbent is expected to be the same.

As shown in Picard et al. (2014), the capacity of the adsorbent after n elution cycles can be written as

$$C_n = C(1 - d)^n, \tag{5}$$

where d is the degradation per cycle. Additionally, the average capacity of the adsorbent over n adsorption/elution cycles can be calculated using a geometric progression:

$$\bar{C} = \frac{1}{n} \sum_{k=0}^{n-1} C(1 - d)^k = \frac{C}{n} \left[\frac{1 - (1 - d)^n}{d} \right]. \tag{6}$$

Mechanical Parameters

From (2) and (5), it is clear that the two mechanical parameters involved in the recovery of uranium are the time of exposure of the adsorbent to seawater, t, and the number of elution cycles of the adsorbent before replacement, n. After one cycle, the amount of uranium adsorbed in g-U/kg-ads, Γ_1, after a harvesting time of t_1, is given by

$$\Gamma_1 = C_{ratio} \frac{\beta_{max} t_1}{K_D + t_1}. \tag{7}$$

However, for every cycle thereafter, the degradation of the adsorbent becomes a factor. For instance, the amount of uranium adsorbed in g-U/kg-ads after two cycles, Γ_2, each with a harvest time of t_1 and t_2 respectively is,

$$\Gamma_2 = C_{ratio} \frac{\beta_{max} t_1}{K_D + t_1} + C_1 \frac{\beta_{max} t_2}{K_D + t_2}, \tag{8}$$

where C_1 is the capacity of the adsorbent after one elution cycle. As a result, Γ_2 becomes

$$\Gamma_2 = C_{ratio} \frac{\beta_{max} t_1}{K_D + t_1} + C_{ratio} \frac{\beta_{max} t_2}{K_D + t_2}(1 - d). \tag{9}$$

Following this procedure, assuming that the harvest time for each cycle is the same, that is $t_1 = t_2 = \cdots = t_n = t$, the amount of uranium adsorbed in g-U/kg-ads after n cycles, Γ_n, is

$$\Gamma_n = C_{ratio} \frac{\beta_{max} t}{K_D + t} \left[1 + (1 - d) + (1 - d)^2 + \cdots + (1 - d)^{n-1} \right]. \tag{10}$$

Using a geometric progression, the amount of uranium adsorbed in g-U/kg-ads after n cycles, Γ_n, becomes

$$\Gamma_n = C_{ratio} \frac{\beta_{max} t}{K_D + t} \left[\frac{1 - (1 - d)^n}{d} \right]. \tag{11}$$

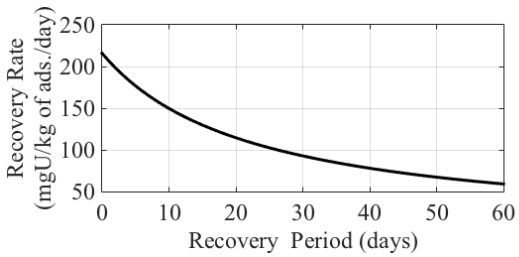

Fig. 3 Recovery rate of uranium, R, as a function of the harvest time, T_h, for the AF1 adsorbent.

From (11), it is clear that if the chemical properties of the adsorbent are fixed (C_{ratio}, β_{max}, K_D, and d), the harvest time, t, and the number of elution cycles, n, are the mechanical parameters that determine Γ_n, the amount of uranium adsorbed in g-U/kg-ads after n cycles.

Sorption Optimization

The soprtion process can be mechanically optimized by using (11) and the chemical parameters for the AF1 adsorbent from Gill et al. (2016):

- Saturation capacity: β_{max} = 5.4 kg-U/t-ads,
- Half-saturation time: K_D = 23 days,
- Degradation per cycle: d = 5 %.

The functional requirements of the symbiotic system require that 1.2 tonnes of uranium are harvested annually, therefore the parameter space can be further analyzed to highlight the combinations of harvest time and elution cycles that are feasible, as shown in Fig. 4. Additionally, the amount of adsorbent required on the system as a function of t and n can also be determined, the results of which are shown in Fig. 5. As can be seen from the Figs. 4 and 5, the parameters chosen by Picard et al. (2014) would not fit within the one year time limit. The optimal values for the AF1 adsorbent within this timeframe actually occur with t = 23 days and n = 15 cycles, resulting in Γ_n ~26 kg-U/t-ads and requiring ~45 t-ads.

FUNCTIONAL REQUIREMENTS

The functional requirements of the continuous seawater uranium harvester are as follows:

1. Use the amidoxime polyethylene braid adsorbent developed by Oak Ridge National Laboratory known as AF1 (Gill et al., 2016).
2. Recover 1.2 tonnes of uranium from seawater per year, enough annual fuel for a 5-MW nuclear power plant.

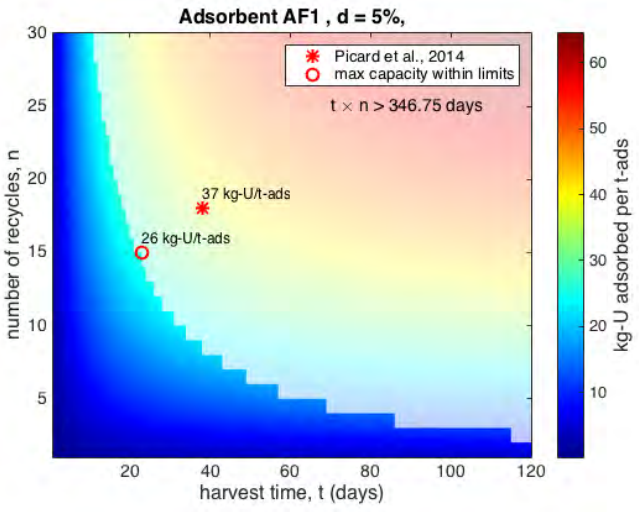

Fig. 4 Amount of uranium adsorbed in g-U/kg-ads, Γ_n, as a function of harvest time, t, and number of elution cycles, n. The value resulting from t and n from the study conducted by Picard et al. (2014) is indicated by the red star. Parameter combinations outside of the one year timeframe are shaded. The optimal value within the limited region is shown by the red circle.

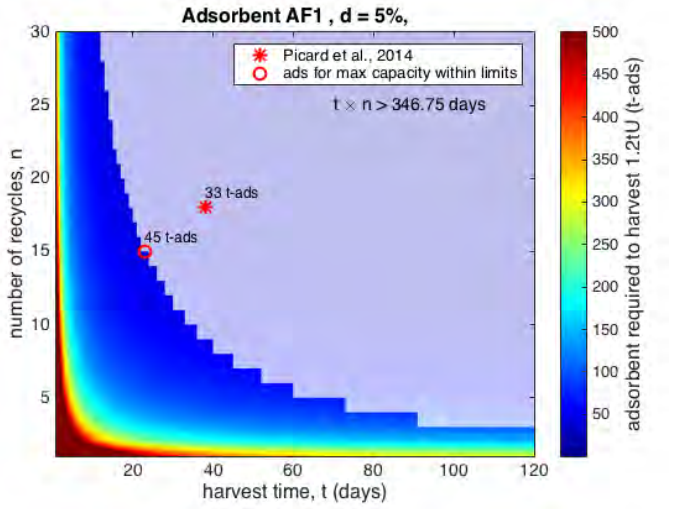

Fig. 5 As in Fig. 4 but for the amount of adsorbent required in kg to harvest 1.2 t-U annually.

3. Bring the cost of uranium extraction from seawater as close as possible to terrestrial uranium mining.

As shown in the previous section, to achieve functional requirement (2) requires approximately 45 tonnes of adsorbent that is submerged in seawater for 23 days and cycled 15 times.

ELUTION AND REGENERATION

As in Picard et al. (2014), both systems presented in this paper for recovering the adsorbent utilized on-site continuous elution and regeneration processes. The elution process requires 30 minutes and consists of two consecutive steps. In the first, the adsorbent chemically reacts with the hydrochloric acid to selectively remove alkali and alkali earth metals. In the second step, the adsorbent is submerged in nitric acid to remove uranium (Schneider and Sachde, 2013). Elements including iron, nickel, lead, cobalt, aluminum, and potassium are adsorbed in amounts comparable to that of uranium (Tamada et al., 2006), some of which occupy the uranium binding sites and therefore their removal is critical to adsorbent reuse. In the regeneration process, which requires 60 minutes, the adsorbent is submerged in an alkali wash after the acid elution steps and returned to sea for repeated use (Schneider and Sachde, 2013).

MOORING AND RECOVERY

In general, uranium-adsorbing materials with the optimal chemical properties for high adsorbent capacity have inherently low tensile strength and durability (Mayes, personal communication). Therefore, the AF1 adsorbent will likely not have enough durability and tensile strength for the designs previously studied by Picard et al. (2014). Hence, the two designs presented in this paper for the mooring and recovery of the adsorbent utilize a two-part system to decouple the mechanical and chemical needs of an adsorbent for seawater harvesting of uranium. In the system, a hard permeable outer shell with sufficient mechanical strength and durability for use in an offshore environment and chemical resilience against elution treatments serves as the protective element for uranium adsorbent material with high adsorbent capacity in its interior (Haji et al., 2015). Fig. 6 depicts one shell design in which a spherical hard permeable outer shell encloses uranium adsorbing material inside.

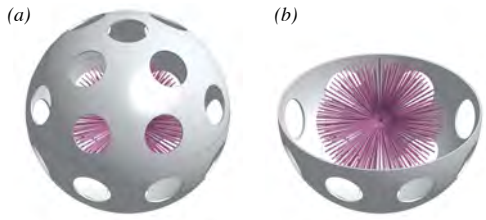

Fig. 6 Initial adsorbent concept with decoupling of mechanical and chemical requirements. Soft, inner adsorbent sphere is encased in tough, outer protective sphere. Outer sphere features holes to allow adequate seawater to adsorbent interior (Haji et al., 2015).

Both systems presented in this paper utilize adsorbent shells that are incrementally spaced along high strength mooring rope, resembling conventional ball-chain belts. These systems connect to a platform that is attached to a floating offshore wind turbine and located above the ocean surface. In each system, at some point the adsorbent ball-chain reaches the top of the platform where the adsorbent is run through the required elution and regeneration baths to remove the uranium and prepare the adsorbent for redeployment in the ocean.

As previously detailed, in the case of the AF1 adsorbent, the amount of uranium adsorbed per kg of adsorbent is maximized if the adsorbent was submerged for 23 days. In order to accommodate both this immersion time and the combined time for elution and regeneration (90 minutes), two designs for looping the ball-chain of adsorbent shell enclosures are investigated. In the first, the ball-chain is looped circumferentially around the turbine, and in the second the ball-chain is looped under the platform in four separate systems by extending the platform and looping the ball-chain several times beneath it. In the case of both designs, the shell diameter, d_s is taken to be 0.25 m, the spacing between shells, L_s is 0.1 m, and the total number of shells is N_{st} = 16,000, resulting in a total ball-chain system length of $L_{sys} = 5,600$ m. Both systems were designed to be used with 5MW OC3-Hywind turbine developed by NREL (Jonkman 2010).

Strategy 1: Circumference Looping System

The first strategy, shown in Fig. 7, uses one continuous chain of incrementally spaced adsorbent spheres connected in a loop. The chain enters the water and is looped around a series of gears spanning the circumference and length of the turbine, and finally returns to the surface and proceeds to move through a series of elution and regeneration tanks before it is returned to the ocean. From the known system length and the required amount of harvest time, the ball-chain speed is 18 cm/min. This speed can then be used to determine the minimum length of the path of the ball-chain in the elution and regeneration tanks, approximately 5 m and 10 m respectively.

Each ball-chain loop requires a gear and shaft protruding from the turbine that would need to be the length of the platform. Using the known system length, the number of submerged shafts and gears for the whole system can be determined using the equation for the total path along the turbine using

$$L_{sys} = (N+1)(D_{sys} - H_{ts} - d_g) + \left(\frac{N}{2}+1\right)\pi d_g + 2\left(H_{ts} + H_p + L_t\right), \quad (12)$$

where L_{sys} is the known, total system length, N is the unknown minimum number of shafts and gears, d_g is the gear diameter, D_{sys} is the maximum system depth (determined by the turbine draft), H_{ts} is the distance from

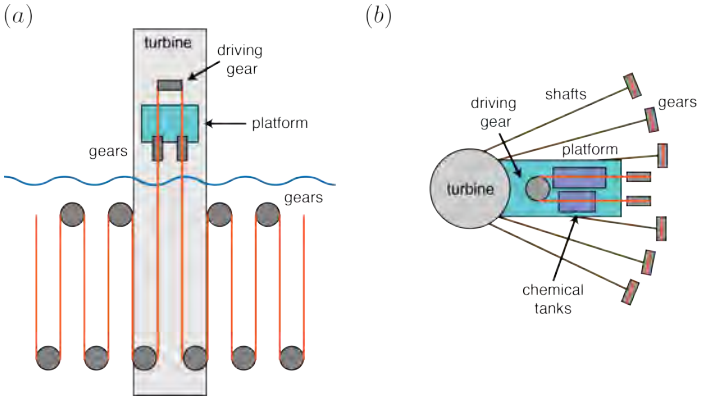

Fig. 7 Schematic of circumference looping system, view from the (*a*) side and (*b*) top. The adsorbent ball-chain is shown in orange. Gears are shown as dark gray circles or rectangles depending on if viewed straight on or from the side. Shafts connect looping gears to the turbine. Note that the gears loop around the entire turbine, though only a few are depicted here.

the top shafts to the sea surface, H_p is the distance from the sea surface to the platform, and L_t is the distance between the front redirectional gears at the edge of the platform to the driving gear. For this design, H_{ts} = 12 m, H_p = 10 m, D_{sys} = 120 m. Note that the value of L_t has little affect on the resulting number of gear shafts, and is taken to be at least 1 m for this study (though the value of the platform length will determine the final value for L_t.)

The diameter of the gear is determined using

$$d_g = \frac{2}{\pi}\left(N_s d_s + L_s N_s\right), \quad (13)$$

where d_g is the gear diameter, N_s is number of shells per 1/2 gear, L_s is spacing between shells , and d_s is the shell diameter. Taking N_s = 8, it was found that d_g would need to be 1.8 m. By Eq. (12), this results in 53 required shaft-gear pairs (note that the number of shaft-gears must be odd) to ensure the entire length of the ball-chain can be looped around the wind turbine. From this, the platform length can be determined as

$$L_p = \frac{(N+1)d_g}{2\pi} - r_t, \quad (14)$$

where r_t is the radius of the turbine at the location of the platform. This results in a platform length of 12.1 m.

Modeling the platform as a square cantilever beam with the force due to the driving gear, elution and regeneration tanks, elution and regeneration chemicals, and storage tanks focused at the end, the thickness of the platform is given by

$$x_{th,pl} = \left(\frac{4F_{pl}L_p^3}{\delta_{pl}E_{pl}}\right)^{1/4}, \quad (15)$$

where F_{pl} is the net force on the platform, L_p is the length of the platform from the turbine edge, δ_{pl} is the maximum allowed deflection of the platform, E_{pl} is the Young's modulus of the platform's material, and $x_{th,pl}$ is the platform thickness. Assuming the platform is made of steel, and a maximum allowed deflection of 1.2 m at its end (10% of the length of the platform), the platform will need to be $\approx$ 0.4 m thick.

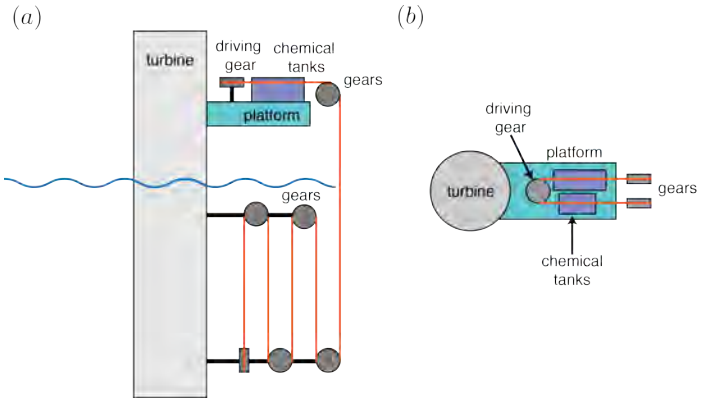

Fig. 8 Schematic of the under-platform looping system, viewed from the (*a*) side and (*b*) top. The adsorbent ball-chain is shown in orange. Gears are shown as dark gray circles or rectangles depending on if viewed straight on or from the side. Note, only one subsystem is shown. In principle, multiple subsystems of driving gears and chemical tanks could be placed around the turbine.

Strategy 2: Under-Platform Looping System

In the second strategy, the continuous chain of shell enclosures is looped several times perpendicular to the turbine under the platform of the uranium harvester instead of around the turbine's circumference. In this strategy, shown in Fig. 8, multiple subsystems can be utilized, each with its own elution and regeneration tanks to process the adsorbent.

The number of times the chain can loop beneath the platform is based on the length of the platform. Each gear the chain loops around is parallel to the shaft it is attached to, except for the gear closest to the turbine. This gear is perpendicular and allows the two sets of loops (one on each side of the shaft) to connect, forming one continuous chain.

By setting the length of the ball-chain path in the elution or regeneration tank and knowing the required processing times of the adsorbent in each chemical bath, the minimum chain speed can be determined. Taking the ball-chain path in the elution tank to be 0.7 m, the resulting chain speed is approximately 2.3 cm/min. This chain speed combined with the total length of the system, and the required immersion time of the adsorbent, results in a minimum submerged path length of 772.8 m. This is the minimum length that each subsystem in the under-platform looping system must be. Using the maximum system length, $D_{sys} = 120$ m, the minimum number of gears per subsystem can be determined to be $N_{d,sys} = 18$, for a total number of 72 gears, and the required number of subsystems to be $N = 4$.

The number of subsystems on the turbine determines the platform length by the equation

$$L_p = \frac{d_g + 2d_s}{2}\left(\frac{1}{\sin\left(\frac{\pi}{N}\right)} - 1\right) + d_g + L_{ct} - r_t, \tag{16}$$

where L_p is the platform length, d_g is the diameter of the driving gear, d_s is the shell diameter, N is the number of subsystems, L_{ct} is the length of the longest chemical tank, and r_t is the turbine radius at the platform. As in strategy 1, the diameter of the driving gear is based on Eq. (13). Since the same shells and number of shells are assumed for both designs, d_g remains the same for this design as 1.8 m. This combined with $N = 4$ results in a platform length of $L_p = 12.3$ m.

As for the circumferential looping concept, Eq. (15) can be used to determine the thickness of each systems rectangular platform segment. Assuming the platform is made of steel, and a maximum allowed deflection of 1.23 m at its end (10% of the length of the platform), each platform spoke (one for each system) will need to be 0.147 m thick. Because the weight of the chemicals can be distributed over multiple subsystems, this design reduces the size of the platform and significantly reduces the required number of submerged shafts to two per system.

PROOF-OF-CONCEPT PROTOTYPE

A 1:50-scale benchtop prototype was built to study the feasibility of the under-platform looping strategy. The 3-D CAD model of the prototyped system is shown in Fig. 9. The prototype objective is to demonstrate that (a) each subsystem can be driven independent of the others, (b) slip between the ball-chain and the gears can be avoided, and (c) entanglement of the ball-chains can be avoided under turbulence in water. The prototype was tested both on land and in the Massachusetts Institute of Technology swimming pool in the Alumni Pool and Wang Fitness Center.

The turbine is modeled by two pieces of PVC of 7 inches and 5 inches in diameter respectively, accounting for the shape of the full scale turbine and a reducer coupling to connect the two pieces together. The four-spoked platform was cut out of aluminum using an OMAX Abrasive Waterjet. The elution and regeneration tanks were modeled by rectangular boxes of appropriate sizes made out of acrylic. Plastic bead chain was used to simulate the 1:50-scale shell enclosures. A total of 72 gears of about 1.5 inches in diameter and 1/4 inch thick were needed for the prototype and they were fabricated from acrylic. All of the shafts of the prototype were modeled by aluminum rods of the appropriate sizes. The gears were designed to be a bead chain sprocket that exactly matched the plastic bead chain. In the full-scale prototype, these gears would also fit the dimensions of the adsorbent ball-chain

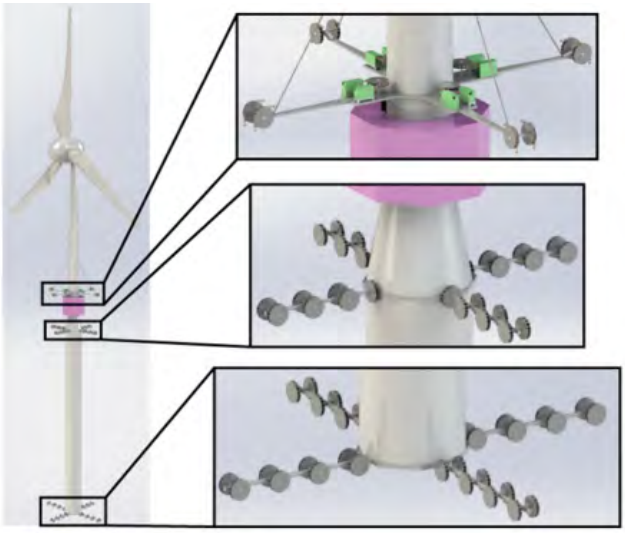

Fig. 9 Three-dimensional view of under-platform looping system for uranium recovery using adsorbent shell enclosures looped around the turbine mast. Only portions of the adsorbent ball-chain shown. The upper platform of each subsystem houses an elution and regeneration tank out of the seawater.

Fig. 10 1:50-scale prototype.

exactly. Bead chain sprockets and their corresponding bead chains take advantage of the swivel characteristics and the spherical shape of bead chain links, thereby enabling the design of omni-directional positive drives with great freedom of orientation of the components. Finally, the required adsorbent immersion time for the prototype was kept at 23 days, resulting in a required chain speed of 2.3 cm/min. The final prototype is shown in Fig. 10.

Figs. 11 and 12 show the upper platform and upper gear shafts of the prototype in the pool, respectively. The bead chain and gear system worked extremely well at reducing slip and eliminating issues of entanglement. The gears allowed for a great deal of compliance in the system, even under strong turbulence (induced by a swimmer kicking violently at depth with fins) there were no observed issues of the ball-chain coming loose from the gears.

The main issue discovered during the pool test related to the initial installation of the bead chain. Due to the number of gears in and the depth of each subsystem, it was extremely difficult to weave the bead chain

Fig. 11 1:50-scale prototype upper platform during pool testing.

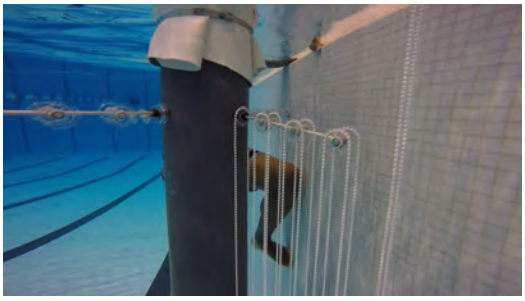

Fig. 12 1:50-scale prototype upper gear shafts during pool testing.

onto the gears with sufficient tension. In an ocean scenario, the distance between the upper and lower shafts would be approximately 100 m. Although this may be technically feasible since the proposed depths of most spar buoy floating offshore wind turbines is greater than 120 m, it is an unreasonable distance to be covered by remotely operated vehicles attempting to install the chain around all gears in a timely manner. However, the design could be modified by keeping the lower shaft on a rail such that the upper and lower shafts can be kept closer together during the chain installation process, after which the lower shaft can be released to its final depth resulting in the ball-chain self-tensioning as it is released. Proving that this proposition works and that the chain can be tensioned efficiently will be an important step towards improving this concept.

CONCLUSIONS

This paper demonstrates two concepts that could potentially reduce the price of recovery of uranium from seawater using unique adsorbent shell enclosures. These shell enclosures allow for the decoupling of the mechanical and chemical requirements of the system. In both concepts, the shell enclosures are strung together using high strength mooring rope, resulting in an adsorbent ball-chain. In the first concept, the entire length of the ball-chain is looped around the length and circumference of the turbine in one single system. In the second concept, the ball-chain is subdivided into multiple systems distributed around the turbine and looped underneath an upper platform. First-order engineering analyses were conducted to evaluate the feasibility of the designs.

It was found that the circumferential looping design utilizes fewer gears, but requires a greater number of shafts, a large platform, and the use of a single loop makes the overall system susceptible to less uptime should any issues arise. In the case of the under-platform looping design, more gears are required than the circumferential looping design, however the number of shafts is greatly reduced. Furthermore, because the weight of the tanks and chemicals may be distributed among multiple systems, the required thickness of the platform is over 60% less than that

required for the circumferential looping system. Additionally, because the design modularized the overall uranium harvesting into multiple systems, should any complications arise at sea, it is highly unlikely that all subsystems would be affected, thereby allowing the system to have a higher uptime.

Due to these many advantages, the under-platform looping design was selected for construction and testing of a 1:50-scale prototype. The pool testing demonstrated that modifications to the design are required to increase the feasibility of the installation of the ball-chain. It also demonstrated that the ball-chain and corresponding gears are extremely robust in holding tension, preventing slip and entanglement, and allowing for a great deal of compliance in the system under turbulence. Detailed cost-analysis of both systems is underway and will be the topic of a future publication. Work is also currently underway to determine the affect of the shell enclosures on the uranium uptake and behavior of the adsorbent as compared to a freely suspended adsorbent in water and will be the topic of additional publications. Further work will focus on incorporating a wave energy device to provide direct ocean-to-mechanical power for the uranium harvester.

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