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# The Science of Fast Reactors and Why it has Been Studied [and Discussion]

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# The science of fast reactors and why it has been studied

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The basic advantage, not to say the *raison d'être* of fast neutron reactors, is clear cut. This type of nuclear reactor is the only one which makes possible to use in principle the whole and in practice a large part of the fission energy of natural uranium. By this it is meant the energy which would be released if all nuclei present in natural uranium could be fissioned. Slow neutron reactors in current use today release only a small fraction of the total energy.

## The case for the slow neutron reactor

There is on Earth only one nuclide, namely $^{235}$U, which can undergo fission under the impact of neutrons of whatever energy. However, this uranium isotope is radioactive with a half-life of 700 million years, so that there now remains only 1 % of the quantity that existed when the Solar System and the planet Earth were formed. In uranium mined at present, there is only 0.7 % of $^{235}$U. The remaining 99.3 % is $^{238}$U, which can be fissioned only by neutrons whose kinetic energy exceeds 2 MeV, slower neutrons being absorbed.

To achieve a self-sustained chain reaction of fissions in a medium containing natural uranium, it is necessary to reduce the speed of the neutrons emitted by the fission process down to the lowest energy achievable in practice, namely the energy of thermal motion of matter at the ambient temperature (around 0.03 eV). The reason appears on the broken line of figure 1. Only below a neutron energy of 1 eV is the ratio of the fission cross section of $^{235}$U to the absorption cross section of $^{238}$U large enough (*ca.* 200) to compensate for the small number of $^{235}$U nuclei in comparison with those of $^{238}$U in natural uranium (*ca.* 1–140).

To produce energy in a nuclear reactor using natural uranium as fuel, uranium-bearing fuel assemblies have to be interspersed within a medium called a moderator made of light elements, typically heavy water or graphite. The fast neutrons emitted by fission lose rapidly their kinetic energy through a series of elastic collisions on the nuclei of the moderator before they can produce a further fission. As the fission chain reactions go on, $^{235}$U progressively dwindles and fission products, which are neutron absorbers, build up. After a few thousands megawatt-days of heat have been released from each tonne of uranium, the irradiated fuel must be removed and replaced by fresh fuel. The total energy then produced is less than 1 % of the fission energy of natural uranium.

Another scheme, allowing the adoption of cheap ordinary water as a moderator, is to use uranium in which the $^{235}$U content has been increased, say up to 3 %, by processing natural uranium in an enrichment plant. Now one has more elbow room and fuel burn-up can be increased roughly 10 times, up to 50000 MW d t$^{-1}$. But here again, only 1 % of the fission energy of the natural uranium entering the enrichment plant has been used.

Fortunately, there is another way of releasing a much larger fraction of this energy. As was mentioned earlier, $^{238}$U is primarily a neutron absorber, a kind of poison for the chain reaction.

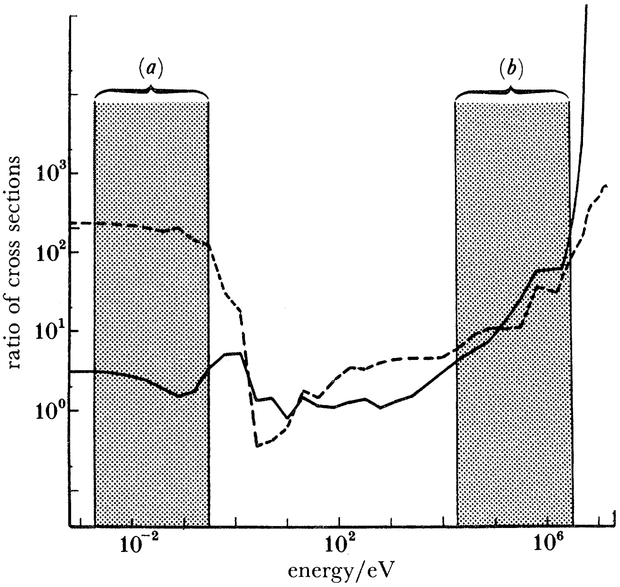

FIGURE 1. (*a*) Slow and (*b*) fast neutron reactor domains. ----, $\sigma_f(^{235}\mathrm{U})/\sigma_c(^{238}\mathrm{U})$; ——, $\sigma_f(^{239}\mathrm{Pu})/\sigma_c(^{239}\mathrm{Pu})$.

But after absorbing a neutron, a nucleus of $^{238}$U is transmuted into $^{239}$U, which, after two successive spontaneous radioactive transformations, gives rise within a few days to a new nuclide, $^{239}$Pu. The latter, which no longer exists on Earth as it decays by radioactivity with a half-life of 24000 years, is a fissile material similar and even superior to $^{235}$U.

To burn $^{238}$U the straightforward idea then arises to proceed in two steps: first to transform $^{238}$U into $^{239}$Pu, and then to burn $^{239}$Pu. To acknowledge this good point, $^{238}$U is called a fertile material.

It is not so easy to take full advantage of this idea in practice. Only 2.4 neutrons are emitted on an average for each $^{235}$U fission, and 3 for each $^{239}$Pu fission. One of these neutrons is of course earmarked for sustaining the chain of fissions. To transform $^{238}$U into $^{239}$Pu at such a rate that the total amount of fissile material in the reactor will not go down but will possibly go up as the chain reactions proceed, at least a second neutron must be absorbed in $^{238}$U each time a $^{235}$U nucleus disappears. As it is impossible to avoid losing neutrons through wasteful absorption in the many elements the surrounding medium is made of, one sees that the margin is sharply limited.

The ratio between the number of new fissile nuclei (say $^{239}$Pu) that are produced from fertile ones (say $^{238}$U) to the number of fissile nuclei (say $^{235}$U) that disappears during the same operating time of the reactor is called its breeding ratio.

Typical values of breeding ratios of heavy-water or graphite-moderated reactors range from 0.7 to 0.8. In a current light-water moderated reactor (LWR), the value is even lower, something like 0.6. It is indeed feasible to design special LWRs by increasing the ratio of fissile to fertile material in the fuel, and by decreasing the volume ratio of water to fuel in the core, so that the breeding ratio reaches about 0.9. Yet it seems definitely ruled out that it could exceed 0.95.

Slow neutron reactors, whatever combination of uranium and plutonium is used, fall short of reproducing fissile material at the same rate they are burning it. As a consequence, even with successive irradiations of the nuclear fuel in the reactor, only a few percent of the fission energy of natural uranium can be made available.

### The case for the fast neutron reactor

It happens that the object of achieving a breeding ratio equal or superior to 1 is possible under rather narrow conditions, if the chain reaction of fissions is conveyed by fast neutrons.

Among the many ways a neutron may be lost by parasitic absorption, there is one which is truly unavoidable, namely its capture by a fissile nucleus itself without any fission occurring. The solid line on figure 1 shows the variation, as a function of the energy of the incident neutron, of the ratio between the fission cross section of $^{239}$Pu and the capture cross section, without fission, of the same isotope. It can be seen that this ratio increases significantly in the range of energies which the neutrons have when they are emitted by the fission process, i.e. around 2 MeV. The spectrum of neutrons in any nuclear reactor is indeed somewhat shifted downwards as a result of elastic or inelastic collisions with the nuclei of the medium. Yet if care is taken to remove light elements from it, the energies of most neutrons carrying on the chain of fissions will exceed $10^5$ eV, so that their wasteful absorption by the fissile material itself is reduced to a minimum.

It is also required to fix within a rather narrow range the relative amounts of fissile and fertile materials that make up the nuclear fuel of a fast neutron reactor. If $^{235}$U is used as fissile material, the ratio between $^{235}$U and $^{238}$U nuclei has to be selected between about 0.17 and 0.25, and then a breeding ratio up to 1.2 can be obtained. If $^{239}$Pu is used as fissile material, the ratio between $^{239}$Pu and $^{238}$U nuclei has to be selected between about 0.13 and 0.25, and then a breeding ratio as high as 1.4 can be obtained.

Of course the exact values depend in each case on the kind and abundance of other elements present in the medium, either as structural materials or as a coolant to carry away the heat produced by the fission reactions. Besides, as long irradiations proceed, neutrons induce in the fissile and fertile nuclei a great many different reactions, followed by a wealth of spontaneous radioactive decay processes. Even if one starts with pure $^{235}$U or $^{239}$Pu, a lot of other isotopes of both these elements and of higher actinides build up progressively, till at the end a kind of equilibrium distribution is reached, depending on the composition of the medium and the neutron spectrum. To compute a meaningful breeding ratio, one must consider all the various fissile isotopes that are consumed or created in the course of the operation of the reactor, and ascribe to each of them a corrective factor to take into account its relative value in producing a new fission in comparison with $^{239}$Pu taken as a reference. For instance, after a very long irradiation in a fast neutron reactor, the distribution of plutonium and americium isotopes tends to the following equilibrium:

| $^{238}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu | $^{241}$Am |
|---|---|---|---|---|---|
| 0.8 % | 62 % | 25.2 % | 5.2 % | 4.7 % | 2.1 %. |

The average fission cross section of this mixture of isotopes in a typical fast neutron spectrum, is only 72 % of that of pure $^{239}$Pu.

Experience confirms that breeding ratios significantly higher than 1 can be achieved in practice in fast neutron reactors. Let us take as an example the 250 MW$_e$ FBR Phénix at Marcoule (France), which uses plutonium as a fuel. The consumption and production rates of many different heavy nuclei were carefully measured all over the volume occupied by fissile and fertile materials. The measured value of the breeding ratio of Phénix resulting from these experimental data was 1.12 ∓ 0.03, in good agreement with the one computed beforehand (1.10).

## PECULIAR FEATURES OF FAST NEUTRON REACTORS

Whether the chain reaction is driven by fast or slow neutrons does not change the underlying principles nor the overall scheme for the energy generation in a nuclear power station. Both types of reactors bear many more similarities than differences. Yet fast neutron reactors exhibit peculiar features, which I now discuss.

(*a*) In the range of neutron energies from $10^5$ eV to a few $10^6$ eV, fission cross sections are small (roughly 100 times smaller than the ones for thermal neutrons). This is why the fuel of a fast neutron reactor must contain a high proportion of fissile material and also occupy a large fraction of the volume of the core. Figure 2 shows that both the volume of the core of a typical fast neutron reactor and the amount of fissile material which it contains decrease steadily as the ratio of fissile to fertile nuclei is increased.

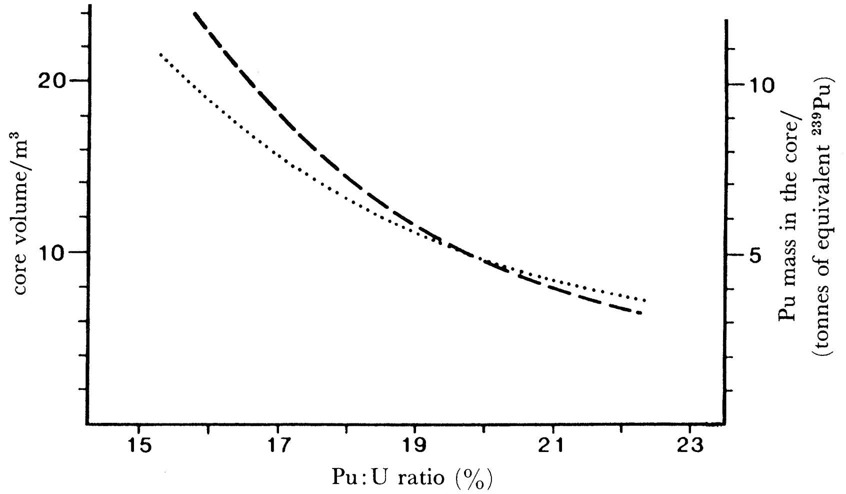

FIGURE 2. Volume of core in a typical fast neutron reactor and amount of fissile material. ––––, Core volume; ······, Pu mass.

Let us compare two reactors designed for generating the same output of power, the one using fast neutrons and the other slow neutrons. If the cores of the two reactors have to contain similar total amounts of fissile material, the volume of the former will be about three times smaller than the volume of the latter.

Fast neutron reactor cores are thus basically compact. Heat is produced therein at a high rate (an average of 0.4 $\mathrm{MW_t\ l^{-1}}$) and correspondingly neutron fluxes there are large (typically $4 \times 10^{15}\ \mathrm{cm^{-2}\ s^{-1}}$). Those are the main challenges with which engineers designing fast neutron reactors are confronted.

(*b*) Contrary to what happens in the domain of slow neutrons, cross sections for absorption of fast neutrons do not differ significantly from each other among the many various nuclei of the chemical elements throughout the periodical table. They are in all cases small, of the order of $10^{-25}\ \mathrm{cm^2}$.

As a consequence, the designer of a fast neutron reactor core has more freedom to select the best structural and coolant materials by taking into account essentially their mechanical, thermal and chemical properties, as their nuclear peculiarities play a minor role. Of course there remains the strict requirement to avoid the presence of light nuclei, so that the mean energy of the neutron spectrum is kept high enough.

(*c*) Absorption cross sections of fast neutrons are similarly small for fission products (the distribution of which among the various chemical elements is only slightly different whether the fissions are produced by fast or slow neutrons).

As they accumulate, fission products bring about a continuous decrease in the reactivity. However, for a given burn-up of the fuel, this decrease is less when the chain reaction is carried by fast neutrons instead of slow ones.

(*d*) As the core of a fast neutron reactor is relatively small for reasons explained in (*a*), the fraction of neutrons which, once produced, would leak out of it is correspondingly high.

To avoid wasting them, fertile material is set out to form what is called a blanket around the core, so that neutrons leaking out of the latter can be absorbed in the fertile material of the blanket to produce additional fissile material. In the so-called homogeneous arrangement, shown in a schematic way in figure 3*a*, the breeding ratio of the whole reactor is split into two additive parts. One, called the internal breeding ratio, takes into account the fissile material that is produced within the core. The other, called the external breeding ratio, takes into account the fissile material that is produced within the blanket.

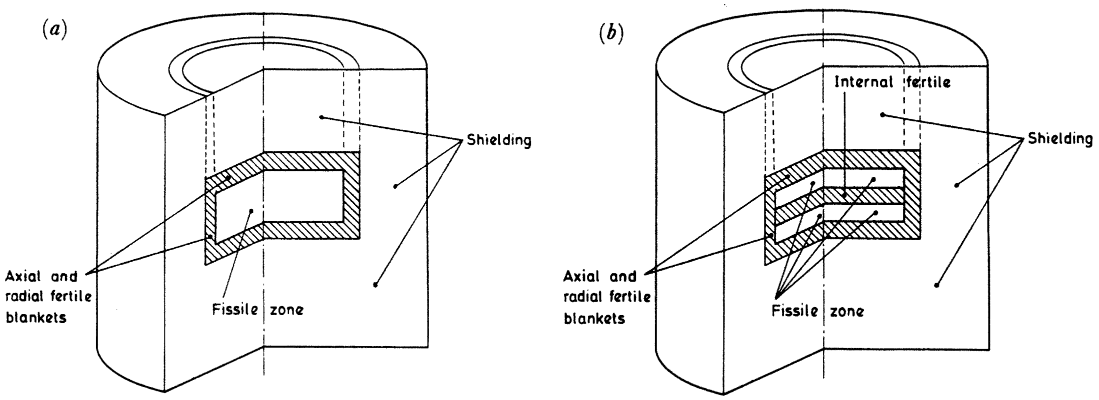

FIGURE 3. (*a*) Homogeneous and (*b*) heterogeneous types of core.

In present fast neutron reactors, which use plutonium as a fissile material, typical values of the internal breeding ratio range from 0.8 to 0.9, while the external breeding ratio, depending on the thickness of the blanket, can be brought up to 0.4 or 0.5.

(*e*) The ability of the plutonium produced from $^{238}$U to help sustain the chain reaction depends very much on where it is formed in the reactor. The closer it is located to the centre of the core, where the neutron flux is higher, the more helpful it is. In a homogeneous arrangement, where the value of the internal breeding ratio is likely to be less than 1, the amount of fissile material in the core will decrease as the operation of the reactor goes on, until the chain reaction can no longer proceed. To take full advantage of the favourable effect of fuel breeding and to counter the adverse influence of fission products as far as keeping up the chain reaction is concerned, there is at present a clear trend to design core and blanket arrangements so that the internal breeding ratio is enhanced, up to values between 1 and 1.1, while the external breeding ratio would thereby be decreased, down to values as low as 0.2 or 0.3. Particularly interesting in that respect are the so-called heterogeneous schemes, depicted in figure 3*b*, where zones containing fertile material are interspersed within the core itself. In such an arrangement, the reactivity of the system can in principle be kept constant for very long periods (several years) and the time at which fuel assemblies must be removed from the reactor will only depend on their ability to support the growing metallurgical defects or mechanical strains brought about by long irradiations.

(*f*) The average lifetime of a neutron, from the moment it is emitted in the core till it produces the next fission, is very short in a fast neutron reactor, about $10^{-6}$ s, compared with $10^{-3}$ s for a slow neutron reactor.

Anyhow, both figures would be too low to make the control of a chain reaction manageable under safe conditions in any nuclear reactor, were there not in both cases a subsidiary phenomenon of major importance in solving the problem. Although most neutrons are released at the very moment of the fission process, it happens that a few of them are emitted as a consequence of the radioactive decay of some of the fission products, i.e. within seconds or even a few minutes after the fission has taken place. Though these delayed neutrons number less than 10 compared with 1000 emitted without delay, there are enough of them to set the pace at which the chain reaction is going and to make the reactor easy to control. The fraction of neutrons that are delayed is pretty much the same whether the chain reaction is driven by fast or by slow neutrons, but it depends on which fissile material is used. Its value is lower with $^{239}$Pu ($2.3\times10^{-3}$) than with $^{235}$U ($7\times10^{-3}$).

(*g*) The reactivity of the system – a measure of the ability of the reactor to sustain a chain reaction – is sensitive to the temperature of the core, the pressure within it, the density of the coolant, etc., through the joint operation of many elementary processes. These usually combine in such a way that the reactivity decreases as the temperature increases. It is of prime importance to make sure that the reactor is designed accordingly, so that inherent mechanisms provide a feedback loop that makes the reactor stable and prevent any cumulative power surge.

In the Superphénix power plant, for example, the reactivity goes down by $1.2\times10^{-5}$ when the temperature increases by 1 °C. It goes down by $10^{-5}$ when the power produced increases by 1 $\mathrm{MW_t}$. Such figures are somewhat smaller than the ones typical of power plants using slow neutron reactors, but the orders of magnitude are similar in both cases.

It has to be mentioned that decreasing the density of the coolant in the centre of the core of a fast neutron reactor (while keeping its temperature constant) increases the reactivity. In Superphénix, for instance, draining the whole coolant from a central fuel assembly would bring in a reactivity increment of $8\times10^{-5}$. This is an unpleasant feature of big fast neutron reactors. Care must be taken to prevent the occurrence of large voids within their core.

(*h*) To control the reactivity as the power of the reactor is changed use is made, as in slow neutron reactors, of control rods that contain a neutron absorbing substance and that can be moved at a slow pace throughout the core. Similar shutdown rods are permanently available, ready to be introduced quickly into the core in case an accident occurs that requires the immediate shutdown of the reactor.

Control and shutdown rods for fast neutron reactors make use as an absorbing substance of boron containing a high proportion of $^{10}$B, this isotope being one of the few nuclei whose absorption cross section is relatively large for neutrons of energies around $10^5$ eV.

## FAST NEUTRON REACTORS IN A GLOBAL NUCLEAR ENERGY SYSTEM

The starting point for the introduction of fast neutron reactors is the existence of a large number of slow neutron reactors, like the present ones. Whether they use natural or slightly enriched uranium as a fuel, the latter generate plutonium as an unavoidable byproduct of their operation. Being chemically different from uranium, plutonium can be separated from it and from the fission products in reprocessing plants where fuel assemblies are sent after they have been irradiated.

The total production of plutonium by the 400 nuclear reactors operating at present in the world is, as an order of magnitude, 40 t $a^{-1}$. Only a small fraction of the plutonium produced so far has been separated in reprocessing plants.

At a second stage, plutonium will be mixed with an adequate amount of natural uranium – or, even better, of cheap depleted uranium delivered at the low end of enrichment plants – to form new fuel assemblies to be used in fast neutron reactor cores. In addition, fertile assemblies made of depleted uranium only will be manufactured to constitute the blanket of the same reactors.

About 4 t of plutonium are needed in the core of a fast neutron reactor designed for generating 1000 $MW_e$. An extra 2 t must be permanently invested outside the reactor, in the various facilities required to perform the whole chain of operations of the fuel cycle.

In one year of operation, assuming that the average availability factor of the power station is 80%, such a fast neutron reactor will burn by fission 700 kg of plutonium and produce 850 kg of it from an equal quantity of depleted uranium (roughly 600 kg in the core and 250 kg in the blanket). Taking into account 100 kg of depleted uranium which will have been directly fissioned at the same time, everything goes on as if the reactor would have, during that year, consumed *ca.* 1 t of depleted uranium and produced a net excess of 150 kg of plutonium.

After the fuel and blanket assemblies of the fast neutron reactor have been irradiated up to the point they must be removed and replaced by fresh ones, they are sent to a chemical reprocessing plant, where plutonium and uranium are separated from fission products.

Once again plutonium and uranium will be mixed to manufacture new fuel assemblies for the same or another fast neutron reactor, and a similar sequence of operations can continue so long as there is enough depleted uranium available.

As the operation of the fast neutron reactor proceeds, the total amount of excess plutonium it produces goes up. In the reference case mentioned above, after about 40 years, enough plutonium will accumulate to meet the needs of another reactor identical to the initial one. Likewise, 10 reactors operating simultaneously will produce in four years enough plutonium to feed an eleventh one.

The time required to double the total installed power of a series of breeder reactors by using the excess plutonium they produce, as soon as it is available, to supply new ones, is called the doubling time. The values of the doubling time that can be obtained in practice are very sensitive to the characteristics of the individual reactors. As a rough indication, they could be as short as 15 years but the ones achieved under realistic schemes of operation are likely to be significantly longer.

Such figures show that the introduction and deployment of fast neutron reactors is a very progressive and rather slow process. Yet, if we look at the distant future, they offer the unique opportunity to fully exploit the fission energy of uranium present on Earth, and to make it an energy source able to meet the needs of mankind for many thousands of years.

In addition to uranium, there is another element present in the Earth's crust in even larger quantities, namely thorium, which is also able to produce energy through the fission process. Thorium as it exists today is made up of a sole isotope, $^{232}$Th, which is similar to $^{238}$U. It is not fissile, but it is fertile as, after absorbing a neutron, it gives rise to $^{233}$U, which is a fissile material similar to $^{235}$U and $^{239}$Pu. FBRS transforming thorium into $^{233}$U are entirely feasible and it might be that in the remote future use will be made of them, which would further extend the fission energy resources of our planet. Yet this possibility cannot be expected to be turned into account at a significant scale in the foreseeable future.

The main aim of this paper is to show that only through the use of fast neutron reactors can breeding ratios larger than 1 be obtained and thus the whole fission energy of uranium and thorium can be used.

But, if wanted it would be easy to reduce the breeding ratio down to the desired value above or below 1 by adjusting the relative amounts of fissile and fertile materials in the reactor, so that the total amount of plutonium produced by a number of fast neutron reactors would at any time exactly match the needs of power production and no useless surplus would accumulate.

This argument can be taken to the extreme. Suppose that fission nuclear energy will some day become redundant, for example because a yet unknown way to produce cleaner and cheaper energy would become available in large amounts. If at that time, one would also wish to get rid of the many tonnes of plutonium and other heavy $\alpha$-radioactive elements which will have accumulated, the best way – if not the only way – to solve the problem would be to burn these elements in fast neutron reactors designed to have a breeding ratio close to zero, as they will contain no fertile material at all. Instead of being breeders, such reactors would be used as plutonium incinerators. Of course it would take a long time to destroy all these heavy nuclides that way, much less time, however, than to let them disappear by radioactive decay, and with the additional bonus of obtaining energy from them instead of considering them as useless long-life radioactive wastes.

## *Discussion*

J. M. CASSELS, F.R.S. (*Norwich, U.K.*). 1. Is there any fundamental reason why the ratios of fission/capture cross sections for $^{235}$U and $^{239}$Pu should show significant differences when expressed as functions of incident neutron energy? 2. I note there is a political dimension to FBR development, the abandonment of the U.S. Clinch River project is an example. Would the speaker like to comment?

G. VENDRYES. 1. This ratio would be similar across a wide range of neutron energies for both isotopes. However, the curves shown in my illustration were not comparable in this manner. These showed the ratio of fission to capture cross sections for $^{239}$Pu, but the ratio for $^{235}$U fission to $^{238}$U capture cross sections. 2. There is a strong political element to FBR development. As to the specific reasons behind the cancellation of Clinch River, I would refer you to the delegates present from U.S.A.

J. D. LEWINS (*Cambridge University, U.K.*). I note there is the possibility of positive void coefficients in fast reactors, is this overcome in the proposed U.S. PRISM reactors using metal fuel?

G. VENDRYES. The void coefficient would be slightly reduced with metal fuel due to a harder neutron spectrum. However, it is difficult to make a simple statement, rather, specific reactor designs must be compared. Of possibly greater importance is the size of the core. Smaller cores with lower power outputs tend to have reduced void coefficients. The axially heterogeneous core offers another way to overcome the problem.