RECENT DEVELOPMENTS IN THE PHYSICS AND SAFETY
OF LARGE FAST POWER REACTORS*

by

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The term "fast reactor" is a broad one, covering a host of reactor types and sizes. And the physics and safety considerations of these many reactor types are too numerous to be covered in twenty minutes, even if I take twenty-five. In my talk today I shall restrict myself to three principal areas. First, some recent cross section measurements and their effect on fast reactor calculations. Second, the question of Doppler and sodium void reactivity effects in large fast power reactors and the conflicts inherent in simultaneous optimization of performance, breeding, and safety characteristics. And third, the matter of hybrid fuel cycles.

Back in 1958 fast reactor physicists had reasonably good luck in correlating the considerable existing body of critical experiments for $^{235}$U-fueled systems (1, 2, 3) and in predicting forthcoming experiments of a similar nature. Usually a judiciously biased choice of cross sections, plus some witchcraft, was needed, but it could be done.

However, it was also clear that an objective evaluation of direct microscopic cross section measurement would lead to a consistent prediction of smaller critical masses than were observed experimentally. One such study in 1960 consistently underpredicted experiment by 6 to 17% (4).

Three things have happened since which lead to a much better agreement between microscopic cross sections and integral, $^{235}$U-fueled experiments. They are:

1) $v$, the neutrons emitted per fission of $^{235}$U, has been found to increase more slowly with increasing neutron energy (5).

2) $\sigma_f$ for $^{235}$U has recently been measured to be 5 to 8% lower in the region between 100 and 500 kilovolts than has generally been used in calculations (5).
3) The effect of resonance scattering for mixtures of isotopes has been computed more accurately.(6)

In addition, \( v \), the neutrons emitted per fission of \( ^{238}\text{U} \), also seems to be somewhat lower.

Thus, agreement between theory and experiment on critical mass has markedly improved. Also, a systematic error of about 10% in threshold fission ratio measurements at the ZPR-III facility has been found. It was due to excessive inelastic scattering in the fission chamber walls. This correction also helps agreement between experiment and theory.

However, sharp differences still exist on certain other parameters such as the prompt neutron lifetime, which is also a spectral index. So, all is not yet understood for medium-sized \( ^{235}\text{U} \) fueled criticals. And medium size critical experiments with plutonium fuel are just beginning.

In the first slide, \( v \) for \( ^{235}\text{U} \) is plotted against neutron energy.

The major consequence of recent measurement is the conclusion that the rate of increase with energy is lower for the first several Mev than at higher energies. Previously, a linear relation, which gave higher values at 1 or 2 Mev, was used.

This is again illustrated in the first line of the next slide, slide two. At 1.5 Mev the 1960 cross section set of Yiftah, et al., predicted a \( v \) for \( ^{235}\text{U} \) of 2.63. A. B. Smith, on the other hand, in a recent review at the Conference on Large Fast Power Reactors at Argonne, estimated the number to be more nearly 2.58.

The same slide shows how \( v \) at 1.5 Mev had varied for other fissionable isotopes during the past three years. Of particular interest are the values for
U$^{238}$. Prior to 1960, this number was taken to be in the vicinity of 2.5, at 1.5 Mev. In 1960, the work of Yiftah, et al., provided a value of 2.65 leading to a considerably greater fast fission bonus to the breeding ratio. The most recent value has dropped back appreciably to 2.57.

$v$ for thermal neutrons is shown in the next slide, slide three. There has been little change in the last three years except for $U^{233}$, where a drop in the measured value is indicated. Actually $U^{235}$ had suffered a similar drop, earlier. In 1958 the accepted $v$ for $U^{235}$ was 2.47.

The fission cross section for $U^{235}$ is plotted as a function of energy in the next slide, slide four. Very recent data from the Aldermaston Laboratory in England indicates that the previously accepted cross section is 5 to 8% too high in the vicinity from 100 to 500 kilovolts. Since other fission cross sections are usually measured relative to that of $U^{235}$, the same shift may be anticipated for $Pu^{239}$ and $U^{233}$ in this energy range.

I should like to mention one more major cross section change. In the next slide, slide five, alpha, the ratio of capture to fission, for $Pu^{239}$ is plotted versus energy. The dashed curve is a theoretical estimate previously used in calculations. Recent data by Hopkins and Diven(7) is plotted as the circles. The new data has an accuracy of roughly 20%, much better than earlier measurements. Below 30 kilovolts, the situation remains very uncertain.

As a consequence of the new data, breeding ratios for $Pu^{239}$ fueled fast reactors have gone up by 0.1 to 0.15.

One must realize that we have been talking about the better measured cross sections. Our knowledge of cross sections is still only fair for inelastic scattering above about 1-1/2 Mev, for fission below about 100 kv, and for capture at practically all energies. So far as capture is concerned, these cross sections
have still not been measured for many important isotopes. And where measurements have been made, they frequently disagree appreciably. This situation is well illustrated in the next slide, slide six, where the capture cross section for tantalum is plotted against energy. Two different laboratories provided widely varying measurements over the overlapping energy range.

Needless to say, as a consequence of these various cross section uncertainties, considerable error must be expected in the prediction of critical mass, breeding ratio, or other performance characteristics for large fast power reactors today.

So much for cross sections. Next, let us consider reactivity coefficients briefly. The EBR-II and Enrico Fermi reactors use an unrestrained, one-piece metallic fuel element, which should expand axially during an excursion in power, losing reactivity and minimizing the undesirable effects of the excursion. Both these reactors have very small Doppler coefficients and substantially negative sodium void coefficients.

However, these reactors are rather small by today's standards. For reactors in the 1000 Mw electrical class, neutron leakage from the core is less important, and fuel expansion effects on reactivity are smaller. Furthermore, most attention today is being given either to a restrained metallic fuel element or to some form of ceramic fuel, neither of which seems certain to provide a reliable, prompt, thermal expansion effect on reactivity which is negative and of sufficient magnitude.

Other reactivity coefficients, namely the Doppler effect due to fuel heating and the sodium void effect resulting from changes in coolant density, promise to become dominant in ascertaining reactor stability and safety.
It seems very likely that large fast power reactors can be designed to have a substantially negative Doppler coefficient. The fertile thorium or U\(^{238}\) have been calculated to provide large negative reactivity effects upon heating\(^{(8, 9)}\) and this is being confirmed in recent experiments.\(^{(10, 11)}\) Furthermore, recent improvements in theoretical methods,\(^{(12, 13, 14, 15)}\) in which allowance has been made for the overlapping effect between resonances of the same isotope, as well as for overlapping between resonances of different isotopes, indicate that the reactivity contribution from the fissile isotope should be very small and possibly even negative.

Of course the magnitude of the Doppler coefficient will vary from reactor design to reactor design. Other things being equal, it will be larger for that reactor having a higher proportion of low energy flux in the region from 500 to several thousand volts. This is the case for the oxide or carbide fueled reactors, compared to the metallic fuel. However, small amounts of moderator can be added to a metallic-fueled reactor to give it the Doppler coefficient corresponding to that normally achieved with ceramic fuel. And consideration is being given to the addition of extra moderating material to at least one ceramic-fueled reactor concept for the deliberate augmentation of the Doppler effect achieved in normal fashion.\(^{(16, 17)}\) A penalty accompanies this softening of the spectrum, of course. Parasitic capture in the fissile plutonium rises and the breeding ratio drops accordingly. In the oxide fueled concept cited, the breeding ratio dropped from 1.3 to 1.1.

An appreciably negative, prompt acting Doppler coefficient can have a marked beneficial effect on reactor safety. As shown by Zaleski,\(^{(18, 19)}\) it may ensure reactor stability in the face of other positive reactivity coefficients.
As illustrated by Nicholson\(^{(20)}\) and again by Wolfe,\(^{(21)}\) a large negative Doppler coefficient can markedly reduce the kinetic energy available and the total energy released in a super prompt critical burst in a fast reactor.

Unfortunately, large fast reactors, particularly those fueled with Pu\(^{239}\) plus U\(^{238}\), are susceptible to a considerably positive reactivity effect upon the loss or expulsion of sodium.\(^{(22)}\) This sodium loss reactivity problem arises mainly from the hardening of the neutron spectrum when sodium atoms are expelled. When the spectrum hardens, the ratio of capture to fission in plutonium decreases. The fast fission yield in U\(^{238}\) increases. And the capture rate in U\(^{238}\) and in fission products decreases more rapidly than does the fission cross section of Pu\(^{239}\). All these effects add reactivity.

The net effect is illustrated in the next slide, slide seven, where \(\bar{\eta}\), the average number of neutrons emitted per absorption in all reactor materials is plotted as a function of neutron energy for a metal-fueled reactor. Note that except at the very low energies, \(\bar{\eta}\) rises rapidly with energy. Hence, when sodium loss hardens the spectrum, the reactivity tends to rise.

The same trend is illustrated in the next slide, slide eight, where the adjoint flux, that is, the relative reactivity worth of a neutron, is plotted against energy for an oxide-fueled reactor.\(^{(23)}\) Above 10 kilovolts, the neutron value rises as the spectrum hardens. Note that Pu\(^{240}\) and fission products make the slope steeper, aggravating the situation.

A compensating factor is the increase in neutron leakage upon loss of sodium atoms, which reduces reactivity. However, neutron leakage tends to become less important as reactor size increases. The positive reactivity component from spectral hardening tends to dominate and it becomes increasingly difficult to design a reactor having an overall negative sodium void reactivity effect without compromising on other aspects of reactor performance.
In the next slide, slide nine, the sodium coefficient is plotted as a function of reactor core volume for plutonium-uranium-metal fueled reactors. As core size gets larger, the sodium coefficient becomes more positive. For this specific design with steel structure the cross-over point was in the vicinity of only 1200 liters. When niobium structure was used, the cross-over point from negative to positive sodium coefficient was less than 500 liters.

In the next slide, slide ten, the sodium coefficient is plotted as a function of reactor core volume for oxide and carbide fueled reactors using steel structure. These fuels are lower in density; hence, if the same volume fractions of fuel, structure, materials, and coolant are maintained as in the metal-fueled reactor, there is less room for the fertile material in the core and the fuel enrichment is higher. As a consequence, the sodium coefficient is more negative for the same size reactor than it is for the metal fueled reactor. As we see, the cross-over point for the oxide fueled reactor is above 3000 liters, according to these rough scoping calculations.\(^{(24)}\)

There are various reasons for wanting to use low enrichment fuel, in the vicinity of 10%. A large volume fraction of \(^{238}U\) can make for a more negative Doppler coefficient. It can lead to a higher overall breeding ratio. And it provides a large internal breeding ratio, helping to minimize long term reactivity problems. But it also can aggravate the sodium void reactivity problem. Thus, a major conflict between desirable design goals exists.

On the next slide, slide 11, we find the results of a few calculations on the sodium void effect in large oxide reactors as computed by the most sophisticated techniques available. These were reported by Himmel at the recent conference on
large fast power reactors at Argonne.\(^{(23)}\) One quickly observes that the net sodium void effect is the result of the difference between two very large and opposing reactivity contributions, that due to the spectral effects plus some capture in the sodium and that due to leakage. The core volume at which the sodium coefficient changes sign depends strongly on core composition. But sizes less than several thousand liters are indicated for spherical geometry.

The manner in which the sodium void effect varies with sodium volume fraction for given geometry in very large fast reactors is illustrated in the next slide, slide 12. On this slide sodium coefficient is plotted against volume fraction for several reactors of very large radius, each having a certain axial height. In each case we see that for very small sodium volume fractions, the sodium coefficient is positive but small. As the sodium volume fraction increases to the neighborhood of 40 or 50\%, the sodium coefficient reaches a positive maximum, and then starts turning down sharply. The problem of whether to design the reactor at 25\% sodium, at 50\% sodium, or at 70\% sodium becomes increasingly complex.

A further complication is introduced by the fact that the sodium coefficient has a very strong spatial dependence. The negative leakage component is very small near the core center. Hence, for a reactor having an overall zero sodium coefficient, there is a strong positive component from the inner portions of the core which is balanced by a negative contribution from the regions near the boundary. Thus, expulsion of sodium initially from the center of the core may lead to a gain in reactivity in a reactor where total loss of sodium leads to a loss of reactivity. This effect is illustrated in the next slide, slide 13.\(^{(17)}\) The change in reactivity with progressive axial loss of sodium is plotted for each of two oxide
fueled reactors. In Case A where total loss of sodium leads to a gain of reactivity of 0.008 $\Delta k/k$, there is a peak gain of greater than twice this amount when about $2/3$ of the core only has been voided. Case B describes a reactor in which some beryllium oxide has been added. The addition of this small amount of moderator serves two purposes. First, it makes the sodium coefficient less positive by shifting the spectrum downward and by reducing the dependence of the reactor spectrum on the presence or absence of sodium. Second, by increasing the amount of low energy neutrons present at all times, that is in the presence or absence of sodium, it insures a considerably larger negative Doppler coefficient than would be present in Case A. Of course, as previously mentioned, the beryllium oxide addition has a bad side effect. The breeding ratio drops from about 1.3 to about 1.1.\(^{(16)}\)

This last design modification, that of adding some moderator to the core in an effort to tailor the reactivity coefficients to a more desirable pattern, is one of a variety of attempts underway to handle the sodium void effect problem. Another avenue being explored is to modify the reactor core geometry appreciably. Pancake or annular cores lead to higher enrichment and hence an improved sodium coefficient for the same core volume. Modifications in the relation between blanket and core, that is, the introduction of a sodium transition region between these two, can help achieve an overall negative sodium void effect.

Thus far, each modification has had its drawbacks. It may be a lower internal breeding ratio, making refueling operations more frequent. It may be that economical operation of a blanket which can capture a large fraction of the neutrons escaping from the core becomes very difficult.
At the recent fast reactor meeting, studies were reported by Cohen (17) and by Zaleski (19) on the safety characteristics of large fast reactors having positive sodium void effects. As mentioned previously, Zaleski found that with a large negative Doppler coefficient the reactor would still be stable in the presence of a positive sodium void coefficient. Cohen and Zaleski both found that the course of an accident involving the expulsion of sodium by boiling depends very strongly on the manner in which the sodium is lost from the reactor. For a mild power transient or a partial loss of flow, boiling might be limited to the upper core regions and upper blanket. In this case boiling would lose reactivity. However, model experiments, using water, (25) have exhibited a chugging behavior leading to periodic voiding of the central regions of subassemblies. Further study is needed to see when such a phenomenon might provide a mechanism for rapid reactivity gain.

For the hypothetical accident involving full loss of coolant flow and a delay in scram, boiling may begin at the core center. The course of such an event would depend strongly on the magnitude of the Doppler effect and the variation in sodium void reactivity effect with position in the reactor. (17)

Clearly, intensive study is needed on the role of positive sodium void effects in the safety of large fast power reactors. If, in order to go to the 1000 Mwe size, one has to pay a large penalty in the form of reduced breeding ratio, higher fuel cycle costs, or greater capital investment for containment purposes, it may be that two 500 Mwe reactors at a common site will prove more desirable. Or, an increased emphasis on higher power densities, leading to smaller reactor sizes, may result. Time should tell.
One thing is clear. The complexity of optimizing conflicting parameters for purposes of safety, performance and breeding has added a new dimension to the field of fast reactor physics. As Haefele recently put it, second order effects have become paramount. And our knowledge of microscopic cross sections is very inadequate for the job.

Now, for a final brief comment on hybrid fuel cycles. It is well known that fast reactors should be capable of breeding either on the thorium-U^{233} fuel cycle or the U^{238}-Pu^{239} fuel cycle. What is illustrated in the last slide, slide 14, is that fast reactors using thorium plus plutonium or U^{238} plus U^{233} also breed, that is, make more of a thermally fissile isotope than they consume. (26) For these particular metal-fueled fast reactors, the breeding ratio with either hybrid fuel cycle lies between that of the two usual forms.

The sodium void effect also lies between the slightly positive result for U^{238} plus Pu^{239} and the very negative result for thorium plus U^{233}.

Thus, if thorium-plutonium metallic alloy turned out to be a super-fuel, metallurgically speaking, its physics characteristics might be quite tolerable.

More interesting, perhaps, is U^{238}+U^{233}. It has a much higher breeding ratio than the usual thorium-U^{233} combination. Furthermore, U^{238}-U^{233} should provide less control difficulties than the usual combination, first because of a higher delayed neutron fraction and second, because of the absence of the considerable reactivity holdup expected from protactinium buildup.

Hence, uranium fuels, either as metal or ceramic, seem to have considerable
long-range potential in an economy using both thorium and uranium resources. Such a reactor would make plutonium in the core, for use elsewhere. It would obtain $^{233}\text{U}$ from its thorium blanket and from other thorium-bearing reactors.
References


References (Cont'd.)

16. P. Greebler, "Recent Improvements in Calculations of Doppler and Sodium Reactivity Effects for Large Fast Reactors", ibid.


\[ \bar{\nu} = 2.427 + 0.085E + 0.0138E^2 - 0.00067E^3 \]
<table>
<thead>
<tr>
<th></th>
<th>1960 (YOM)</th>
<th>1963 (A.B. SMITH)</th>
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<tbody>
<tr>
<td>$^{235}$U</td>
<td>2.63</td>
<td>2.58</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>3.07</td>
<td>3.09</td>
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<tr>
<td>$^{233}$U</td>
<td>2.69</td>
<td>2.66</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>2.65</td>
<td>2.57</td>
</tr>
<tr>
<td>Th</td>
<td>2.36</td>
<td>2.17</td>
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</table>
$U$ AT 0.025 ev

<table>
<thead>
<tr>
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<th>1960</th>
<th>1963</th>
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<tbody>
<tr>
<td>$U^{235}$</td>
<td>2.42</td>
<td>2.42</td>
</tr>
<tr>
<td>$Pu^{239}$</td>
<td>2.9</td>
<td>2.91</td>
</tr>
<tr>
<td>$U^{233}$</td>
<td>2.5</td>
<td>2.45</td>
</tr>
</tbody>
</table>
$\alpha = \sigma_c / \sigma_f$

$\alpha$ OF Pu$^{239}$

- NEW DATA

OLD CURVE

NEUTRON ENERGY, ev

$10^3$ $10^4$ $10^5$ $10^6$
52 VOL % Na
\[
\frac{\text{U}^{238} + \text{Pu}^{240}}{\text{Pu}^{239}} = 7
\]
INCREMENTAL CHANGE IN CRITICAL MASS, $SM/M$

$X \times 10^{-2}$

POSITIVE Na COEFFICIENT

NIOBIIUIM

STEEL

NEGATIVE Na COEFFICIENT

CORE VOLUME, liter

$0 \quad 1000 \quad 2000 \quad 3000$
SODIUM VOID EFFECT IN OXIDE REACTORS

<table>
<thead>
<tr>
<th>CORE VOLUME, LITERS</th>
<th>% Na</th>
<th>% FUEL</th>
<th>% δK ON LOSS OF Na</th>
<th>SPECTRAL + CAPTURE</th>
<th>LEAKAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>70</td>
<td>18</td>
<td>+1.89</td>
<td>+7.61</td>
<td>-5.72</td>
</tr>
<tr>
<td>2500</td>
<td>70</td>
<td>18</td>
<td>-0.89</td>
<td>+5.53</td>
<td>-6.42</td>
</tr>
<tr>
<td>2000</td>
<td>52</td>
<td>32</td>
<td>+1.56</td>
<td>+4.42</td>
<td>-2.86</td>
</tr>
<tr>
<td>1000</td>
<td>52</td>
<td>32</td>
<td>-0.11</td>
<td>+3.38</td>
<td>-3.49</td>
</tr>
</tbody>
</table>

*EACH REACTOR CONTAINS Pu$^{240}$, SOME FISSION PRODUCTS AND 1.6 VOL% Mo PLUS STEEL STRUCTURE
SPATIAL DEPENDANCE OF SODIUM LOSS $\Delta k$

PROGRESSIVE AXIAL LOSS, SYMMETRICAL ABOUT CORE MIDPLANE.

\[ \Delta k \text{ VOID} \]

\[ \text{VOID HALF-THICKNESS, cm} \]

CASE A (No BeO)

CASE B (BeO)
### 3000-LITER METAL-FUELED FAST REACTORS

<table>
<thead>
<tr>
<th>FUEL TYPE</th>
<th>CRITICAL MASS kg</th>
<th>BREEDING RATIO</th>
<th>SODIUM VOID EFFECT Δk/k</th>
</tr>
</thead>
<tbody>
<tr>
<td>THORIUM - U²³³</td>
<td>918</td>
<td>1.27</td>
<td>- .031</td>
</tr>
<tr>
<td>U²³⁸ - U²³³</td>
<td>878</td>
<td>1.50</td>
<td>- .012</td>
</tr>
<tr>
<td>THORIUM - Pu²³⁹</td>
<td>1060</td>
<td>1.36</td>
<td>- .013</td>
</tr>
<tr>
<td>U²³⁸ - Pu²³⁹</td>
<td>1030</td>
<td>1.60</td>
<td>+ .0025</td>
</tr>
</tbody>
</table>

All reactors have 15 vol-% fuel, 18 vol-% steel and 67 vol-% sodium.