



COMMENTS ON "AN AXIALLY HETEROGENEOUS CORE CONCEPT FOR LARGE LMFBRs AND ITS HCDA BEHAVIOR"

The recent paper by Inoue et al.¹ and others on the same subject list several advantages of axially heterogeneous (or parfait) liquid-metal fast breeder reactor (LMFBR) core designs. Among these advantages are (a) a flatter axial power distribution with a resulting lower peak burnup and fluence, (b) a smaller core volume, (c) increased breeding ratio and optimum (minimum) doubling time, and (d) decreased energy release in hypothetical core disruptive accidents (HCDAs). We would like to comment on each of these perceived advantages in turn.

1. *Flatter axial power distribution and resulting lower peak burnup and fluence.* Whereas it is true that the peak power density near the core midplane is reduced in the axially heterogeneous core, compared with a conventional homogeneous core, the power density, local fuel burnup, and fast neutron fluence are all *increased* at the core/upper axial blanket boundary (see Figs. 7 and 8 of Ref. 1). The top of the core is the region of highest cladding temperature and maximum cladding damage, so that the fuel lifetime is reduced rather substantially in the axially heterogeneous core. The reduction in fuel lifetime, and the associated increase in fuel cycle cost, is a rather strong negative consequence of this type of axial heterogeneity.

2. *Smaller core volume.* The reduction in core volume (height) in the subject axially heterogeneous core, maintaining the same peak linear power, appears to be the result of radial, as well as axial, power flattening. This radial power flattening is associated with comparing a three-radial-zone, axially heterogeneous core design (i.e., zones containing no midplane blankets near the outer core periphery, zones with 12-cm-thick midplane blankets, and zones with 22-cm-thick midplane blankets at the core center) with only a two-zone, enrichment-flattened, conventional homogeneous core. This is an inconsistent comparison. Had the conventional homogeneous core been further power flattened with the same three fuel enrichment zones, the peak power reduction attainable in the axially heterogeneous core would result mainly from the reduction in axial peaking (this is only ~4% from

Figs. 7 and 8). Since the volume of midplane blankets is ~11% of the core volume, the total axially heterogeneous core volume could in fact be 7% *larger* than the conventional power-flattened homogeneous core with the same peak linear power.

3. *Increased breeding ratio and optimum (minimum) doubling time.* The reason for the increase in breeding ratio in the axially heterogeneous core design is the relatively small (7.4-mm) fuel rod diameter employed in the conventional homogeneous core design. The addition of fertile material does indeed increase the breeding ratio in this design and result in a lower doubling time. However, this breeding ratio increase is not just a generic characteristic of axial heterogeneity, and a similar optimum doubling time could have been achieved by varying the fuel rod diameter in the conventional homogeneous core. It is of further interest to note that the internal blanket thickness optimization on p. 216 et seq. of the paper is a function of the fuel rod diameter, and the "optimum blanket thickness" approaches zero for larger fuel rod diameters.

The reduction in burnup reactivity observed by Inoue et al. is attributable, at least in part, to the higher breeding ratio in the axially heterogeneous core. It is therefore a consequence of the less-than-optimum fuel rod diameter (which is not a generic characteristic of axial heterogeneity) as well as the preferential relocation of breeding at the core midplane. Some attention should be paid to the magnitude of the changes in the control rod worths themselves. If the control rod worths are lower in the axially heterogeneous core, because of the higher average fertile material content or because of redistribution effects, this could result in a net reduction in the shutdown margin, even though the control rod excess reactivity shim requirements are slightly lower.

4. *Decreased energy release in HCDAs.* The proof that the energy release in a typical loss-of-flow-initiated HCDA is *generally* reduced in an axially heterogeneous core is not totally convincing in the subject paper. Nor is it obvious that the resulting HCDA energetics are sufficiently small in an axially heterogeneous core to be "acceptable" (in comparison with those obtained in a radially heterogeneous core, for example). The safety philosophy in the U.S. LMFBR program is that void incoherency (the time phasing of voiding in different parts of the core) is just as important as the magnitude

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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REFERENCE

1. K. INOUE, K. AZEKURA, K. KAWASHIMA, S. KOBAYASHI, and Y. WATARI, "An Axially Heterogeneous Core Concept for Large LMFBRs and Its HCDA Behavior," *Nucl. Technol.*, **63**, 215 (1983).

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

In reply to the comments by Lake and Doncals¹ 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.