Stabilizing the chain reaction

Soon after the discovery of an abundant neutron emission from uranium ~~and even before it was known whether a way would be found to set up a chain reaction~~ the question of stabilizing such a reaction was a subject of dicussion,(14,15) but the situation as we see it appears to be rather different ~~in practice:~~

If a chain reaction could be maintained in a homogeneous mixture of water and uranium or carbon and uranium it would have a certain natural stability in the sense that with rising temperature there would be a decrease in the neutron production. The reason for this is the fact that the absorption of both uranium and hydrogen obey the 1/v law in the thermal region and thus at higher temperatures the range of thermal neutrons in the mixture is larger. Correspondingly, at higher temperatures a larger fraction of the thermal neutron will escape across the boundary of the mixture without having reacted with the uranium in the mixture. This natural stability could even be enhanced by having bodies of strong thermal neutron absorbers inserted in the mixture. Fairly thin sheets of such absorbers as boron, for instance, are practically "black" for thermal neutrons and any strong thermal neutron absorber would stabilize equally well.

A system, on the other hand, in which uranium bodies which are almost "black" for thermal neutrons are embedded in carbon, like the system which we have considered in great detail in the present paper, has no such stability. This is due to the fact that with rising temperature the capture cross-section of the carbon decreases whereas the absorption by the uranium spheres remains almost unchanged. Accordingly, at higher temperatures, a larger fraction of the thermal neutrons is absorbed by uranium and a smaller fraction is absorbed by carbon and this leads to an increase in q. and thermal instability.

It is, however, quite easy artificially to stabilize the chain reaction by slowly shifting the position of absorbing bodies within the system in such a way as to reduce the average value of q whenever the intensity of the neutron radiation emanating from the chain reaction increases. One might perhaps think that the time within which such controlling action would have to take place is very short. We shall therefore now show that this is not so.

Of the neutrons which are emitted in the chain reaction by uranium only a fraction ψ is absorbed within the system and $1-\psi$ escapes across the boundary of the system without reacting with uranium. A stationary state can be maintained as long as

$$\mu q \psi < 1$$

We write

$$q\psi = \delta(T,\ x(t))$$

In order to indicate that this product is a function of the temperature T and also depends on a parameter such as the position of some absorbing or scattering body near or within the system which can be shifted by some controlling mechanism and thus be made a function of time t.

In order to have a large neutron production we must maintain a chain reaction near the point

$$\mu \delta_0 = 1$$

If this product becomes larger than one, as it may well happen then there is an exponential rise in the neutron production and accordingly also in the temperature. In case of a sudden small deviation from one

$$\delta = \delta_0 \times (1+\xi)$$

$e^{\frac{t}{t_2}}$

the time t_2 in which the number of neutrons doubles is given by

$$t_2 = 1/\xi\ t_1$$

where t_1 is the time which a fast neutron emitted by a uranium atom in the system would require to produce two fast neutrons if it is slowed down ~~(as a thermal neutron)~~ and absorbed within the system.

For instance if we had a sudden change in δ of ~~1 0/00~~ 0.1% as we well may have and if we have $t_1 = 8 \cdot 10^{-3}$ sec, then it would take 4 seconds for the neutron production to double its value and accordingly there ~~would~~ may be only an insignificant rise in the temperature if the control responded within 4 seconds.

It is easy to see that for a lattice of uranium spheres in carbon τ_1, the mean life-time of a thermal neutron within the system is given by

$$\tau_1 = \alpha \frac{\sigma_{sc}(C)}{\sigma_c(C)} \frac{\lambda(C)}{v}$$

1000 2.5 / 1000 $\sqrt{2}$ 2×10^2

For $\sigma_c(C) = 0.005$ at room temperature, for instance, we have ~~at 900 C.~~

$\psi_m = 0.66$ and $\alpha_m = \frac{1-\psi_m}{2} = 0.17$ ~~giving at 900 C.~~

$$\tau_1 \simeq 4 \times 10^{-3} \text{ sec}$$

τ in carbon 10^{-2} sec

In calculating t_2 we did not take into consideration the fact that a fraction of the neutrons is emitted by uranium with a time delay of about ten seconds. Though this fraction is small it has a marked effect in leading to still longer times than those which we have estimated. But as for all practical purposes the time t_2 which we have found is already long enough we need not include for the present the delayed neutron emission in the treatment of the subject.

A way to stabilize the nuclear chain reaction in a lattice of uranium spheres which is "economical" from the point of view of the nuclear phenomena involved is illustrated in figure 1. The uranium sphere which is surrounded by a spherical layer of liquid bismuth (serving the purpose of cooling the uranium in a way which does not reduce the nuclear efficiency of the arrangement as expressed by q) is shown in this figure. A short rod or disc composed of an element which strongly absorbs thermal neutrons is near the center of the uranium sphere and is shielded by the uranium from thermal neutrons. This rod or disc can move within a tube or slit and its position may be controlled by the intensity of the neutron radiation emitted by the chain reaction. If the intensity of this radiation increases the rod or disc may be automatically moved away from the center of the uranium sphere and ultimately if required entirely out of the uranium sphere. It would then absorb a larger and larger fraction of thermal neutrons thereby reducing the value of q and thus stabilizing the chain reaction.