of the sodium-void reactivity itself because both of these parameters affect the potential ramp reactivity insertion. Hence the preference for radially heterogeneous core designs in the United States where the thermal inertia associated with the larger inner blanket rods significantly delays the initiation of blanket voiding relative to the onset of fuel voiding. In the axially heterogeneous core, on the other hand, the midplane blankets are in the same sodium flow channels as the fuel and they would seemingly have no effect on retarding the number of channels voiding in the core. Rather, axial heterogeneity primarily lowers the magnitude of the void reactivity (but only ~10% according to Inoue et al.). It is not clear to us why a difference in sodium-void reactivity potential of only 60 to 70 cents (out of nearly 9-dollar total), between the conventional homogeneous core and the axially heterogeneous core, results in such a large reduction in reactivity ramp rate. We would welcome additional papers by this group which might shed further light on the difference in generic void mechanics between the homogeneous and axially heterogeneous core designs. We note finally that the void reactivity potential in the axially heterogeneous core exceeds +8 dollars, whereas comparable 1000 MW(electric) radially heterogeneous core designs are successful in restricting the void reactivity potential to less than +3 dollars, which, coupled with the inherent void incoherency between the fuel and inner blankets, makes a very substantial reduction in the HDCA energy release compared with that for a conventional homogeneous core.

In summary, we do not feel that axial heterogeneity offers a substantial improvement in LMFBR core performance or safety, especially in comparison with the characteristics of radially heterogeneous cores.

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## REPLY TO "COMMENTS ON 'AN AXIALLY HETEROGENEOUS CORE CONCEPT FOR LARGE LMFBRs AND ITS HCDA BEHAVIOR'"

In reply to the comments by Lake and Doncals[1] on our paper,[2] we would like to clarify our position by addressing their comments individually.

1. *Flatter axial power distribution and resulting lower peak burnup and fluence.* The steady-state fuel lifetime is mainly restricted by the bundle/duct interaction (BDI) and the duct/duct interaction (DDI) as well as the cumulative creep damage. Since the peak damage due to the BDI or DDI occurs in all fuel pins or ducts well below the core top, where the fast flux is much higher, the axially heterogeneous core (AHC) having inherently a lower peak fast flux is advantageous over the homogeneous core (HOC).

To estimate the cumulative creep damage of the cladding, the so-called cumulative damage fraction (CDF) is widely used. The CDF depends on the cladding temperature, fast fluence, and fission product (FP) gas pressure, and is usually maximized at the core top both in the AHC and the HOC. At the core top, while the AHC has almost the same cladding temperature as that of the HOC, and higher fast fluence (~8% for the AHC of 95-cm core height), as indicated by Lake and Doncals, than the HOC, the improved radial power peaking (~4%) of the AHC results in a smaller peak pin burnup leading to a lower FP gas pressure (i.e., the reduction in the cladding hoop stress), assuming the same gas plenum volume.

Fuel pin damage calculations using the CDF are based on the creep rupture correlation. Compared to the HOC, a higher fast fluence at the core top in the AHC is disadvantageous, but the smaller cladding hoop stress of the AHC is advantageous. Therefore, it does not necessarily follow that the fuel lifetime of the AHC is rather substantially reduced. In our paper, the gas plenum volume of the AHC is reduced due to its improved radial power peaking. However, it was demonstrated in our past calculations that the peak CDF of the AHC was far below the design limit (<1.0) under nominal operating conditions.

Consequently, we do not feel that a higher fast flux at the core top in the AHC definitely reduces the fuel lifetime when compared to the HOC.

2. *Smaller core volume.* To make a consistent comparison between the AHC and the multizoned HOC, we have several choices to determine how many core zones the HOC should have. From the viewpoint of the complexity of the fuel pin fabrication process, it appears that the AHC is favored; although the AHC has three types of core fuel assemblies, it has only a single enriched core fuel and this can simplify the fuel pellet fabrication in comparison with the three-zoned HOC (adding an internal blanket region to the core fuel pins does not complicate significantly the fuel pellet loading process). A three-zoned HOC needs three kinds of enriched core fuels as well as three types of core fuel assemblies. Therefore, we do not think a comparison between the AHC and the three-zoned HOC is necessary on this point.

We would like to note that Lake and Doncals confused driver core volume with core volume as presented in our paper. While the core includes both the driver core and the internal blanket, the driver core does not include the internal blanket. Since the power peaking factor (including the power generated in the internal blanket) of the AHC is ~4% smaller than the HOC, it is possible to reduce the core volume (driver core plus internal blanket volume) by this amount.

3. *Increased breeding ratio and optimum (minimum) doubling time.* Based on our parametric survey, the doubling time can be minimized by arranging the internal blanket such that its volume occupies 10 to 12% of the core volume. This ratio is almost independent of the fuel volume fraction, i.e., the core fuel pin diameter. The thickness and diameter of the internal blanket should, of course, be changed depending on the fuel pin diameter which changes the core volume.

Our past calculations also show that the nearly minimum doubling time is achieved by such an internal blanket configuration that the power peaking factor is minimized. It is therefore highly unlikely that the doubling time is minimized as the internal blanket thickness approaches zero, even when a larger diameter fuel pin is used.

It is not directly related to the higher breeding ratio of the AHC that it has a smaller burnup reactivity than the HOC. The AHC owes its smaller burnup reactivity to the preferential plutonium buildup in the internal blanket where the fissile material worth is high. This characteristic is almost independent of the fuel pin diameter, and the relationship of a smaller burnup reactivity of the AHC than the HOC still holds for a fuel pin diameter >7.4 mm.

The control rod worth becomes slightly lower in the AHC than in the HOC because of the lower flux in the internal blanket and harder spectrum in the driver core. The $^{10}B$ enrichment can be adjusted to meet the same shutdown margin as the HOC, while the control rod worth requirement in the primary control system is lower in the AHC due to a smaller burnup reactivity. For further information, see "Control Rod Worth and Related Nuclear Characteristics of Axially Heterogeneous LMFBR Cores" by Kawashima et al.[3]

4. *HCDA behavior*. Differing from the radially heterogeneous core (RHC), reactivity ramp rate at prompt critical in the AHC is reduced to about half that in the HOC, not because sodium voids generate incoherently, but because fuel/coolant interaction (FCI)-driven fuel motion and FCI-driven sodium-void reactivities are smaller compared with the HOC.

In the pessimistic hypothetical core disruptive accident analysis described in our paper, both AHC and HOC rapidly approach prompt criticality due to sodium-void reactivity insertion. Then, FCIs occur one after another in many channels within a very short period of time (<5 ms), causing FCI-driven fuel motion and FCI-driven sodium-void reactivities. Because of these reactivities, both cores become superprompt critical. Therefore, 70 to 80% of reactivity increase after prompt critical is caused by FCI. In other words, reactivity ramp rate is determined by FCI-driven reactivity increase.

According to SAS-3D calculations, in the case of the AHC, fuel motion and sodium-void reactivities account for 40 and 60%, respectively, of the FCI-driven reactivity. Of these, fuel motion reactivity is three times larger in the HOC than in the AHC. As for FCI-driven sodium-void reactivity, most FCIs in the HOC occur near the core midplane, while, in the AHC, FCIs occur over 10 cm above the internal blanket, i.e., 20 to 30 cm away from the midplane. Therefore, sodium-void coefficient at FCI positions is ~30% less in the AHC than in the HOC, as shown in Fig. 17 of the paper. After all, the FCI-driven reactivity (fuel motion reactivity plus sodium-void reactivity) in the AHC is about half that in the HOC.

It can thus be understood that reactivity ramp rate in the AHC is reduced to about half that in the HOC, because fuel worth distribution is axially flattened and because the sodium-void coefficient at the FCI positions is small compared with the HOC. This is shown in Fig. 15 of our paper.

Finally, although we did not directly compare the AHC with RHCs, we feel that the AHC is favored for the following reasons: (a) it is easy to design a compact core; (b) power distribution change due to burnup and control rod manipulation is less severe, and so is thermal stripping; and (c) large reactivity insertion due to control rods' motion is less likely to occur in a seismic event because of axially flatter neutron flux distribution.

We are very thankful to Lake and Doncals that they gave us useful comments on our work and this opportunity to discuss them.

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