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Research Article

Uranium Recovery from Phosphates for Self-Sufficient Nuclear Power in the Eastern Mediterranean

Nassar H. S. Haidar

Euclidean Press LLC, 77 Ibrahim Abdul Al Str. Hamra, Beirut, Lebanon

Correspondence should be addressed to Nassar H. S. Haidar; nhaidar@suffolk.edu

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Production of phosphate fertilizers (PF), without uranium recovery, amounts to dispersing uranium compounds on agricultural fields. These compounds are naturally hidden in phosphate rock deposits prior to processing. Such a dispersion is a cumulative environmental damage, that may become rather catastrophic in few hundred years, under the current rates & impurities of phosphate fertilization of agricultural lands. It is also an avoidable irreversible waste of one of the world's major energy resources. This study demonstrates quantitatively the low impact of U costs on the nuclear power generation costs, which happens, so far, to be a main reason for nonrecovery of uranium from the present PF industry. It reports on novel procedures for (i) estimating the required U feed to nuclear power plants (NPPs), (ii) pricing U as a function of its cumulative world production, and (iii) for quantifying U accumulation in phosphate fertilized lands. We also demonstrate that countries of the eastern Mediterranean can, in the long run, become collectively U partially self-sufficient, by recovering U from their phosphate resources, to power 13.2% of their entire electric energy generation contemporary needs.

1. Introduction

It is common knowledge that a light water reactor (LWR) nuclear fuel cycle operates with a low enrichment (2–5% ^{235}U) uranium (U) fuel. Distinctively, a heavy water reactor (HWR) fuel cycle operates on natural (non-enriched) U-fuel or on spent fuel from LWR reactors. Self-sufficiency in uranium supply to an NPP is the ability of the owner to produce, economically, enough triuranium octoxide (U_3O_8) feed to the pertaining nuclear fuel cycle. This has nothing to do with the capability to process, enrich (if applicable), fabricate the UO_2 pellets, to manufacture the, usually Z_r-cladded, fuel elements, or to dispose of radioactive wastes. These services of the nuclear fuel cycle have traditionally been provided by the NPP supplier. With the current availability of rather cheap U ore concentrate (UOC: yellow cake) on the international market, its self-sufficiency appears to be technically non-essential. It is, however, first, more of strategic relevance to the uncertain future of U supply and demand, and to possible future competitivity, see [1, 2], of its price with prices of alternative energies. Second, U self sufficiency, via recovery of uranium from unconventional resources, e.g. as a byproduct of the PF industry, as to be detailed later, is increasingly becoming a pressing environmental issue.

In groups of countries with sizable operating nuclear power programs, the long-term radiotoxicity of the final nuclear waste is currently the main drawback of nuclear power. In these countries there is a pressing need for reducing the long-term radiotoxicity of this waste that is being stored in geological respositories, and for better exploitation of all nuclear fuel (^{235}U,^{239}Pu and^{327}Np) resources. These goals have been shown in [3, 4] to be achieved by combining different concepts of reactor cores in a symbiotic way, [5]. Incidentally, the previously mentioned self-sufficiency in U supply to an open fuel cycle, in countries just entering the era of nuclear power, has nothing to do with symbiotic fuel cycling.

On another note, phosphorous (P) is an essential plant nutrient required for optimum crop production. With respect to fertilizer use, it is second only to nitrogen (N). Plants need P for growth, utilization of sugar and starch, photosynthesis, nucleus formation and cell division. The

triple superphosphate (TSP) fertilizer has been widely used in the 20th century. Technically it is known as calcium dihydrogen phosphate and as monocalcium phosphate $[Ca(H_2PO_4)_2 * H_2O]$ and is produced by interacting phosphate rocks (PR) with H_3PO_4. A number of fertilizers are derived from TSP, e.g. by its blending with ammonium sulfate and potassium chloride. Today PR provides the P element in the N-P-K mix that exists in most widely used fertilizers, [6]. P compounds in these fertilizers are involved in the transfer and storage of energy within plants. Energy from photosynthesis and the metabolism of carbohydrates is stored in P compounds for later use in growth and reproduction. Phosphorous is readily translocated within plants from older to younger tissues as the plant develops roots, stems and leaves.

Phosphate fertilizers are particularly used in the cultivation of wheat, barley, peas, beans, corn, potatoes, conola, sugar beats, sunflower, alfalfa and all perennial grasses. A deficiency in P will slow overall plant growth and delay crop maturity.

In fact, recovery of U from the PF industry can be an important secondary source, [7–9], of uranium that offers quadruple additional advantages: (i) in preventing the otherwise semi cumulative contamination of soils and crops by toxic radioactive U, (ii) in saving funds needed for cleaning the eventual underground water pollution by U, (iii) in reduced regulatory demands on storage or disposal of low-level radioactivity in the piled phosphogypsum byproduct of the PF industry, and (iv) in cutting down on healthcare expenditure, by reducing the incidence of cancer disease enhanced by U infiltration into drinking water and the human food chain. The aim of this paper is to demonstrate quantitatively the low impact of U costs on nuclear power generation costs. A fact that may not encourage U-recovery from the PF industry even when its costs break-even with the costs of U-mining.

This paper is organized as follows. After this introduction, section 2 is followed by a third section on the Annual Uranium Feed to Standard NPP's. Section 4 is on U Recovery From H_3PO_4 Production & Its History. A basic analysis of this work is in Section 5, where a novel procedure is reported for pricing the U supply as a function of the world cumulative U demand. Financing of self-sufficiency in U supply is addressed in Section 6. Section 7 is on Potential of U Self-Sufficiency in the Eastern Mediterranean, surveys the U deposit of the phosphate reserves in countries of this region with forecasts of the number of supportable NPP's by U recovery in the region PF future industry. All these aspects are illustrated by analyzing the current transient status of nuclear power generation in countries of the eastern Mediterranean, namely Turkey, Syria, Lebanon, Jordan, Israel/ Palestine (I/ P) and Egypt. The health hazard associated with nonrecovery of U in the PF industry is analyzed in section 8 on Health Hazard of Uranium Environmental Contamination, where the concept of the number of years of safe utilization (NYSU) of P fertilized lands is introduced for the first time. The paper ends with a concluding Section 9, stating, on one hand, that in the near future, U recovery from PFs can make either the Akkuyu or Al Dabaa $4 \times$ VVER-1200 MW(e) NPP uranium self-sufficient. In the long run, on the other hand, these countries can become collectively U partially self-sufficient, by recovering U from their phosphate resources, to power 13.2% of their entire electric energy generation needs. for the 2020 year.

2. Existing, Under Construction & Planned NPP's in the Eastern Mediterranean

Recent gas and oil exploration activities in the Eastern Mediterranean (*Levanite*) sea have extensively been reported in press during the last decade. Contrary to that, a contemporary 2022 year look at a geographical crescent embracing this sea, reveals a little publicized activity of NPP operation, construction and planning. The Eastern Mediterranean Crescent (EMC), ilustrated in the map of Figure 1, is bounded, in the east, by the Sinop-Medsamor-Amra-Shivta longer arched line, and in the west, by the Al Dabaa-Akkuyu-Sinop shorter arched line. As a matter of notation, we shall assume that a PWR stands for a pressurized water reactor of American, western, Japanese or Korean design, the VVER is its Russian version and CANDU is the Canadian HWR. Furthermore, Table 1 contains a summary of the NPP site nodal points of the previous lines.

In this table T_o stands for the year of commisioning the first unit in an NPP site, T_d is the year of the plant decommisioning and T_p is the year of planned start of NPP operation. In Table 1, * refers to thermal power of a secret reactor (EL-3 French design), designated for plutonium production, in the area of Negev of I/ P, and is now awaiting or undergoing decommissioning.

Moreover, the only qualified future sites for NPP's on the eastern Mediterranean coast appear to be: one on the Syrian coast, south of Banias, [10], one in north Lebanon (close to or within the Syrian border), [11], one in south Lebanon (close to the I/ P border), [11], and one to the south of I/ P (close to or within the Egyptian border), [10].

As for the dimensions of the EMC, the following approximate distances can serve to define its geometry.

Al Dabaa-Akkuyu ~ 820 km (through Cyprus)

Akkuyu-Sinop ~ 540 km

Sinop-Medsamor ~ 700 km

Medsamor-Amra ~ 900 km

Amra-Shivta ~ 100 km

Shivta-Al Dabaa ~ 700 km

Seemingly, this crescent is ~ 1100 km long, ~ 400 km wide, i.e. of an area of $\sim 440 \times 10^3 km^2$, bounded by a perimeter of ~ 3800 km, as illustrated in Figure 1.

Seismically, the EMC, which overlaps with a major part of the historical Fertile Crescent, [12], happens also to be actively faulting due to its dominated span, [13], primarily by.

(i) The Arab-African grand fault that diverts from the Dead Sea-Yammouneh-Al Ghab line towards Cyprus via Lebanon.

(ii) The Ararat-Araks fault, to its east.

(iii) The northern Anatolian fault, to its west.

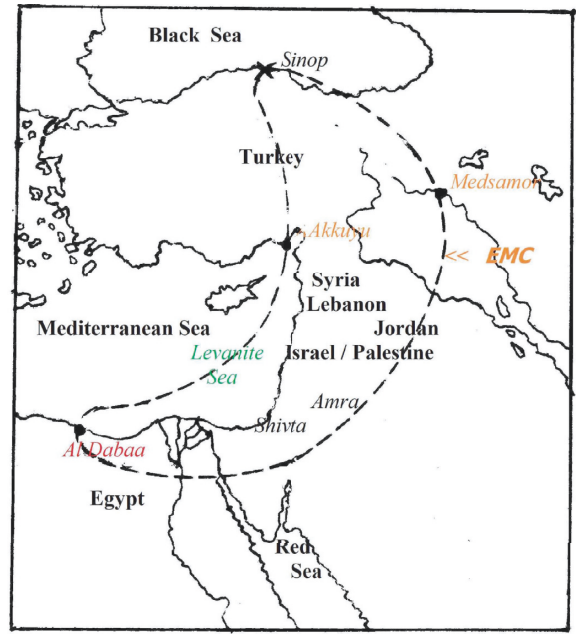

Figure 1: Geography of the East mediterranean crescet (EMC).

Table 1: List of NPP's in the EMC.

Site	Country	Type	Rating [MW(e)]	T_o, T_d or T_p
Akkuyu	Turkey	VVER	4×1200	$T_o = 2023$
Al Dabaa	Egypt	VVER	4×1200	$T_o = 2026$
Amra	Jordan	VVER	2×1150	
		or CANDU	2×750	$T_p = 2022$
Dimona	Israel/P	HWR	20–150*	$T_o = 1950's; T_d > 2022$
Medsamor	Armenia	VVER	2×440	$T_o = 1970's; T_d = 2030$
Shivta	Israel/P	PWR	2×1000	$T_p = 2022 - 2027$
Sinop	Turkey	VVER	4×1200	
		or CANDU	4×750	$T_p > 2026$

Environmentally the EMC is strongly interconnected by seasonal winds, border-crossing rivers (e.g. Ephrate, Assi, Hasbani-Yarmouk, & Nile), shared ground water resources, and via the Levanite sea and its dominant currents, driven essentially by the flow of waters from the Red to Mediterranean and Black seas. Clearly then, the dangerous impact of a possible maximum credible accident (MCA) at any NPP in the EMC can easily spread across all countries of this crescent. The intrinsically globalized nature of nuclear safety for the ongoing nuclear power generation projects across the EMC clearly calls for an unavoidable regional cooperation, at least on common environmental problems between all its member states.

The EMC, particularly its east Turkish or Lebanese parts, is so far not known to contain any important uranium ore deposits. The situation is, however, quite different with phosphate rock deposits that can yield uranium as a byproduct of an anticipated future PF industry.

3. Annual Uranium Feed to Standard NPP's

Section 2 indicates that typical HWR and LWR mostly offered on the EMC power market are the CANDU-6 and VVER-1200 NPP's respectively. The next Table 2 contains a comparative summary of the basic characteristic fueling parameters for these NPPs. To compare their fuel cycles we shall use the following notation.

p: rating of the NPP, MW(e),

$\wp = (N/8760)$: the plant factor, where N is the annual number of hours of plant operation. For newly built NPP's, $\wp$ varies between 50% and 88%,

η: the NPP net efficiency; which is in the range of 37–38%.

T: is the average residence time of a fuel assembly inside the reactor core, d,

G: reactor core equilibrium load, tU,

$\rho = (pT/\eta G)$: the nuclear fuel burn-up, MWd/ tU,

S: annual NPP refuelling load, tU/y,

x: is the fuel enrichment with ^{235}U, in (%); natural uranium has $x_o = 0.71\%$,

x_w: the weight fraction of ^{235}U in tails of the fuel enrichment process; x_w is normally about 0.42%, [1],

S_f: annual NPP nuclear fuel feed, t U_3O_8/y.

Table 2: Fuel core data for standard NPP's, [14, 15].

Parameter	CANDU-600	2 × CANDU −600	VVER-1200	Unit
p	600	1200	1200	MW(e)
x	x_o	x_o	4.95	%
#of fuel elements	380	760	163	channel/assembly
Refuelling	on-load	on-load	1/4 (batched)	
G	87.8	175.6	77.4	t U
S	119.5	239	19.95	t U /y
S_f	140.6	281.2	370.6	t U_3O_8/y
ρ	7500	7500	60000	MWd/tU

Based on a single cascade model, [1], for the U enrichment process, S_f can constructively be approximated by

$$S_f = \frac{S}{0.85}\left(1 + \frac{x - x_o}{x_o - x_w}\right). \quad (1)$$

The reported figures in this table for S_f , which are quite sensitive to the actual magnitude of x_w, happen to be in good agreement with the recent data of Ye et al., [9] or [16].

The channel-type design of the CANDU allows its on-load refuelling, while the vessel-type design of VVER (or PWR) can only be refuelled in batches, of its fuel assemblies, when shut down. A difference with an impact on the respective power generation costs, via their different plant factors, $\wp$. It is clear from this table that the needed annual U_3O_8 feed, S_f , for a 2×600 CANDU twin NPP should be about 31% less than the feed for a VVER (or PWR) of the same rating. Moreover, recent designs of the CANDU reactor can use spent fuel, from PWR's, in addition to natural U.

Clearly, the primary distinction of a CANDU NPP, from the VVER, is its use of natural U fuel with the on-load refuelling. This creates operational flexibility, i.e. it improves outage planning since fixed refuelling cycle times are not required, and it allows the prompt removal of defective fuel bundles without shutting down the reactor. The pertaining fuel management is extremely simple: a regular 2- or 4-bundle shift, bidirectional horizontal refuelling schemes. Fuel bundles -which are 12 in a channel- can also be reshuffled during on-load refuelling. The entire refuelling process is automated and remotely controlled from the station control room.

It should be underlined that ρ accounts not only for the burnt ^{235}U content of the U fuel but also for the burnt ^{239}Pu during the course of its generation from ^{238}U during reactor operation. Moreover, in a CANDU, T can vary between 180 and 720 d, depending on the location of the fuel bundle within the reactor core. This T is however rather fixed (365 d) for a VVER reactor. Table 2 illustrates that while $S > G$ in a CANDU reactor, the opposite $(S < G)$ is true in a VVER reactor. Hence ρ is a neutron physical parameter of the reactor core design and its refuelling management schemes. Eventually ρ in a VVER spent fuel turns out to be 8 folds its value in a CANDU spent fuel. Furthermore, only $< 30\%$ of S is lost as a result of of the previous burnup ρ. The remaining $> 70\%$ goes either to spent fuel storage or to nuclear fuel processing plants.

Despite all the mentioned fuel cycle dissimilarities, latest generations of VVER and CANDU NPP's are nowadays both designed for 60 (instead of previous 30) years of reactor operation.

4. U Recovery From H_3PO_4 Production & Its History

U extraction as byproduct of the WPA (H_3PO_4) process in the fertilizer industry shall be described here only in a sketchy (non-technical) way, [17, 18]. The mined phosphate rock $(2Ca_5(PO_4)F$ and $2Ca_3(PO_4))_2$, which has traces of salts like $UO_2(H_2PO_4)_2$, is digested with sulfuric acid viz Equation (2), and reacted with additional phosphate rock according to (3). The calcium dihydrogen phosphate product is then reacted with additional sulfuric acid to yield more H_3PO_4 viz (4). Simultaneously, a reaction with this sulfuric acid, like (5), goes on with UO_2^{2+} and SO_4^{2-} ions continually migrating to the aqueous phase of the acid.

$$2Ca_5((PO_4)F + 10H_2SO_4 + 20H_2O) \rightleftarrows 6H_3PO_4 + 10CaSO_4^*2(H_2O) + 2HF, \quad (2)$$

$$Ca_3(PO_4)_2 + 4H_3PO_4 \longrightarrow 3Ca(H_2PO_4)_2, \quad (3)$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 \rightleftarrows 6H_3PO_4 + 3CaSO_4, \quad (4)$$

$$3UO_2(H_2PO_4)_2 + 3H_2SO_4 \longrightarrow 6H_3PO_4 + 3UO_2SO_4. \quad (5)$$

In the aqueous phase of this multi-stream process the calcium sulfate sludge $CaSO_4 * 2(H_2O)$ and UO_2^{2+} ions are separated from the H_3PO_4 acid as byproducts using hydrocyclons and solvent extractors (or ion exchangers), respectively.

Historically, U recovery from the phosphate industry has evolved in time over four characteristic periods.

(i) 1950–1960. Military nuclear stockpiling, mainly in the US, had initiated research and development of techniques for U recovery from H_3PO_4 production.

(ii) 1970–1990. Worldwide expansion in nuclear power generation accompanied with a dramatic increase in U demand. This period ended in the early 1990s (after the Chernobyl accident of 1986) with a sharp fall in U prices, which resulted with ceasing U recovery from existing H_3PO_4 plants.

(iii) 1995–2015. Nuclear energy renaissance/ era of resource conservation & CO_2 mitigation, with renewed interest in future U supplies. This had taken place, after a setback though, following the Fukushima accident of 2011. Based on US data, [7, 8], over the period 2014–2018, the cost of U-recovery was \$ 44–61/ lb U_3O_8 (\$ 114.4–158/ kg U) for solvent extraction while the mined U price was \$ 38.81/ lbU_3O_8 (\$100.9/kg U).

(iv) 2020-present. U recovery is marginally more expensive (or may be cheaper) than prime U mining. It is, moreover, a well tested additional profitable opportunity in H_3PO_4 production. Indeed, the U recovery cost went down, [8], in 2020 in the US to the range of \$ 33–54/ lb U_3O_8 , by direct leaching of U, before the digestion process, and by benefication of the phosphate rock.

This history indicates that for U recovery from $H_3PO_4$to be widely implemented in the immediate future, either recovery costs must fall or U prices must rise, [19].

5. Role of Uranium Cost in Nuclear Energy Generation Costs

5.1. Cost of Uranium Supply. Like fossil fuels, uranium resources though are abundant, are not inexhaustible. Hence, extraction of uranium from its various poor deposits, or as a by-product of other industries (like copper mining or PF production) is controlled by the market price for uranium, which is subject to supply and demand. The price of U recovered, e.g. from wet process phosphoric acid (WPA) H_3PO_4, can not be defined locally by any particular producer of phosphate fertilizers. This price C_g, in \$/lb U_3O_8, can only be defined, on the international market, and by the world major producers of phosphates, with an assumed average 100 ppm U content, listed in Table 3, which are namely China, Morocco and the USA.

Clearly, despite the fact that phosphate rock is the fourth-most mined material on Earth, its reserves in the US, for example, of only 1000 Mt, are rather limited. Actually the US phosphate reserves happen to be equal to the reserves of a much smaller country, Jordan, and less than the reserves of either Egypt or Syria. Moreover, current and projected US mine production capacity, [20–22], in Mt of phosphorite rock, shown in Figure 2, demonstrates a falling trend, which implies rising (U-containing) phosphate prices for the future. More globally, it should be noted that, under the current annual mine production rates, the phosphate reserves of China and the US will totally be exhausted in 29 and 40 years, respectively. Because of the world population growth, this is of course an over estimation. Had it not been for the huge reserves of Morocco, such consumptions, and their enhancements, of phosphates should result with their price increase as of the period 2020–2035. Uranium recovery from such phosphates can possibly be motivated to maximize their future challenged revenue. The extremely large supply of Moroccan phosphates has, however, a long-term stabilizing impact on their varying prices, which may perhaps discourage a desired U recovery.

To analyze the temporal behavior of C_g, one should underline that in the absence of new discoveries of U-deposits, C_g of U_3O_8 production from known resources is affected by the necessity to exploit first the high grade deposits.

Let $q(t)$ be the the world annual U-demand during the year t, then $Q(\tau)$ is the cumulative world production up to the year τ viz

$$Q(\tau) = \sum_{t=1}^{\tau} q(t). \tag{6}$$

As a first approximation, the U-ore grade, y, is inversely proportional, [23], to the cumulative production $Q(\tau)$ of U, and $y \sim 1/Q(\tau)$, i.e.,

$$Q(\tau) \sim \frac{1}{y}. \tag{7}$$

$y(t)$ at $t = \tau$ is $y(\tau)$ which can be approximated, [24], by

$$y(\tau) = AQ^{-\mu}(\tau), \tag{8}$$

where A and μ are constants. Clearly, when $\mu \approx 1$, $y(\tau) = A/Q(\tau)$, as expected in (6).

On average, the cost Cg (τ), at $t = \tau$, of U production is directly proportional to the amount of excavated ore. Hence $C_g(\tau)$ is inversely proportional to its grade, i.e. $C_g(\tau) \sim 1/y(\tau)$. However, the production process also involves fixed expenditures that are independent of $y(\tau)$. therefore, $C_g = C_g(y)$ can be approximated by a relation like.

$$C_g(y) = by^{-\gamma}, \tag{9}$$

where the constants b and γ are constants to be fitted to data collected from U-mining experience, [24]. The values $b = 0.4$ and $\gamma = 0.7$ can typically be used to obtain $Cg(y)$ in \$/kg U.

By combining (8) and (9) one obtains a first-order relation between $C_g(y) \sim C_g(\tau)$ and $Q(\tau)$, viz

$$C_g(\tau) = BQ^{\mu\gamma}(\tau), \tag{10}$$

where $B = bA^{-\gamma} = 5.5 \times 10^{-4}$, $\mu = 1$, $\gamma = 0.7$ and $Q(0) = 2 \times 10^8$ kg U. A plot for $C_g(\tau)$ versus $Q(\tau)$ of (10) in this exhaustible U-resource model, [24], is exhibited in Figure 3 against curves corresponding to various availabilities of U-resources. The curves L, M, and H refer respectively to low, medium, and high such availabilities.

Most phosphates of the EMC are U containing sea phosphorites, with U content proportional to the P_2O_5 content, and inversely proportional to the content of $CaCO_3$.The U is attached primarily with Carbonate-Fluorapetite, and seemingly substitutes Ca in the crystallitic network of this mineral. Furthermore, recovery of U from phosphates, in the H_3PO_4 stage, during the production of PFs is expected to cause $C_g(\tau)$ to follow a path over $Q(\tau)$ between the L and M curves above. Hence the assumption on exhaustibility of U resources clearly causes C_g to increase more rapidly, in time, than real trend could be. Furthermore, as with future oil prices, uranium

Table 3: Annual mine production, [20, 21] of phosphate rock.

Country	Reserve [Mt]	Production: [Mt/y]	
		2018	2019
Morocco	50.000	34.8	36
China	3.200	120	110
Syria	1.800	0.1	2
Egypt	1.300–2.800	5	5
USA	1000	25	25
Jordan	800–1000	8.02	8
I/P	62	3.55	3.5

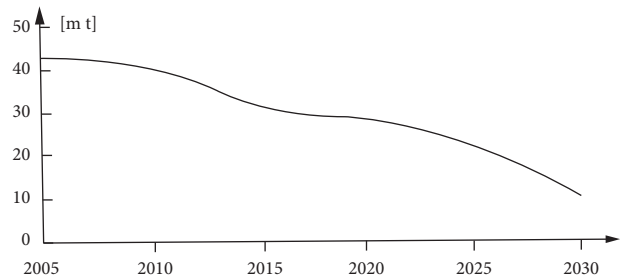

Figure 2: US mine production capacity of phosphate rock.

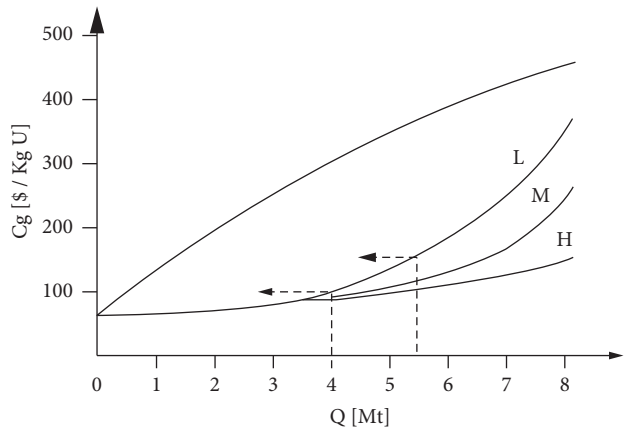

Figure 3: $C_g(\tau)$ versus $Q(\tau)$ plot. *L M* and H refer to low, medium and high availabilities of U-resources.

future prices, though are also rather unpredictable, they follow a general rising trend, after a sizable time lead, even if U is recovered from the PF industry. Nonetheless, the rather flat H curve should not be free of sharp down steps corresponding to critical accidents in the nuclear power industry such as Chernobyl, 1986, and Fukushima Daiichi, of 2011. Such steps happen, however, to unmotivate U recovery from the PF industry.

5.2. Uranium Pricing Procedure. It is well known that the $C_g(\tau)$ on the international market has reached in 1988 the range of $ 57–140/ kg U (with a weighted average of $ 88/ kg U), [19]. After plummeting during the 1990s, this price returned back to the same figure of $ 88/ kg U in 2020, [21]. Parallel to that, the world annual demand, $q(t)$, of U has fluctuated from $63 \times 10^3 t$U, in 2016, down to $60 \times 10^3 t$U, in 2017, further down to $54 \times 10^3 t$U, in 2018, then up to $59 \times 10^3 t$U, in 2019.

Being generically cumulative, the curves in Figure 3 happen neither to reveal the nonsystematic fall in prices during the 1990s, nor volatilities in the U market, or undeclared military U demand, nor purchases of U from the nuclear fuel processing industry. These tenuous considerations may heuristically affect the location of $Q(0) \neq 0$, as an empirical U initial cumulative demand. For $Q(0) = 0$. However, we have

$$Q(\tau) = \overline{q}\tau, \tag{11}$$

where $\overline{q}$ is the average annual world U demand during the period of τ years, to be used in the data of Figure 3.

Hence assuming that $\overline{q} = 50 \times 10^3 t\,\mathrm{U}\,y^{-1}$ during the 80 years between 1940 ($\tau = 0$) and 2020 ($\tau = 80$), then

$$Q(80) = 50 \times 10^3 + 80 = 4\mathrm{MtU}. \tag{12}$$

The ordinate in a curve of Figure 3 corresponding to an abscissa of 4 Mt U happens to yield $C_g(80) = \$\ 91$/kg U, which is close to the correct price, which has been around $ 88/kg U in 2020, [21].

As for the period 2020–2040, $q(t)$ is expected to rise from $50 \times 10^3 t\,\mathrm{U}\,y^{-1}$ to $100 \times 10^3 t\,\mathrm{U}\,y^{-1}$ due to expectations of expansion in nuclear power generation, particularly in East Asia. Furthermore, to foretell the 2040 $C_g(100)$ price, one can assume $\overline{q}_1 = 75 \times 10^3 t\,\mathrm{U}\,y^{-1}$ and extend the argument of (7) to write

$$Q(100) = Q(80) + \overline{q}_1\tau_1 = 5.5\mathrm{MtU}, \tag{13}$$

where $\tau_1 = 20$ years.

In a similar fashion to the earlier $C_g(80)$ price determination, the curves in Figure 3 can be revisited again to read, the corresponding to $Q(100)$, values for $C_g(100)$ in the range of $ 109–157/kg U, according to the *L*, M or H assumed availabilities.

5.3. Nuclear Energy Generation Costs. It is common knowledge, in these days, that NPP's in the 600–1200 (MW) size range are quite competitive, [1, 2] with fossil fueled power plants of the same rating. Competitively, however, though is a major criterion for the adoption of nuclear power for expanding electric power systems, it is not an exclusive criterion. Moreover $C_g \sim C_g(y) \sim C_g(\tau)$ of U_3O_8 feed to the associated nuclear fuel cycle, happens to be insignificant

for the power generation costs $\mathfrak{N}(p,n)$ in mills/kwh. This $\mathfrak{N}(p,n)$ refers to an NPP of rating p that is commissioned after n years of construction work. These explicit variables, and not C_g, are a reflection of the dominant role of capital and finance in $\mathfrak{N}(p,n)$.

Based on invester-owned electric utility practice of calculating depreciation charges year by year, $\mathfrak{N}(p,n)$ for LWR NPP's can be broken down, see e.g. [1], into three basic components: capital ($\mathfrak{C}$), operation & maintenance ($\mathfrak{M}$) and fuel ($\mathfrak{F}$), as detailed in Appendix A.

The derived expression for $\mathfrak{N}(p,n)$ in this appendix demonstrates the relative marginal role played by Cg in $\mathfrak{N}(p,n)$ to justify, e.g. recovery of U from unconventional resources like H_3PO_4, is by far not comparable with the dominant role played by the cost of coal, oil or gas in the pricing of conventional energy generation.

6. Capital Cost Estimates for U Recovery Units

As long as the H_3PO_4 production is commercially viable on its own, only additional costs of extracting the U by product should be attributed to U. Hence our cost estimates shall refer to an assumed U recovery unit adjacent to an H_3PO_4 plant. Costing of such units shall be based on adjusted historical (published) figures, see e.g. [7], as order-of- magnitude estimates that depend on the level of project definition for which the probable accuracy lies between -30% and +50%, [7].

For a fixed capital cost of a new U recovery unit of $\text{Capacity}_{\text{new}}$, in $10^3 t$ PR/y, the historical (reference) \$ figure Cost_{ref} (of 1987, say) for a unit of $\text{Capacity}_{\text{ref}}$ is first escalated to an updated (upd) \$ value, Cost_{upd} (of 2022, say). This is done using the Chemical Engineering Plant Cost Index (CEPCI) viz

$$\text{Cost}_{\text{upd}} = \text{Cost}_{\text{ref}} \frac{\text{CEPCI}_{2022}}{\text{CEPCI}_{\text{ref}}}. \tag{14}$$

Clearly, this is a time adjusted cost. Second, the capital cost of the new unit is obtained by adjusting (14) for differences in capacity by invoking the "seven-tenth" estimation rule (Williams coefficient), viz

$$\text{Cost}_{\text{new}} = \text{Cost}_{\text{upd}} \left(\frac{\text{Capacity}_{\text{new}}}{\text{Capacity}_{\text{ref}}} \right)^{0.62}, \tag{15}$$

which accounts for the economy of scale.

Following [25], let a reference U recovery from H_3PO_4 unit be of processing capacity of 100×10^3 t P_2O_5/y, i.e. of 300×10^3 t PR/y. If the acid P_2O_5content is 350 kg P_2O_5/m^3 and its U content is 0.09 kg·U/m^3, then the amount of recoverable uranium is 23.1tU/y, and is accompanied by an acid production of $285 \times 10^3 \cdot m^3$/y, i.e. 783 m^3/d. The capital investment, [25], in the above unit is Cost_{ref}:mm \$ 13. The unit used a solvent extraction DEPA/ TOPO, [25], process of 90% U recovery rate to produce 23.1tU/ y.

Taking into consideration that $\text{CEPCI}_{1987} = 325.3$ and $\text{CEPCI}_{2022} = 666.1$, [7], then the updated (2022) cost for the reference unit is $\text{Cost}_{2022} = 13(666.1/325.3)$:mm . For similar units of higher capacity, the new (2022) capital costs are evaluated using (14) and (12) to generate the data listed in Table 4.

Future updates of the costs in this table are expected to escalate, by inflation, in time,but moderately due to continually ongoing developments in the technology of U recovery from WPA H_3PO_4 and possibly due to the rather uncertain U market factors.

This table illustrates that for a standard H-1200 NPP, S_f =370.6t U_3O_8/y corresponds to U production of 315tU/y, associated with a PR processing capacity of 4.08 Mt PR/ y.

In countries of the EMC, like Turkey or Lebanon, with minimal or no PF industries, U recovery can be conceived only as regional collaborative ventures with other countries of the EMC. These countries can, e.g., share the financing of the mm \$ 134, mentioned in Table 4, to install a U recovery unit somewhere in the EMC fertilizer industry. This money is enough to secure the annual U needs for a future shared first VVER-1200 NPP project.

7. Potential for Uranium Self-Sufficiency in the Eastern Mediterranean

Phosphate rock (phosphorite) in the EMC is a marine sedimentary rock which contains 18–40% P_2O_5 as well as some U and its decay products, often 50–200 ppm·U. The earlier mentioned technology of U recovery from the PF industry is still marginally more expensive than current prices for mining conventional U rock ores. The U resources dormant in the phosphates of countries of the EMC are, however, extremely large, as illustrated by the data of Table 5.

From Table 5 it is clear that Egypt, I/ P, Jordan, and Syria had in 2010 estimated phosphate rock respective resources of 3400, 1600, 1800 and 2000 million tons (Mt). Their annual production of phosphate ore, during 2009, was respectively 3.3, 3.3, 6.0 and 3.0 Mt. Moreover, Turkey was expected in 1989 to have a rather modest phosphate ore resource of only 329 Mt, while Lebanon did not have any such resources. Hence a uranium self-sufficiency of this crescent appears to be restrictively tied, for the foreseeable future, to the possible recoverability of uranium as a byproduct of its rather sizable PF industry.

Let the U deposit in the phosphate ores be $\mathfrak{R}_u$. in 10^3 t U_3O_8,then the number, M, of units of VVER-1200,(L-1200), or 2 × CANDU-600, (H-1200), that can, in principle ideally be supported by this deposit, for a period of 30 years, is $M = (\mathfrak{R}_u/30\,S_f)$, where

$$S_f = \begin{cases} \dfrac{370\,t\text{U}_3\text{O}_8}{y}, & \text{for } L-1200, \\ \dfrac{282\,t\text{U}_3\text{O}_8}{y}, & \text{for } H-1200, \end{cases} \tag{16}$$

The M data of Table 6 about U deposits in the phosphate rocks of the EMC is 19.7 VVER-1200 units or 25.8 (2 × CANDU-600) units. This means that these deposits can be exploited to generate, during a period of 30 years, 5.82 MGWh (million Gegawh) of electric energy by 23.6×10^3 MW(e) of VVER power. Alternatively, the same deposits can be exploited to generate 7.62 MGWh of electric energy by 30.91×10^3 MW(e) of CANDU power.

Table 4: Capital costs of U recovery units in 2022.

Capacity	H_3PO_4 Throughput	Annual U Production	$Cost_{new}$
[Mt PR/y]	m^3/d	t U/y	mm $
0.3	783	23.1	26.6
4.08	10649	315	134

Table 5: Phosphate rock resources and annual productions, [20, 26], in countries of the EMC.

Country	Year	Reserve [Mt]	Resource [Mt]	Production [Mt/y]	P_2O_5 [%]	U resource [10^3 t U]
T	1980–89		**300–329**		9–13	
u	2007–09					
r	2010–12					
k	2015			0.713		**9**
e	2016			0.7		
y	2019					
S	1980–89	400	400–1057	8	29–31.5	
y	2007–09	100		3.7-3.0		
r	2010–12	250	**2000**	1.534		
i	2015			0.538		**40**
a	2016					
	2018-19	**1800**		0.1–2.0		
J	1980–89	100	200–1574	3.97	28	
o	2007–09	900–1500		5.54–6.0		
r	2010–12	1300	**1800**		26.5	
d	2015			8.336		
a	2016			8		**60**
n	2018-19	**1000–1500**		8.02-8		140
I	1980–89	100	100–1000		26–30	
s	2007-09	180		2.2–3.3		
r	2010–12	200–220	**1600**			
a	2015			3.8–9.0	28	**25–50**
e	2016			3.94		
l/P	2018-19	62		3.55–3.5		
E	1980–89	800				
g	2007–09	180–100		2.2–3.3		
y	2010–12	100	**3400**	6.33	29-30	
p	2015	100		5.30		**40**
t	2016			5		
	2018-19	**1300**		5		

Table 6: Estimated potential for uranium self sufficiency in some countries of the EMC.

Country	[10^3t U]	$\mathfrak{R}_u$ Ref.	[$10^3 t U_3O_8$]	M S_f: L-1200	S_f: H-1200	Installed Power in 2020 [10^3 MW(e)]
Turkey	9	[27]	11	0.96	1.33	95.5
Syria	40	[28, 29]	47	4.22	5.51	9-5
Jordan	60	[30]	71	6.37	8.36	3.4
Israel/P	25–50	[31]	29–59	2.59–5.18	3.42–7.03	15
Egypt	40	[32]	47	4.22	5.51	59.5
Total	186		219	19.7	25.8	180.4

Despite their fuel cycle and safety advantages, the CANDU's remain, however, less competitive than VVER's, because of higher capital costs of the first.

In Table 6 it is remarkable how the entire EMC group of countries total installed power capacity of 180.4×10^3 MW(e) can in principle be furnished by ~150 VVER-1200 units, out of the feasible number $M \approx 20$ of such units. This picture happens to vary very little, if one includes Lebanon in the EMC, with $3 - 2 \times 10^3$ MW(e) installed capacity, and zero phosphate resources. It should be underlined that this analysis is directed more towards an anticipated future for U-recovery from phosphates in the EMC than towards its presently

realizable U-recovery capabilities. In this respect, let us assume that U-recovery, $\mathfrak{T}_u$, in t U/ y, from WPA H_3PO_4 is currently carried out with the annual phosphate rock (PR) production, summarized in Table 7, in countries of the EMC, of a U content ranging between 50 and 100 ppm. Accordingly the number, $M_r = (\mathfrak{T}_u/S_f)$, of VVER-1200 (MW) supportable units in each of these countries is listed in the same Table 7, together with the average $\overline{M_r}$.

Realistically then one can expect only **4.64** VVER-1200 units, out of the assumingly required 150 units, to support the 2020 power generation in countries of the EMC, by U-recovery from the current PR annual production in this crescent. It should be noted, nevertheless, that this power capacity happens to exceed the rating of either the Akkuyu or Al Dabaa NPP, which are $4 \times$ VVER-1200 MW(e) each.

Against this motivating background, it is surprising how very little effort appears to have been applied towards industrial scale U recovery in the EMC. Nevertheless, Jordan has currently ongoing joint projects with India on U recovery from the PF industry on Indian soil. Moreover, in Jordan, at a P_2O_5 production plant, with a capacity 0.676 Mt/y, in 2019, the U extraction potential is 135 tU/y. An amount representing 36% feed for a VVER-1200 MW unit. Turkey also has a number of modest industrial-scale U-recovery plants, operating partially on imported phosphates. Finally, estimates, made in the 1990s, [33], suggest that I/ P was recovering from H_3PO_4 10 t of U_3O_8 per year.This is, however, less than 3% the annual feed, S_f=370t U_3O_8, needed for one VVER-1200 MW unit.

8. Health Hazard of Uranium Environmental Contamination

Phosphate fertilization is known to be the main source of U contamination of agricultural land, and fertilizer-derived U has been entering drinking water supplies in many countries, [34]. This uranium is highly soluble as uranyl (U^{6+}) complex under oxidizing conditions and is mobile in surface soils depending on prevailing PH and Eh conditions. Hence, the level of U enrichment of cultivated soils varies, depending on the rate of phosphate fertilizer application, its U content, soil type and prevailing climate.

Natural U is comprised of three isotopes, with ^{238}U (99.27%) being the most abundant (^{235}U: 0.72%; ^{234}U: 0.01%). As for specific activity, 48.9% can be attributed to ^{238}U, 2.2% to ^{235}U, and 48.9% to ^{234}U, [35]. Upon ingestion, uranium is distributed primarily to bone, liver, kidneys, and soft tissue. Alpha particles emitted by uranium are readily absorbed by the human body and can damage DNA, resulting in genetic mutations or chromosomal aberrations, [34]. Uranium can, however, damage biological systems primarily through its chemical toxicity (particularly as an endocrine-disrupting chemical) as well as its radioactivity, as a secondary effect. The main health concerns with respect to U are renal, developmental, reproductive, diminished bone growth and brain damage. Links between elevated groundwater uranium, or its decay products, and cancers of the blood, bone, lung, bladder, breast, or reproductive system have been suggested, [35], and are still an area of active research.

Table 7: Current realistic potential for uranium self sufficiency in some countries of the EMC.

Country	Production [Mt PR/y]	$\mathfrak{T}_u$: U recovery [t U/y]	M_r	$\overline{M_r}$
Turkey	0.7	35–70	0.13–0.26	0.19
Syria	2.0	100–200	0.32–0.64	0.5
Jordan	8.0	400–800	1.27–2.54	1.91
Israel/P	3.5	175–350	0.56–1.12	0.84
Egypt	5.0	250–500	0.8–1.6	1.2
Total	19.2	960–1920		4.64

The annual increase, i, in U concentration of soil, in $[\mu\, g\, g^{-1} y^{-1}]$, by P fertilization is representable, [36, 37], as

$$i = 10^{-4} l^{-1} d^{-1} \chi f, \tag{17}$$

where 10^4 is the area of one hain m^2, d: is the soil bulk density, [t/m^3], l: length of sample of top soil, [m], χ: concentration of U in applied P fertilizer, $[\mu\, g\, g^{-1}]$, f: annual fertilizer application, $[\mathrm{kg\,ha^{-1}}\, y^{-1}]$.

Typical values, [37], of these parameters in countries like New Zealand, Iceland and Japan are: l =0.5 m; $d = 2.5\,(t/m^3)$, $\chi = 31 - 121\,[\mu\, g\, g^{-1}]$; $f = 39.3 - 78.6\,\mathrm{kg \cdot ha^{-1}}\, y^{-1}$, which upon consideration in (17), results with the annual U accumulation of

$$i = 0.13 - 0.30\,\mu\, g\, g^{-1} y^{-1}. \tag{18}$$

In formula (18) the magnitude of χ is obviously controllable by U recovery in the PF industry prior to P fertilization. Distinctively, f remains as a rather free critical parameter in (17), that can be abusively increased in some Third World countries, with weak environmental safeguards.

since the transfer factor of U from soil to plant is below 1%, [38], the uptake by plants & then entering the food chain should not be a predominant health issue. However, it has been suggested in [36] that drinking water can become a main source for U intake. Indeed more than 20% of U applied in fertilizers is leached to waterways as elevated U concentrations, and the remaining 80% accumulates in top soils. These features prompted the US Regulatory Commission to establish (USNRC 1992) the residual U contamination admissible limit, I, in soil:

$$I = 30\,\mu g g^{-1} = 30\,\mu g U g^{-1}\mathrm{soil} = 10\,pCi\, g^{-1}. \tag{19}$$

This limit is only $23\,\mu\, g\, g^{-1}$ i.e. rather stricter, in Canada.

Remark 1. The number of years, $\mathcal{N}$,of safe utilization (NYSU) of P fertilized land is

$$\mathcal{N} = \frac{I}{i} = 10^4\, l\, d \frac{I}{\chi f}. \tag{20}$$

Substitution of the average value of (18), namely $i = 0.22$, $\mu\, g\, g^{-1} y^{-1}$, together with (19) in (20) leads to $\mathcal{N} = 150$ years. After these $\mathcal{N}$ years, the P fertilized agricultural fields should either be deserted forever or have their top soil removed, stockpiled and replaced. Taking into consideration the always growing demand on agricultural land to feed the population explosion of the world, this situation poses a

delayed global catastrophe. A desired prolongation of the NYSU can conceivably be achieved only via:

(i) reduction of f by growing crops that require low P fertilization, which my not always be feasible,

(ii) minimizing χ by all means and as soon as possible by recovery of their fertilizer-derived U.

9. Conclusion

Pricing of U as a function of its cumulative world production is summarized in this paper in the form of a single relation, (10), in association with plots exhibited in a single figure, Figure 3. The paper quantifies in (18) the accumulated U in P fertilized lands and in (20) the NYSU $\mathcal{N}$ number for such lands. Although $\mathcal{N}$ turns out to be in hundreds of years, it is alarming of a posing future environmental catastrophe, if U continues to be unrecovered from P fertilizers.

We have also quantified in this paper the low impact of U costs on the nuclear power generation costs and how this happens, so far, to be a main reason for nonrecovery of uranium from the present PF industry. Countries of EMC are proved to be able, in the long run, to become collectively U partially self-sufficient, by recovering U from their phosphate resources, to power a fraction of their future electric energy generation needs.

The seed money for initiating uranium recovery, on industrial scale is estimated, in Section 6, to be mm $ 134. This is the 2022 installation cost for a U recovery unit in the PF industry to guarantee U self-sufficiency for a single VVER-1200 MW(e) unit.

Quantitatively, during 2020, the entire power generation load of all countries of the EMC can be supported by 150 × VVER-1200 MW(e) plants. In Section 7, we have demonstrated how an anticipated U recovery from the current PR production in the EMC can support only 4.64 such units. Incidentally, this happens to exceed the rating of either the Akkuyu or Al Dabaa NPP, which are 4 × VVER-1200 MW(e) each.

Moreover, future projections of such U recovery policies from P resources of this region can boost, in the future, this support to 19.7 units; which represents 13.2% of the EMC 2020 entire power generation capacity. A good potential that should not be isolated from (but added to) the other important advantages of U recovery from phosphates, particularly in the environmental and healthcare domains.

Nomenclature

$\mathfrak{C}$: Capital component of $\mathfrak{N}$ (mills /kWh)
d: Soil bulk density (t/m^3)
f: Annual fertilizer application (kg/ha·y)
$\mathfrak{F}$: Fuel component of $\mathfrak{N}$ (mills/kWh)
G: Annual U fuel equilibrium load (t)
i: Annual increase in soil U contamination (μ g/g·y)
I: U contamination admissible limit (μ g/g)
l: Length of soil sample (m)
$\mathscr{L}$: Reactor core U fuel charge (t)
M: number of standard NPP's
M_r: National number of VVER-1200 units
$\overline{M_r}$: Average national number of VVER-1200 unit
$\mathfrak{M}$: Maintenance component of $\mathfrak{N}$ (mills / kWh)
n: Duration of construction work (y)
N: annual number of hours of plant operation
$\mathcal{N}$: Number of years of safe utilization of P fertilized land
$\mathfrak{N}(p,n)$: Nuclear power generation costs (mills/kWh)
p: Rating (MW(e))
$\wp$: Plant factor
$q(t)$: World annual U-demand (t)
$\overline{q}$: Average world annual U-demand (t)
$Q(\tau)$: World cumulative U-demand (t)
$R(p)$: Ratio of the maintenance to capital components in $\mathfrak{N}(p,n)$
S: Annual fuel equilibrium load (t U_3O_8)
t: Time (y)
T: Average residence time of fuel in reactor core (d)
x: Fuel enrichment (%)
W: Enriched UF_6 purchase cost ($/kg U)
Z: Nuclear fuel cycle cost

Appendix

A. Nuclear Energy Costs

The generation cost of nuclear energy is, [1].

$$\begin{aligned}\mathfrak{N}(p,n) &= \mathfrak{C} + \mathfrak{M} + \mathfrak{F} \\ &= \frac{1}{8.76}\frac{\varphi}{\wp}C(p,0)(1+\theta)^n + \frac{1}{70}R(p)C(p,0)(1+\theta)^n \\ &\quad + \frac{1000}{24}\left[1 + 6.69\times 10^{-5}\,\frac{T}{\wp}\right]\frac{1}{\eta\rho}Z\left(x, C_g\right),\end{aligned} \tag{A.1}$$

where the several standing financial and technical factors can play even more important roles than C_g. These are namely:

$C(p,0) = D(400/p)^{0.245}$: is the NPP specific capital cost, in $/kW(e), in the year of starting the plant construction, where

$$D = C(400,0) = \begin{cases} \dfrac{1480\$}{\mathrm{KW}(e)}, & \text{for LWR,} \\ \dfrac{2180\$}{\mathrm{KW}(e)}, & \text{for HWR,} \end{cases} \tag{A.2}$$

φ: the annual fixed charge rate, which varies between 6% and 15% according to conditions of financing the NPP project. θ: the annual escalation rate, which is usually 8%but may reach a value of 30% in the event of economic crises. $R(p)$:0.25 exp 0.15 $(1 - (p/100))$: is the ratio of the operation & maintenance component to the annual fixed charge component, [1],which is a rather flat ≈ 0.18 quantity for all NPP's with $p \geq 600$ MW.

The $\mathfrak{F}$- component of $\mathfrak{N}(p,n)$ is essentially

$$\mathfrak{F} = \frac{1000}{24}\frac{GZ}{pT} = \frac{1000}{24}\frac{Z}{\eta\rho}. \quad (A.3)$$

Since the equilibrium core of a typical LWR reactor is normally replaced in three refuellings ($\nu = 1/3$), then the $\mathfrak{F}$-component above may be divided into two terms. The first term is related to the cost of refuelled load, i.e. to the nuclear fuel which guarantees the functioning of the reactor between two refuellings. The second term is related to the cost of two-thirds of the initial reactor core which is spread over the whole service life of the NPP which is considered to be 30 years. Consequently, for LWR plants, relation (A.3) takes the form

$$\mathfrak{F} = \frac{1000}{24}\frac{Z}{\eta\rho} + \frac{1000}{24}\frac{2GZ}{3p\wp \times 30 \times 365}, \quad (A.4)$$

which, by virtue of $G/p = T/\eta\rho$, transforms to $(1000/24)[1 + 6.69 \times 10^{-5}(T/\wp)](1/\eta\rho)Z(x, C_g)$,. As for HWR NPP's, which are normally on-load refuelled, relation (A.3) is expected to hold quite satisfactorily.

Apparently, C_g can affect $\mathfrak{N}(p, n)$ only through one factor in the fuel cycle cost

$$Z\left(x, C_g\right) = W\left(C_g, C_s(x)\right) + C_f + C_r + C_t + C_u + C_v - \mathrm{U}_c - P_c. \quad (A.5)$$

$C_s(x)$: the isotopic separative work unit (SWU) cost, in \$/kg U, or \$/kg SWU,

W: is the enriched UF_6 purchase cost in \$/kgU,

C_f: the UO_2 fuel fabrication cost,

C_t: shipping cost,

C_u: use charge,

C_v: cost of conversion of U_3O_8 to UF_6 , in \$/kgU,

U_c: uranium credit,

P_c: plutonium credit.

Currently, in countries with developed nuclear power industries (unlike those of the EMC), $Z(x, C_g)$, contains additional components, [5], for activities like decontamination, decomissioning, fuel recycling and waste disposition.

As illustrated in [39, 40], $Z(x, C_g)$ is quite complex to analyze and depends also on an unmentioned, but quite important, industrial parameter, namely x_w: the weight fraction of ^{235}U in tails of the fuel enrichment process. This complexity, together with the fact that W accounts for about 70% of Z for LWR fuel [40, 41], motivate adopting the following, [1], approximation

$$Z\left(x, C_g\right) = \alpha\beta[1 + \xi]J(x)L\left(C_g, C_s\right). \quad (A.6)$$

ξ: is the fraction of U lost dring fuel fabrication. $J(x)$: is the ratio of the cost of a gram of U of x% enrichment to the cost of a gram of 93.5% enrichment in ^{235}U. $L(C_g, C_s)$: is a functional nomogram shown in Figure 4 of [1]. α: is a normalization empirical trial constant of the simplified model (A.4) for the nuclear fuel cycle. This α is estimated with the aid of $J(x)$ and $L(C_g, C_s)$, in [41], for a set of fuel cycle data, to be $\alpha = 32.58$ g ^{235}U/kg U. A value that remains practically fixed also for HWR fuel cycle data, despite the fact that in a once-through fuel cycle $C_s = C_r = U_c = P_c = 0$. Also. $\beta = \begin{cases} 1.42, & \text{for LWR,} \\ 1.75, & \text{for HWR.} \end{cases}$.

Greek Symbols

α, β, γ: Empirical normalization constants
ν: Core annual refuelling factor
η: NPP net efficiency (%)
θ: Annual escalation rate (%)
φ: Annual fixed charge rate (%)
ρ: Nuclear fuel burnup (MWD/t U)
τ: Number of years (y)
χ: Concentration of U in in applied P fertilizer ($\mu g/g$)
ξ: Fraction of U lost during fuel fabrication

Superscripts or Subscripts

$C_g(\tau)$: Cost of U production (\$/kgU)
C_s(x): Cost of U isotopic separation (\$/kgU)
C_f: UO_2 fuel fabrication cost (\$/kgU)
C_t: Shipping cost (\$/kg)
C_u: Use charge (\$/kgU)
C_v: Cost of U_3O_8 to UF_6 conversion (\$/kgU)
P_c: Plutonium credit (\$/kgU)
$\mathfrak{R}_u$: U deposit in PR ($10^3 t U_3O_8$)
S_f: Annual fuel feed (t U_3O_8)
U_c: Uranium credit (\$/kg U)

Abbreviations

CANDU: Canadian LWR
CEPCI: Chemical engineering plant cost index
EMC: East mediterranean crescent
HWR: Heavy water reactor
I/P: Israel/Palestine
LWR: Light water reactor
NPP: Nuclear power plant
P: Phosphorous
PF: Phosphate fertilize
PR: Phosphate rock
PWR: Pressurized water reactor
U: Uranium
VVER: Russian PWR.

Data Availability

Some hyperlinks are in the references.

Conflicts of Interest

The author declares that he has no conflicts of interest.

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