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Some comments on Herndon's nuclear georeactor

Dedicated to Dr. Rudolf Weber who died too early by drowning in the Mediterranean Sea

Light was thrown on the nuclear aspects of Herndon's georeactor. His thesis is that a power producing droplet of liquid uranium, possessing a radius of about 5 km, operated during the last 4.5 billions of years in the center of the Earth and producing 3–6 TW of thermal power.

It could be shown that indeed initial criticality was possible due to the high U-235/U-238 enrichment of approximately 30 % at that time. Furthermore, the U-238/Pu-239/U-235 conversion cycle guarantees also a stabilized U-235/U-238 enrichment of about 10 % during the whole history of Earth. For this, a constant critical neutron flux in the realm of 10^8 n/(cm^{2}s) has to be present to convert U-238 via the Pu-239 route and its ed-decay into U-235 with a conversion ratio of exactly unity.

Herndon's georeactor is compared with other exotic fission reactors in Nature, too, but the decisive answer whether such a georeactor really exists needs further – particularly chemical, thermodynamical and geological – research work.

1 Anamnesis

In several articles Herndon et al. [1–2] have postulated that in the center of our Earth a nuclear georeactor exists possessing a thermal power of 3–6 TW since about 4.5×10^9 years, i. e. during the whole life-time of Earth. At that time a 'droplet' of liquid uranium sunk to the center of Earth forming a sphere with a radius of about 5–6 km and possessing a temperature of about 7000 °C. Due to the high pressure there the density of the liquid is 36.84 g/cm^3, about twice as high as under normal conditions [2].

Criticality of the droplet was possible at that time because the U-235 enrichment was much higher than today. In his last publication [2] Herndon assumed a particle density ratio $N^{(5)}/N^{(8)}$ = 30.38 % which guaranteed initial criticality. The conversion process in this fast system via the Pu-239 production due to U-238 (n,y)-capture reactions and the Pu-239 decay into U-235 should then stabilize a minimum U-235 concentration to maintain a critical system and therefore power production for a long time.

As the only evidence of such a georeactor Herndon et al. have analyzed the He-3/He-4 ratio in vulcanic basalt materials being the only physical 'message' from the center of Earth up to now. Since He-3 stems from the tritium decay, produced by ternary fission, and He-4 stems exclusively from the α-decay chains of uranium he could show that this ratio deviates correspondingly from the ratio in air although some of the He-3 stems also from the 'big bang'. Herndon argues also that the 'on' and 'off' times of this deep-earth reactor could exlain the (not yet fully explainable) changes of sign of the magnetic field of Earth every 200 000 years. Thus, the general message of Herndon's theory is that a nuclear fission reactor in the center of Earth is protecting life from the solar wind.

In the following we will go into the nuclear details of such an exotic georeactor.

2 Initial criticality, long-term criticality and kinetics/dynamics

2.1 Initial Criticality

Initially, i. e. 4.5×10^9 years ago, the uranium droplet can be assumed to be an infinite medium consisting of U-235 and U-238 isotopes. The first question is what initial particle density ratio $x = N_0^{(5)}/N_0^{(8)}$ is necessary to ignite a chain reaction? For this we consider the definition of the infinite multiplication constant k_∞ being

$$k_\infty = \frac{\eta^{(5)}\cdot\sigma_a^{(5)}\cdot xN_0^{(8)} + n^{(8)}\cdot\sigma_a^{(8)}\cdot N_0^{(8)}}{\sigma_a^{(5)}\cdot xN_0^{(8)} + \sigma_a^{(8)}\cdot N_0^{(8)}} \tag{1}$$

using the classical symbols (see Nomenclature) and taking into account the fast fission effect, too.

Setting $k_\infty = 1$ we find

$$x = \frac{\sigma_a^{(8)}}{\sigma_a^{(5)}}\cdot\frac{1-\eta^{(8)}}{\eta^{(5)}-1} \tag{2}$$

Introducing roughly estimated figures for this fast system, such as $\sigma_a^{(8)}$ = 0.3 b, $\sigma_a^{(5)}$ = 1.8 b, $\eta^{(8)}$ = 0.3 and $\eta^{(5)}$ = 2.2 we find $x \approx 9.7$ %. Hence initial criticality was indeed possible 4.5×10^9 years ago – even for a relatively small droplet with a diameter of less than one meter. It should be noted that the mean enrichment of present technical fast breeder reactors is only two thirds of that of the initial U-enrichment.

2.2 Criticality in equilibrium

The next question is how can Pu-239 production and Pu-239 decay stabilize the above x-ratio to guarantee criticality in the long term? For this we write down the burn-up equations for U-238, Pu-239 and U-235 neglecting the poisoning effect by fission products and the short-lived intermediate neptunium-239 step being

$$\frac{dN^{(8)}}{dt} = -(\sigma_a^{(8)}\cdot\Phi + \lambda^{(8)})\cdot N^{(8)} \quad \text{with } N^{(8)}(0) = N_0^{(8)} \tag{3}$$

$$\frac{dN^{(9)}}{dt} = \sigma_c^{(8)}\cdot\Phi\cdot N^{(8)} - (\sigma_a^{(9)}\cdot\Phi + \lambda^{(9)})\cdot N^{(9)} \quad \text{with } N^{(9)}(0) = 0 \tag{4}$$

$$\frac{dN^{(5)}}{dt} = \lambda^{(9)}\cdot N^{(9)} - (\sigma_a^{(5)}\cdot\Phi + \lambda^{(5)})\cdot N^{(5)} \quad \textit{with } N^{(5)}(0) = N_0^{(5)} \tag{5}$$

This system of linearly coupled inhomogeneous ordinary differental equations can be solved successively but we will consider only the case of equilibrium.

But first we have to introduce the following basic approximation which we may call here the 'low-flux approximation': Pu-239 can be only a precursor for U-235 if it is not destroyed in the neutron flux and is allowed to decay into U-235 by natural α-decay. Therefore, we set in Eq. (4) in the second term

$$\boxed{\sigma_a^{(9)} \cdot \Phi \ll \lambda^{(9)}} \tag{6}$$

where $\lambda^{(9)} = \ln(2)/T_{1/2}^{(9)}$ with $T_{1/2}^{(9)} = 2.411 \times 10^4$ y.

In this way we obtain from Eqs. (4) and (5) the following equilibrium values for Pu-239 and U-235:

$$\overline{N^{(9)}} = \frac{\sigma_c^{(8)} \cdot \Phi}{\lambda^{(9)}} \cdot \overline{N^{(8)}} \tag{7}$$

$$\overline{N^{(5)}} = \frac{\sigma_c^{(8)} \cdot \Phi}{[\sigma_a^{(5)} \cdot \Phi + \lambda^{(5)}]} \cdot \overline{N^{(8)}} \tag{8}$$

To maintain criticality in this 3-component system the condition

$$k_\infty = \frac{\eta^{(5)} \cdot \sigma_a^{(5)} \cdot \overline{N^{(5)}} + \eta^{(8)} \cdot \sigma_a^{(8)} \cdot \overline{N^{(8)}} + \eta^{(9)} \cdot \sigma_a^{(9)} \cdot \overline{N^{(9)}}}{\sigma_a^{(5)} \cdot \overline{N^{(5)}} + \sigma_a^{(8)} \cdot \overline{N^{(8)}} + \sigma_a^{(9)} \cdot \overline{N^{(9)}}} = 1 \tag{9}$$

must hold. Introducing Eqs. (7) and (8) into Eq. (9) and additionally estimated values for $\sigma_c^{(8)} = 0.2$ b, $\sigma_a^{(9)} = 2.5$ b, $\eta^{(9)} = 2.9$ and

$$\lambda^{(5)} = \frac{\ln(2)}{7.038 \times 10^8 \text{ y}} = 3.12 \times 10^{-17}/\text{s}$$
$$\lambda^{(9)} = \frac{\ln(2)}{2.411 \times 10^4 \text{ y}} = 9.12 \times 10^{-13}/\text{s} \tag{10}$$

we get a quadratic function in Φ possessing the solution

$$\underline{\Phi = \Phi_c = 1.207 \times 10^8 \text{ n}/(\text{cm}^2\text{s})} \tag{11}$$

meaning that $k_\infty = 1$ is stabilized by exactly this critical flux value Φ_c. If Φ was lower, less Pu-239 would be produced and therefore less U-235 would be formed; if Φ was higher the contrary holds and the power would increase. Introducing Eq. (11) into Eq. (6) we see subsequently that the assumption, made in Eq. (5), is justified.

Opposite to technical reactor physics we have to note here that the infinite multiplication constant is controlled by the absolute value of the neutron flux.

According to Eqs. (7) and (8) together with Eq. (11) the particle density ratios for Pu-239 and U-235 relative to $\overline{N^{(8)}}$ result to be

$$\frac{\overline{N^{(9)}}}{\overline{N^{(8)}}} = 2.63 \times 10^{-5} \tag{12}$$

$$\frac{\overline{N^{(5)}}}{\overline{N^{(8)}}} = 9.7 \times 10^{-2} \tag{13}$$

the latter being identical with the initial enrichment value of chapter 1. Eq. (12) indicates that the Pu-239 concentration in this system contributs practically nothing to both power production and to reactivity. Its only purpose is a latent supply basis for U-235 to maintain a constant concentration of it during billions of years. This curiosity results-from the very different half-lives of Pu-239 and U-235.

This analysis shows also that the conversion process in the U/Pu-cycle – opposite to the case of the civilian utilization of nuclear energy – can be instrumental in long-term considerations to stabilize a certain U-235/U-238 ratio which would otherwise continually decrease due to their different natural decay times.

2.3 The conversion ratio C

The conversion ratio C in the above process for the regeneration of U-235 has to be defined here in the equilibrium in the following way

$$C = \frac{\text{U–235 produced by Pu–239 decay}}{\text{U–235 destroyed by burn–up } \textit{and} \text{ natural decay}}$$

$$= \frac{\lambda^{(9)} \cdot \overline{N^{(9)}}}{[\sigma_a^{(5)} \cdot \Phi + \lambda^{(5)}] \cdot \overline{N^{(5)}}} \tag{14}$$

Introducing $\overline{N^{(5)}}$ and $\overline{N^{(9)}}$ from Eqs. (7) and (8) we find that the above conversion ratio C is exactly unity – what we have expected due to physical reasons.

2.4 Kinetics/dynamics questions

Taking into account that in Eq. (9) the third Pu-239 term in both the nominator and denominator can be neglected we obtain as a good approximation with the introduction of Eq. (8) for the prompt decay constant of the flux

$$\alpha(\Phi) = \frac{k_\infty - 1}{l}$$

$$= \frac{0.06(\Phi - \Phi_c)}{l(\Phi + \Phi_1)} \text{ in } [1/\text{s}] \tag{15}$$

where $l = 1/(v \cdot (\Sigma_a)_{tot})$ = prompt neutron lifetime, v = mean neutron velocity, Φ_c from Eq. (11) = 1.21×10^8 n/(cm^{2}s), and $\Phi_1 = 1.04 \times 10^7$ n/(cm^{2}s).

It can be seen from Eq. (15) that in the kinetic's equation $\Phi_t = \alpha\Phi$ for $\Phi = \Phi_c$ the prompt neutron decay constant α is zero and the system is stable. For $\Phi > \Phi_c$ and $\Phi < \Phi_c$ α is positive and negative, respectively, and the power increases and decreases accordingly.

Eq. (15) represents an adjustment of the reactivity to a critical neutron flux Φ_c rather than a feedback mechanism which would stabilize really the reactivity from both sides of Φ_c. Thinkable is, for instance, a reactivity feedback mechanism based on temperature and density (expansion/contraction) effects. In this case we have to consider a finite spherical uranium configuration with all its details like, mass, heat capacity, heat conductivity, buckling changes, the heat transfer from the droplet into Earth with all of the relevant time constants according to the chain of the events: The case $\Phi > \Phi_c$ would mean: higher power density, higher temperature, lower fuel density → reduction of power and flux. The case $\Phi < \Phi_c$ would mean: lower power density, lower temperature, higher fuel density → increase of k_∞ and power and flux. Eventually a process like this may stabilize the reactor at $\Phi = \Phi_c$.

If the georeactor is subcritical for a too long periode of time the Pu-239 decays and subsequently the U-235 beginns to decay and the reactor can never be critical again because the $N^{(5)}/N^{(8)}$ ratio will be too small. The off-time of the georeactor due to any reason is therefore limited and is determined by the relevant dynamical constants of the system. More cannot be said at this moment because a detailed thermodynamic study was neccessary if this way turns out to be a promising one.

The role of the fission-products as well as the decay products of the uranium decay chains down to lead has not yet

been discussed in connection with poisoning the reactivity. Herndon argues that there is a certain buoyancy for the fission products due to their 40 % lower weight compared with liquid uranium. In the opinion of the author, however, neither buoyancy nor convection can play a dominant role to separate the lower density decay waste from the core since near the center of Earth there are micro-gravity conditions. Thinkable are only processes where gravity is not the driving force. E.g. diffusion along the concentration gradient outwards the uranium droplet.

3 On the history of the isotopic U-235/U-238 Ratio, $N^{(5)}/N^{(8)}$

Setting $\Phi = 0$ in Egs. (3)–(5) we obtain the natural decay laws of U-238 and U-235, respectively, given by

$$N^{(8)}(t) = N_0^{(8)} \cdot e^{-\lambda^{(8)} \cdot t}$$
$$N^{(5)}(t) = N_0^{(5)} \cdot e^{-\lambda^{(5)} \cdot t} \quad (16)$$

or

$$\frac{N^{(5)}}{N^{(8)}}(t) = \frac{N_0^{(5)}}{N_0^{(8)}} \cdot \exp[(\lambda^{(8)} - \lambda^{(5)}) \cdot t] \quad (17)$$

where

$$\lambda^{(8)} = \frac{\ln(2)}{4.468 \times 10^9 \text{ y}}$$
$$\lambda^{(5)} = \frac{\ln(2)}{2.411 \times 10^4 \text{ y}} \quad \text{in } [y^{-1}] \quad (18)$$

Today $N^{(5)}/(N^{(5)} + N^{(8)}) = 0.72$ % or $N^{(5)}/N^{(8)} = 0.7252$ %.

Introducing this value into the left side of Eq. (17) and on the right side $t = 4.5 \times 10^9$ y (= life time of Earth up to now) we obtain an initial isotop ratio

$$\frac{N_0^{(5)}}{N_0^{(8)}} = 30.33\,\% \quad (19)$$

which coincides very well with Herndon's value (30.38 %) mentioned at the beginning. Criticality of a liquid uranium droplet immediately after the birth of Earth was definitely possible because the $N_o^{(5)}/N_o^{(8)}$ ratio at that time was about three times higher than necessary.

The next question – which was not answered by Herndon – is, however, how long could have the formation of the georeactor lasted after the birth of Earth in order not to miss the last moment for criticality?

This question can be answered if we introduce Eq. (19) into Eq. (17) and set $N^{(5)}/N^{(8)} = 9.7$ % (minimum U-235 enrichment for criticality) for the left side. The result is

$$t = 1.37 \times 10^9 \text{ years} \quad (20)$$

i. e. $(4.5–1.37) \times 10^9 = 3.13 \times 10^9$ ago the reactor had the last chance to get critical.

With other words, if a georeactor really exists, it must be older than 3.13×10^9 years. And as we know, the fuel itself stems from a preceding super-nova explosion.

4 Comparison with other exotic fission reactors

Contemplating about Herndon's georeactor one remembers inevitably the natural Oklo-Reactors [3] in Gabun/Africa which were in operation during several 100 000 years about almost 2 billions of years ago. According to Eq. (17) the U-235 enrichment was 1.8×10^9 years ago in the realm of

$$N^{(5)}/N^{(8)} = 3.2\,\% \quad (21)$$

being the same as in our earlier pressurized- and boiling water reactors. However, opposite to Herndon's *fast* georeactor the Oklo-reactors were *thermal* reactors with water as the moderator. Fortunately, those natural reactors worked near the surface of Earth and the proof of their existence was easier. Todays uranium probes at that place with $N^{(5)}/N^{(8)}$ ratios down to 0.44–0.3 % and the isotopic composition of the rare earth elements differed completely from that of naturally occuring elements and was strikingly representative of fission product yields.

Another Gedankenexperiment which has to he mentioned in this context is a critical actinide reactor in the deep space after a super nova explosion. Fissionable atoms can thereby be spread over very large distances in the 'ether' forming a very deluted 'cloud' of fissionable material. Due to the finite life-time of neutrons (about 12 min) the macroscopic absorption cross section of the configuration of the fissionable atoms has to be replaced in the critical equation by [4]

$$\Sigma_a \rightarrow \Sigma_a + \frac{\lambda^{(\beta)}}{v} \quad (22)$$

where $\lambda^{(\beta)}$ = beta decay constant of the neutron ($\approx 9.6 \times 10^{-4}$ s), v = velocity of neutrons (about 2×10^9 cm/s for a 2 MeV fission neutron) and $v/\lambda^{(\beta)} = 2 \times 10^{12}$ cm – about 50 times the distance between Moon and Earth. Thus, critical configurations in space with actinide dust would be very large. The problem is still more complicated because fast neutrons will scatter inelastically per collision event reducing their velocity and therefore increasing the effective macroscopic absorption cross section in Eq. (22). There is, however, no evidence that such fast fission reactors existed ever in space.

The last example in this spooky view all around the nuclear kaleidoscope is (perhaps a man-made) thermal reactor at the surface of Earth. Especially in primitive military waste disposal sites aqueous Pu-solutions can ooze away from leaky containers into the soil. It has been estimated [4] that k_∞ to be about 1.3 at a concentration of 7.2 g Pu/liter (critical mass about 4.2 kg Pu). The evaporation of water would increase k_∞ and go through a maximum value ≥ 1.4 during the process. Therefore, criticality would be possible at concentrations below 7.2 g/liter – perhaps as low as 1.7 g/liter in the soil with the proper dryness (H/Pu ~ 200) [4]. Fortunately, no such phenomenon has been observed so far.

5 Conclusions

Some nuclear aspects of Herndon's thesis 'Nuclear Georeactor' could be clarified. The findings are in short:

1. In the first billion of years of the existence of Earth criticality for a droplet of liquid uranium in its center was indeed possible.
2. The conversion process through neutron capture in U-238, via the Pu-239 survival route under neutron irradiation and its decay in U-235, works satisfactorily to keep the U-235/U-238 concentration near 10 % and to stabilize criticality up to now in the unpoisoned reactor.
3. The mechanism of the removal of the fission products and other decay producs from the U-238 and U-235 decay chains from the reactor remains unclear. Micro-gravity conditions prevent buoyancy- and convection transport effects; the efficacy of diffusion is unclear, too.

4. Since the only evidence for the existence of the georeactor up to now is the basalt-volcanic $^3He/^4He$ ratio the author proposes to think about another obvious 'message from the deepness of Earth': A neutrino experiment – preferably directionably. Here the sensitivity of the already existing experimental facilities has to be checked first.
5. Unclear is also the role 'on' and 'off' times of the georeactor in connection with the change of sign of the Earth's magnetic field in relative short time periods every 200 000 years.
   From the nuclear point of view it can only be said that 'off' times cannot be too long compared with the life-time of Pu-239 because then the conversion process would be interrupted and the reactor would be subcritical forever. The reserve in reactivity in a cooled and contracted reactor core with the corresponding time scale has to be determined to clarify this question definitely.
6. In a georeactor only the U-238/Pu-239/U-235 cycle could be identified as the one and only workhorse. A similiar working principle of the Th-cycle is not possible because, first, the half-life of U-233 is only about 160 000 years (too short to survive the time between a super nova explosion and the formation of a planet) and, second, the daughter product in the U-233 α-decay (Th-229) is not a long lived fissionable atom.
7. According to Herndon's figures [2] the volume of the georeactor is 5.68×10^{17} cm^3 corresponding to a sphere with 5.1 km radius. If it was producing 5 TW (a bit more than 10 % of the total geothermal heat production) the specific heat production rate was 8.8 W/m^3 or 0.239 W/t due to the high uranium density.
   Using the critical neutron flux from Eq. (11) and the critical $N^{(5)}/N^{(8)}$ equilibrium ratio from Eq. (13) the author obtains a specific heat production rate of nearly 50 W/m^3 or 1.35 W/t – the overwhelming part produced by U-235 fission. Therefore, to produce 5 TW the uranium droplet had a radius of only 2.9 km and a mass of 3.7×10^{12} t.
   This gradual descrepancy with Herndon's figures could not be clarified.
8. The author can nothing contribute to the early chemical and geological aspects of an early formation process of an uranium droplet in the center of Earth. There is still a stony way to state definitely if such a georeactor really exists.
9. Meanwhile the author received from D. F. Hollenbach/Oak Ridge Nat. Lab. [5] a set of one group microscopic cross sections for U-235, U-238 and Pu-239 from his calculations. According to these (better substantiated) values the x-value of Eq. (2) is somewhat lower: about 5 %. And the critical flux in Eq. (11) results to be 2×10^7 n/(cm^{2}s). But nothing else of the whole philosophy changes.

Nomenclature

σ = microscopic cross section, in barn e.g., $\sigma_a^{(5)}$ = microscopic absorbtion cross section of U-235
Σ = macroscopic cross section, in cm^{-1} with the same index-notation
Φ = neutron flux, in n/(cm^{2}s)
η = neutrons produced per absorbed neutron, e.g. $\eta^{(5)}$ = neutrons produced per absorbed neutron in U-235
λ = natural decay constant = ln(2)/$T_{1/2}$ with $T_{1/2}$ being the half-life; e.g. $\lambda^{(5)}$ = decay constant of U-235
N = atomic particle density, in cm^{-3} e.g. $N^{(8)}$ = atomic particle density of U-238. $\overline{N}$ = corresponding equilibrium value, N_0 = corresponding initial value.

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Antes de sua morte prematura meu amigo antigo, Dr. R. Weber, journalista científico, há informado o público sobre o fenómeno de Oklo com um entusiasmo grande. Por isso hei dedicado 1he estas reflexões sobre um fenómeno semelhante.

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