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THE OKLO "NATURAL NUCLEAR REACTORS" - EVIDENCE OF VARIABLE CONSTANTS?

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ABSTRACT

There is apparently virtually universal agreement that certain deposits found at the Oklo uranium mine in Gabon, Africa are the remains of "natural nuclear reactors." This paper examines the make-up and configuration of some of these reactors and shows that these deposits were <u>not</u> capable of a sustained nuclear fission chain reaction if the nuclear characteristics of the isotopes involved were the same as they are today. If these deposits really are the remains of natural nuclear reactors, then they appear to provide support for the hypothesis that nuclear constants have changed over time.

INTRODUCTION

In June of 1972, a worker at a French uranium enrichment plant discovered that some of the uranium that was being processed had an unusual isotopic make-up -- it was depleted in U-235. The isotopic anomaly was traced back to the Oklo uranium mine in Gabon, Africa. In August of 1972, investigators formulated a hypothesis that a natural nuclear reactor had existed at the site which caused the uranium ore to be depleted in U-235. A natural nuclear reactor isn't considered possible today because the ratio of U-235 to U-238 is too small (the uranium used in nuclear power plants is artificially enriched in U-235). However, it was hypothesized that about 2.0 billion years ago (an age assigned to the reactors based on certain radiometric dates) the ratio of U-235 to U-238 would have allowed certain configurations of natural uranium to become critical (the higher U-235 content in the past is because U-235 decays faster than U-238). Certain isotopes that are the expected end products of a nuclear fission reaction were also discovered; this observation appeared to solidify the notion that the phenomenon in question was the remains of a naturally occurring fission reactor. In September of 1972, researchers reported to the French Academy of Science that they had discovered a natural nuclear reactor [1]. As mining of the deposit progressed, 14 other areas of the deposit were determined to have also hosted a self-sustained fission chain reaction [2, pp.4833-4834]. Since their initial discovery, however, it has been found that some of the reactors are connected, and therefore should be considered just one reactor.

Some of the later discovered "reactors" are very thin slab-like deposits. They are, in fact, too thin to support a self-sustained nuclear reaction -- even 2.0 billion years ago. Therefore, either the isotopes involved in these reactions had different nuclear characteristics when the reactor was operating than they have today, or these deposits are not the remains of in situ natural nuclear reactors.

BASICS OF U-235 FUELED FISSION REACTORS

U-235 chain-reaction

Atoms of U-235 are naturally unstable and their nuclei undergo spontaneous fission at a very slow rate; however, if a U-235 nucleus absorbs a free neutron from its environment it usually fissions (breaks apart) virtually instantly. When it fissions, three things of interest occur: 1) Two smaller nuclei are produced from the splitting of the larger U-235 atom; 2) The masses of the parts produced by the splitting of U-235 do not add up to the original mass of the U-235 nuclei. The missing mass is converted to energy according to the equation $E=mc^2$. This is the source of the energy produced by a nuclear power plant. 3) Usually two or three excess neutrons are produced from the fission of each U-235 nucleus (2.4 neutrons per fission, on average). These neutrons are then available to trigger the splitting of other U-235 nuclei (see Figure 1). If every neutron emitted by the fission of a U-235 nucleus induced a fission in another U-235 nucleus and each of the neutrons produced in those fissions were absorbed by U-235 producing other fissions, and so on, then it is easy to see that the energy produced in the ongoing chain reaction would rise in energy output exponentially in very short order (this exponential build up is exactly what happens in a nuclear bomb). The essence of nuclear engineering for power production is the control of the production of neutrons.

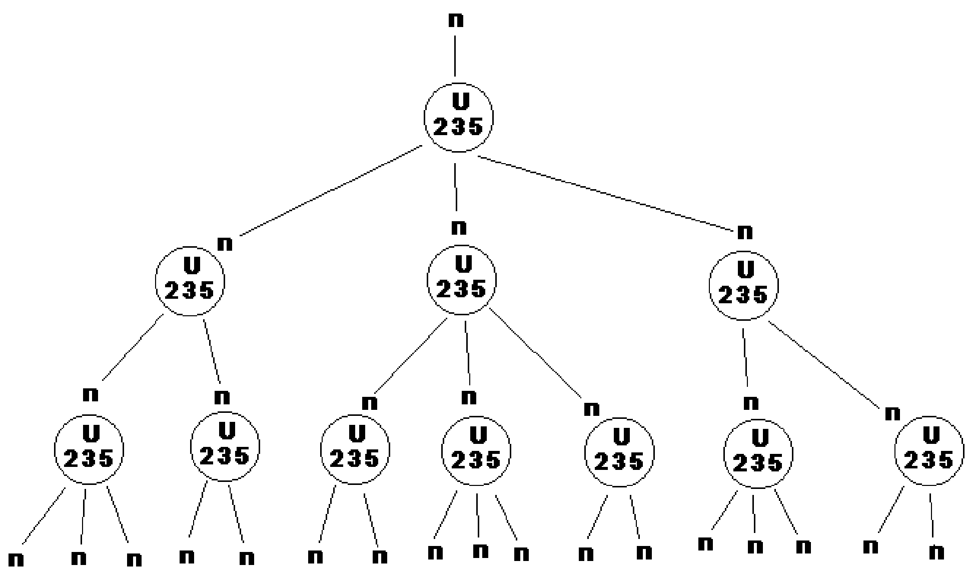

Figure 1. Nuclear Fission Chain Reaction

Two or three neutrons are released in every fission of U-235. These neutrons are then available to cause other fissions (and consequently release more neutrons). In each successive generation there are more neutrons and more fissions resulting in an exponential build-up of energy production.

In nuclear reactors the control of neutrons (which concurrently controls the power production) is accomplished in three basic ways:

1) Control rods

All nuclei are capable of absorbing neutrons but some absorb neutrons more readily than others. Control rods made of highly neutron absorbing material are the main way that the power production of reactors is controlled. When an increase in power is desired, the control rods are partially removed from the reactor core (the part of the reactor where the fuel is concentrated) allowing more neutrons to be available to cause fissions in the U-235 fuel. To decrease the power, control rods are inserted into the core to "soak up" neutrons and reduce the number of fissions that are taking place.

2) Moderators

The neutrons produced by the fission of a U-235 atom emerge from the reaction with a high velocity (they are "high energy" in the lingo of physicists). A U-235 nucleus absorbs a neutron much easier when the neutron has been slowed down to a much lower energy. The energies of neutrons are moderated (lowered) by colliding with other particles, preferably particles of a size similar to the neutrons. The hydrogen nuclei of normal water make good moderators and consequently many reactors use water to both cool the core, and moderate the neutrons. In water-moderated reactors, neutron-absorbing materials can be dissolved in the water as a further way of controlling the free neutron population in the reactor.

3) Reflectors

All the neutrons produced in the nuclear chain reaction are either absorbed in fuel or one of the other components of the core, or they migrate or "leak" out of the core and are lost (they become useless as far as the chain reaction is concerned). Reflectors are materials that are put around the outside of the core to "reflect" the neutrons back into the reactor so that they are then available again to take part in the chain reaction.

CRITICAL REACTOR CONFIGURATIONS

Spherical Homogeneous Reactor

In this paper we are concerned with the smallest configurations of fuel, moderator and reflector that can produce fission chain reactions. Consider a simple spherical core that consists of a homogeneous mixture of pure U-235 and a hypothetical perfect moderator (which only slows neutrons down, but doesn't absorb them) as depicted in Figure 2. If the radius (r) of the sphere is too small, a self-sustained fission chain reaction will not be possible. To see why, first notice that if a fission occurs near region *x* in the core (keep in mind that there is no preferred direction for the produced neutrons to go), neutrons produced there are close to the edge of the core and have a higher likelihood of leaking out of the reactor before they are absorbed by U-235, than do neutrons produced by a fission occurring near region *y*. Intuitively, then, we can see that if the core is a homogenous mixture, the highest concentration of neutrons will be found in the center.

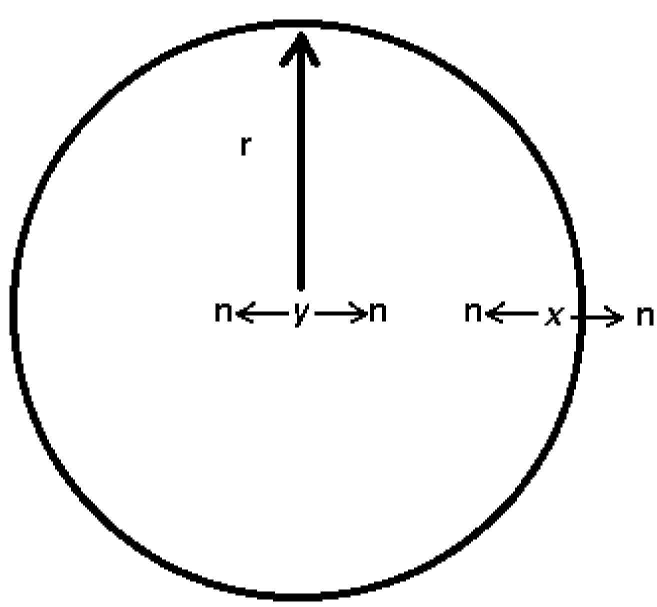

Figure 2. Neutrons Escaping From Spherical Reactor

If a fission occurs near region *x* in the core there is a higher likelihood of neutrons produced leaking out of the reactor than neutrons produced by a fission occurring in region *y*.

Criticality

Consider a particular time interval t_1 (let's say t_1 is one minute, for instance). At the beginning of t_1 there are certain numbers of free neutrons which populate the core of the reactor. Some of these neutrons will leak out of the core and will not cause any fissions during t_1, but some will be absorbed by fuel nuclei (U-235) and cause the U-235 atoms to fission. These fission events will cause new free neutrons to be "born" within the core (recall that 2.4 free neutrons are born, on average, during each fission). These newly born neutrons are then available to cause further fissions, especially after they have been moderated. Of course some of these neutrons born during t_1 will leak out of the core. So then, the number of free neutrons populating the core at the end of t_1 (which is the beginning of t_2) will be a function of the number of free neutrons present at the beginning of t_1, the number of free neutrons born from fissions during t_1, and number of free neutrons that have leaked out of the core during t_1. If the leakage rate of neutrons during t_1 is too high, then the number of neutrons populating the core at the beginning of t_2 will be less than the number of free neutrons that populated the core at the beginning of t_1. By necessity then, the number of fissions that will occur during t_2 will be less than the number of fissions that occurred during t_1. This means that fewer free neutrons will be produced during t_2 than were produced during t_1 so there will be fewer free neutrons available at the end of t_2 than there were at the end of t_1. Obviously then, during t_3 there will be even fewer fissions than there were during t_2, and so on. We can see that in the above scenario the number of fissions is being reduced during each successive time interval, hence the reaction is not self-sustaining. Too many neutrons are leaking out; there are not enough remaining in the reactor to sustain the reaction. When the number of neutrons in the core stays steady over time, the reactor is said to be critical. If the number of neutrons is decreasing in the core over time, the reactor is said to be sub critical. And if the number of neutrons is increasing in the core over time, the reactor is said to be supercritical. The minimum mass of U-235 needed to make a reactor of a particular make-up and configuration critical is called the "critical mass."

Neutron absorbers

An important factor has been left out of the example above; in the real world there is absorption of neutrons by all non-fuel nuclei. Some nuclei absorb neutrons so readily that they are called "poisons" because they tend to poison the chain-reaction. These absorbers mean that much more fuel has to be present in the core than would be needed in the hypothetical ideal reactor above. If the ratio of non-fuel neutron absorbers to fuel is too high, a reactor will never go critical no matter how big it is because the non-fuel components absorb too many neutrons before they can be used to continue the chain-reaction.

U-235 Enrichment

The last point above is very relevant to the Oklo phenomenon. In naturally occurring uranium only 0.72 % of the uranium atoms are U-235 atoms; most of the rest is U-238 (99.27 %), which can't be split with slow neutrons. This means that the concentration of U-235 is too low to allow any combination of natural uranium and natural water to become critical. U-238 naturally decays slower than does U-235 (the half-life of U-235 is 7.04×10^8 years, compared to 4.47×10^9 years for U-238). This means that if one could go back in time, one would see the percentage of U-235 in natural uranium increasing. If we assume the current decay rates cannot change, then 2.0 billion years ago, U-235 would make up 3.7% of the atoms of uranium [2, p.4836]. This is about the enrichment of U-235 used in today's commercial light-water reactors.

Slab shaped homogenous reactors

The uranium deposits at Oklo occur in strata of sandstone. As such, the "reactors" resemble slabs more than they do spheres. The thickness of a slab-shaped reactor can be smaller than the diameter of a spherical reactor; Figure 3 shows why. Figure 3 is a cross-section of a spherical and a slab-shaped reactor. Notice that if a fission occurred near x in the spherical reactor, most neutrons, except those directed toward the center of the sphere, are going to escape from the core. However if a fission occurs near the edge of a slab-shaped reactor, about half of the neutrons are going to be heading in a direction where they may encounter more fuel. (The thickness required for criticality in a slab shaped reactor is a little less than half the diameter required to achieve criticality in a spherical reactor when both have an enrichment and water/uranium ratio similar to what was thought to exist at Oklo [3, p.33].)

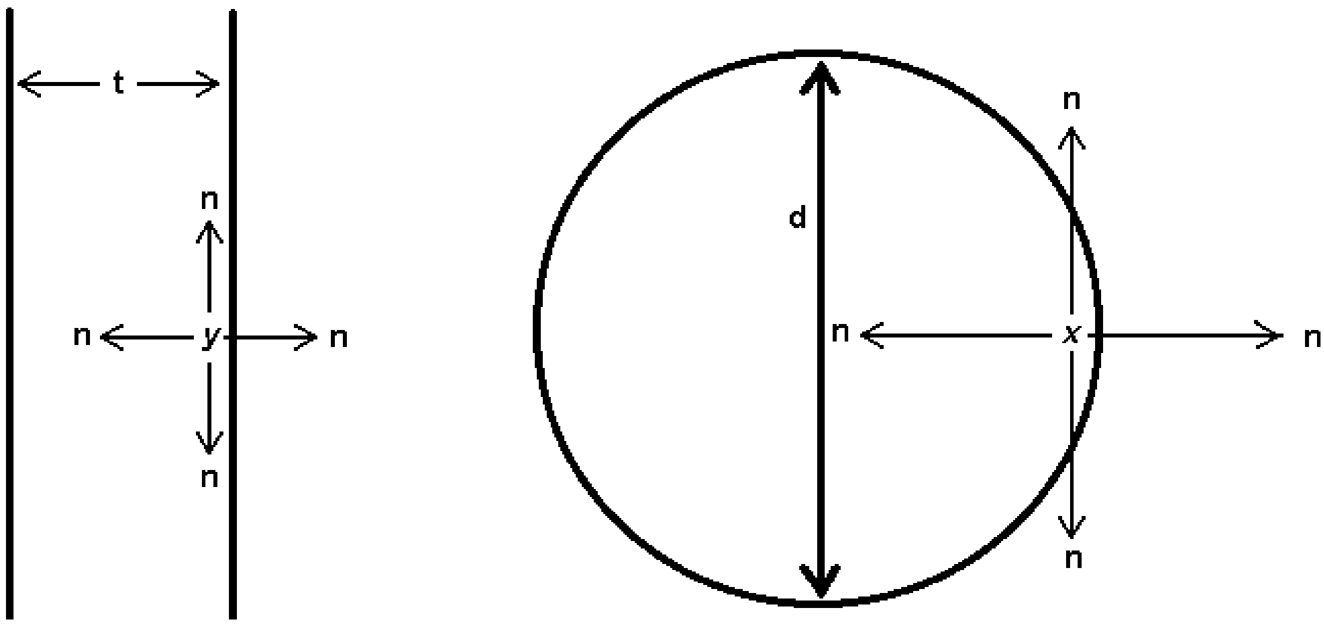

Figure 3. Neutron Savings in a Slab-shaped Vs. Spherical Reactor

The configuration of a slab-shaped reactor allows for less loss of neutrons than a spherically shaped reactor. This allows t to be smaller than d.
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REACTOR CONFIGURATIONS AT OKLO

Critical Conditions

We now turn our attention to the circumstances necessary for criticality to be achieved at Oklo, and whether such circumstances existed at Oklo. Given the geological and geochemical conditions present in the sandstone ore at Oklo, the following conditions must be met for the possibility of a natural nuclear reactor.

1) *The U-235 enrichment must be sufficiently high.* Theoretically, 2.0 billion years ago the U-235 content of the uranium would have been 3.7%, if we extrapolate back in time and assume that the current decay rates of U-235 and U-238 have stayed constant over that time period. It is certainly possible that uranium enriched to 3.7% U-235 could become critical under some plausible natural circumstances.

2) *The uranium in the ore must be of a sufficient concentration.* The uranium content of the Oklo ore averages around 0.5 % by weight. It has been calculated that the uranium content must average at least 10% in the core of a plausible natural reactor [2, p. 4833]. There are portions of the ore deposit at Oklo which satisfy this condition.

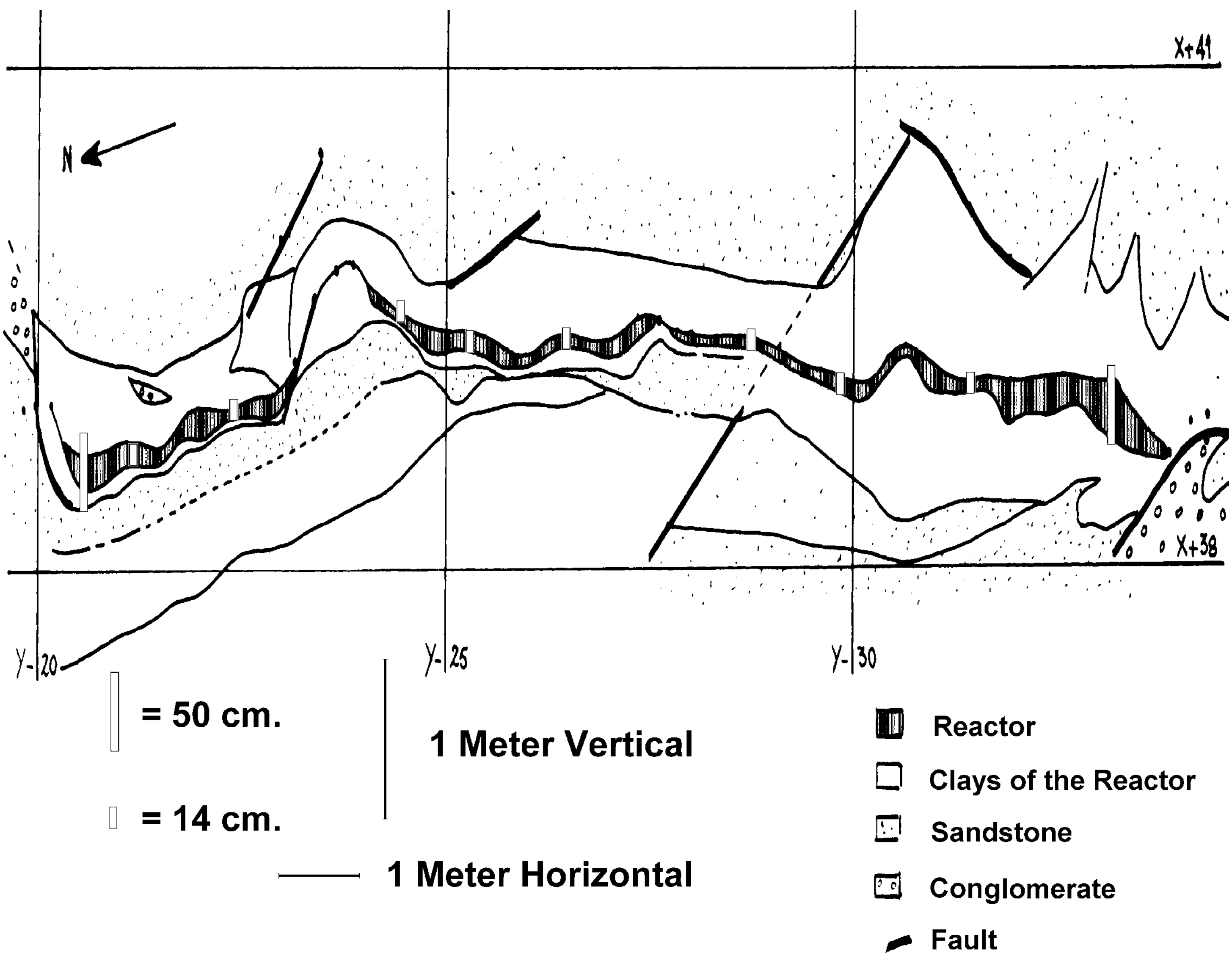
3) *There must be sufficient moderator available to slow the neutrons down so that they can be absorbed by the U-235.* It has been postulated that if the sandstone were fractured enough to achieve an open porosity of between 10 and 15% [2, p. 4833], then enough groundwater would have been present to serve as an effective moderator.

4) *The size of the core area (the area where all of the above conditions are met) must be big enough so that enough neutrons are kept in the core area to feed the chain reaction.* As noted earlier, the "cores" at Oklo are slab-shaped deposits. These slabs must be a certain minimum thickness so that too many neutrons don't leak out of the core and shut the chain reaction down.

Condition 4 above is the main focus of this paper. Cowan [4, p.39] says:

A sphere is the most efficient shape and requires the smallest quantity of uranium, but it is sufficient that the ore be deposited in seams at least half a meter thick. In a thinner deposit too many neutrons would escape. The reactor zones in the Oklo mine meet the requirements of uranium concentration and seam thickness.

Cowan wrote this paper in 1976, and at that time only reactors 1 through 6 were known about. Reactors 3 through 6 were still underground and only known through exploratory drillings. Portions of the exposed and well-studied reactors 1 and 2 did meet this 50 cm. minimum thickness requirement. However "reactors" that were studied and discovered later were <u>not</u> thick enough to meet this minimum thickness requirement! Figure 4 is a cross-section diagram of Reactor 3-4 [5, p.130]. (Initially reactors 3 & 4 were given separate designations because they were only known through drillings and were thought to be separate reactors. Later, reactors 3 & 4 were found to be connected and so they are now considered one reactor designated "reactor 3-4".) The darker shaded layer represents the reactor zone. Notice that nowhere in the diagram does the reactor zone meet this 50 cm. minimum thickness.



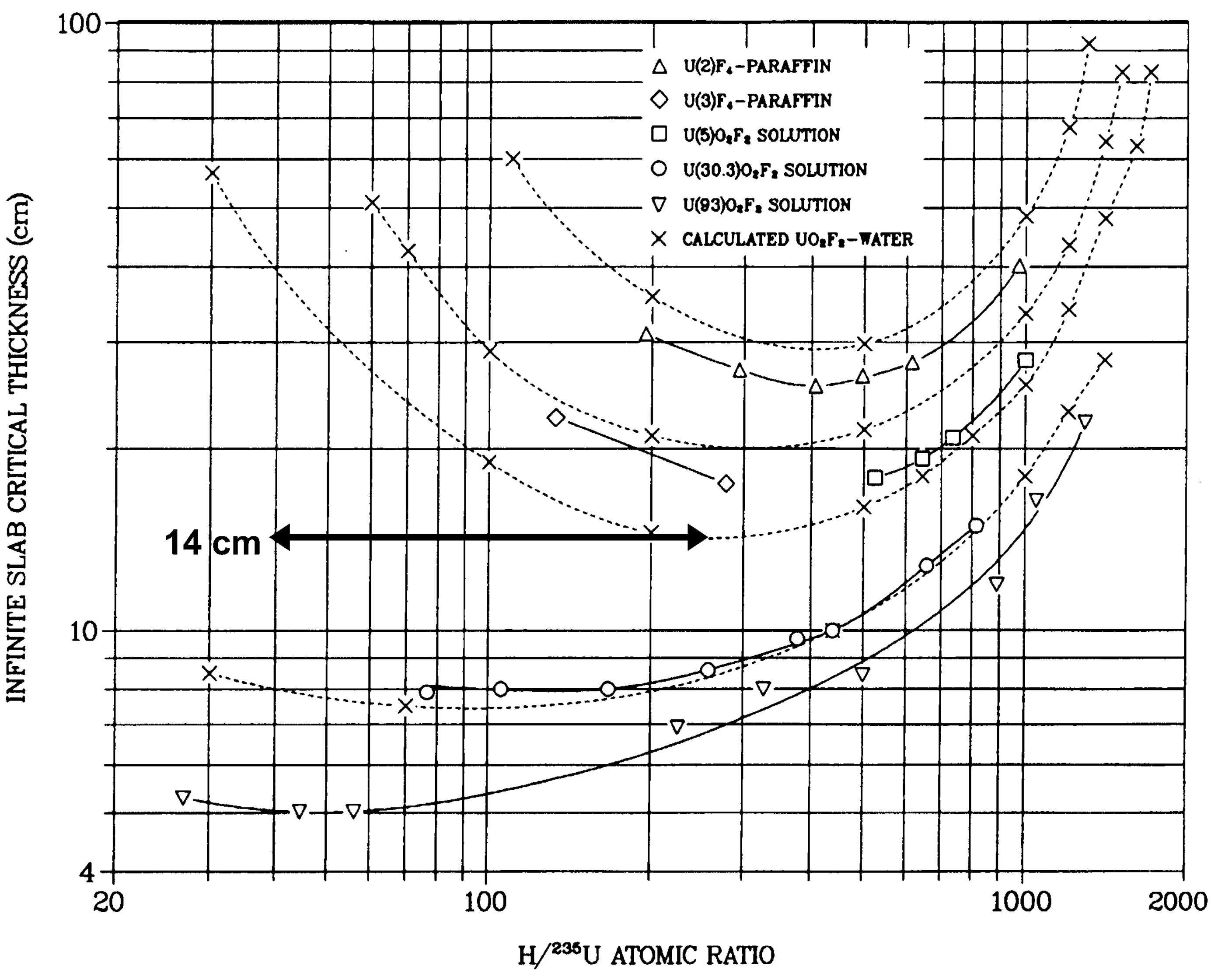
<u>Figure 4. Cross-section of Reactor 3-4</u>

Given the conditions present at Oklo, a slab-shaped reactor would need to be at least 50 cm thick. In this cross-section of reactor 3-4 we can see that nowhere is this reactor 50 cm. thick. Even if the reactor consisted of ideal materials (which it does not) it would have to be a minimum of 14 cm. thick. As can be seen, most of the "reactor" is less than even 14 cm. (This figure is a modified version of Figure 40 in [5, p.130]. The vertical has been stretched to 200% of the original to make the comparison with 14 cm. easier.)

One could speculate that perhaps the geochemical make up of the deposit has changed somewhat since the reactors were operating. Perhaps in the past there were fewer neutron poisons, or other neutron absorbers, present in the deposit. Would that allow a deposit which is thinner than 50 cm. to achieve criticality? As we will see, even under circumstances which are so ideal that they are not realistic for a natural setting, most of the "reactors" at Oklo are too thin to achieve criticality.

Minimal Configurations Necessary for Criticality

Empirical studies have been conducted to find out the minimum reactor sizes needed to carry on a sustained nuclear fission chain reaction with fuel of a given enrichment in U-235 [3]. Figure 5 [3, p.40] graphically shows the minimum thickness needed to achieve criticality in a homogeneous slab-type reactor of varying U-235 enrichment and varying H (hydrogen moderator) to U-235 ratios. The enrichment of U-235 2.0 billion years ago would be 3.7% if decay rates are assumed to be constant over that time. Figure 5 has a curve for uranium at 3% U-235 enrichment and 5% enrichment. As can be seen in the figure, even if we use the higher 5% enrichment figure, the minimum thickness necessary to achieve criticality is 14 cm.



Estimated critical thicknesses of water-reflected slabs, infinite in other dimensions, of hydrogen-moderated U(93), U(30.3), U(5.00), U(3.00) and U(2.00).

Figure 5. Critical Thickness of Slab-shaped Reactors

Figure 5 shows the minimum thickness (at various moderator to fuel ratios (H/U-235) and various U-235 enrichments) that a slab-shaped reactor has to have before it can reach criticality. The number in parentheses represents the U-235 enrichment of the uranium. The dashed lines are based on modeling and the solid lines are based on empirical studies. The minimum critical thickness of a slab-shaped reactor with 5% U-235 enrichment (an enrichment which is greater than that postulated for the Oklo reactors) is 14 cm. under ideal circumstances.

Keep in mind that this graph is showing an *ideal* situation; the core is a mixture of pure UO_2F_2 (fluorine is a very poor absorber of neutrons) and water, with a pure water reflector. A reactor at Oklo would have had to deal with many impurities in the core (about 80% silica sand) and many in the “reflector” (sandstones and clays), all of which absorb neutrons and make the required reactor size larger. The following are some of the factors present at Oklo that would make conditions for fission chain reactions much less than ideal:

1) As seen in Figure 5, the ideal H/U-235 ratio is around 250, but since 80% of the core must have been a silica composition (due to the sandstone), a U content of 10% would mean that the H/U-235 ratio was more like 100.

2) The silica of the sandstone is a much larger absorber of neutrons than is the fluorine which was part of the make-up of the reactor on which the curve in Figure 5 is based.

3) The curve for U enriched to 5% U-235 was used to derive the 14 cm. minimum slab thickness. The enrichment of the Oklo reactors, when they were operating, was supposed to be only 3.7%.

4) At Oklo many impurities (other elements) are present which, although present in small amounts, are potent neutron absorbers. [2, pp.4839-4850]

So, 14 cm. represents a very generous minimum core thickness needed for criticality at Oklo. Figure 4 also shows a comparison of this generous 14 cm. minimum thickness with actual thicknesses at reactor 3-4. Notice that most of the “reactor” is thinner than even 14 cm.

Reactors discovered about 6 years after it was declared that the Oklo Phenomena were the remains of naturally occurring nuclear fission reactors are even more problematic. Gauthier et. al. say [2, p.4838]:

> Reactors 7 to 9 are located 200m deeper than the reactors 1 to 6. In comparison with the previous reactors they appear as small uranium-rich pockets where the core of the reactor is always very thin (a few centimeters), and the hydrothermal clays are never well developed (Fig. 6).

The notion that a reactor at Oklo, which is only a few centimeters thick, could achieve criticality, stretches credulity beyond the breaking point.

CONCLUSION

Some of the deposits at Oklo were not thick enough to sustain a nuclear chain reaction. Consequently, either the nuclear characteristics of some or all of the nuclei involved were different when the reactors were operating than they are at present, or these "reactors" weren't really reactors. There are many lines of evidence used to support the notion that these deposits were once natural nuclear reactors, one being the presence of certain isotopes which are the expected products of nuclear fissions. An evaluation of all this evidence is beyond the scope of this paper, but an initial cursory look at the data reveals that it may not be as conclusive as it is often portrayed. A thorough evaluation of the data is needed before we can be confident that these deposits really are in situ extinct reactors and not some other phenomenon.

If the hypothesis that these deposits are extinct natural nuclear reactors holds up under scrutiny, then Oklo may have several interesting implications for creationist models of earth history. Some creationists (and presumably non-creationists) have hypothesized that nuclear “constants” may not be constant over time, but may vary (see, for example references [6] and [7]). If, for example, the rate of radioactive decay (a nuclear constant) was faster in the past, it may help explain the isotopic content of some rocks which have been interpreted as evidence of ancient age. Also, the question arises (even under an old-earth model) why didn’t other uranium deposits support fission chain-reactions? It certainly looks like other uranium deposits around the world had conditions that were at least as favorable as Oklo for hosting a nuclear reactor. Under a catastrophic sedimentary deposition model one possible explanation might be that the nuclear characteristics of the constituents involved changed on such a short time-scale that only the deposits at Oklo (and perhaps a few other as-yet-undiscovered reactors) were existing at the time when the nuclear characteristics were favorable for a fission chain reaction. Thus, models of time constraints on depositional events and rates of variation of nuclear constants might be built. Oklo may be a rich resource for deciphering earth history -- it may behoove us to give it much more attention.

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