2. Oklo fission reactor (7 points) — *Topi Löytäinen, Jaan Kalda.* Based on the ratio of the uranium isotopes ^{235}U and ^{238}U, as well as the abundances of the isotopes produced by nuclear reactors, researchers have established that self-sustaining natural nuclear reactors operated in Oklo ca $T_0 = 1.8 \times 10^9$ years ago in Gabon, central Africa. For such reactors to exist, two conditions must be met: (a) presence of deposits with high enough concentration of uranium; (b) sufficiently high abundance of ^{235}U in natural uranium. Rich uranium ores were created by floods: scattered uranium was dissolved in oxygen-rich water and transported by it to underground pools. Significant concentration of oxygen appeared in the atmosphere only around 2.5 billion years ago, so the first condition was not met earlier than that. You will learn below that the abundance of ^{235}U decreases relatively fast in time, so the second condition ceased to be satisfied soon after the operation of Oklo's reactor.

What made the operation of Oklo's reactor possible was a stable influx of ground water that kept the uranium deposits sufficiently wet. Water is the so-called moderator for the fission reactor: it slows down neutrons emerging from fission reactions, dramatically enhancing the chances of a neutron triggering the fission of a next ^{235}U nucleus.

In what follows, in addition to T_0, you can use the following numerical values.
Energy released by the fission of a single ^{235}U nucleus: $E_0 = 200\,\mathrm{MeV}$.
Half-life of ^{235}U: $\tau_5 \approx 7 \times 10^8$ years.
Half-life of ^{238}U: $\tau_8 \approx 4.5 \times 10^9$ years.
Latent heat of evaporation of water: $L = 2260\,\mathrm{kJ\,kg^{-1}}$.
Specific heat of water $c = 4200\,\mathrm{J\,kg^{-1}\,K^{-1}}$.
Abundance of ^{235}U in natural uranium today: $R = 0.72\%$. We define abundance as the number of atoms of the isotope, normalized to the number of atoms of the given element.
Average abundance of ^{235}U in the uranium from Oklo's uranium ore today: $R_O = 0.62\%$.
The total amount of uranium in Oklo's mine today: $M = 5 \times 10^8\,\mathrm{kg}$.
The duration of the time period over which Oklo's reactor operated: $T \approx 1 \times 10^5$ year.
Elementary charge: $e = 1.6 \times 10^{-19}\,\mathrm{C}$.
Atomic mass unit: $u = 1.66 \times 10^{-27}\,\mathrm{kg}$.
Avogadro's number: $N_A = 6.02 \times 10^{23}\,\mathrm{mol^{-1}}$.

Note that: (a) the abundance of other isotopes of uranium besides ^{235}U and ^{238}U is negligibly small; (b) ^{235}U is not among the decay products of ^{238}U; and (c) fission channels other than the fission of ^{235}U (e.g., synthesis and fission of plutonium) can be neglected.

i) *(1.5 points)* What was the abundance of ^{235}U in natural uranium when the Oklo's reactor operated?

ii) *(2 points)* What was the average power of the Oklo's reactor?

iii) *(1.5 points)* Qualitatively explain why was Oklo's reactor operating in a stable regime and did not blow up. Water inflow rate varied over time; what happened to the reactor when the water inflow rate increased two times?

iv) *(2 points)* Estimate the total mass of water that flowed into the Oklo's reactor during its operation period.