Design Implications for a 19×19 PWR Fuel Assembly Based on Reactor Physics and Full-Core Fuel Performance Analyses

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1. Introduction

Nuclear power serves as a major energy source, owing largely to the high energy yield per unit mass of nuclear fuel. Consistent with this, light water reactor (LWR) fuel assemblies have evolved toward finer lattices, progressing from 14×14 to 15×15, 16×16, and 17×17 arrays, so that a larger number of rods of smaller diameter are accommodated within an assembly [1]. This progression has been enabled in part by advances in cladding materials and fabrication, which allow thinner cladding to be manufactured and operated reliably. A finer lattice increases the heat transfer area and lowers the linear heat generation rate (LHGR) at a given core power, thereby providing additional thermal and accident margin. Attempts have since been made to extend this trend further, adopting a 19×19 lattice to attain a higher core power density [2].

Adopting thinner rods requires several design aspects to be revisited, of which two are addressed here. First, a reduction in rod diameter simultaneously alters the pellet diameter, the cladding thickness, and the coolant volume, and hence the hydrogen-to-heavy-metal (H/HM) ratio; the rod geometry that optimizes fuel economy must therefore be identified. Second, although the power carried by each rod is reduced, the cladding also becomes thinner in absolute terms. The resulting change in fuel behavior should therefore be examined, in particular the rod internal pressure and the cladding hoop stress. In this study, these two aspects are examined for a 19×19 assembly through lattice calculations over a range of rod geometries and a full-core fuel performance analysis.

2. Methodology

The lattice calculations are performed with STREAM, a deterministic transport code that solves the two-dimensional assembly problem by the method of characteristics (MOC) [3]. The assembly depletion calculations over the range of rod geometries are carried out with this code, and for the geometry adopted in the core design the same calculations provide the assembly-homogenized few-group cross sections, tabulated as functions of burnup and of the local state variables. The front-end fuel cycle cost associated with each candidate geometry is evaluated from these depletion results with NuEcon, an in-house nuclear power plant economic analysis tool [4].

For the core-level analysis, the cross sections are passed to the three-dimensional nodal diffusion code RAST-K [5], which performs the core depletion and provides the power distribution and the cycle length. Pin-wise power histories are reconstructed from the nodal solution using the pin power form functions obtained in the lattice calculation, and are then transferred to the fuel performance code GIFT [6], which evaluates the rod internal pressure, the cladding hoop stress, and the other fuel design limits applicable to normal operation.

3. Results and Discussion

3.1. Rod geometry selection for fuel economy

Fig. 1 shows the quarter geometry of the 19×19 assembly modeled in STREAM. Twenty-eight guide tubes and a central instrumentation tube are employed. The assembly depletion calculations are performed with a uniform fuel rod enrichment, varied from 4.5 to 7.0 wt%, and without burnable absorbers. The pellet diameter is taken as the design variable of interest, ranging from 0.55 to 0.83 cm. The assembly pitch is held fixed at the value of a conventional 16×16 assembly of APR1400, so that the rod pitch is inversely proportional to the number of rods per side. The pellet–cladding gap is kept constant, and the cladding thickness is scaled in proportion to the rod outer diameter at a fixed thickness-to-diameter ratio of 0.06.

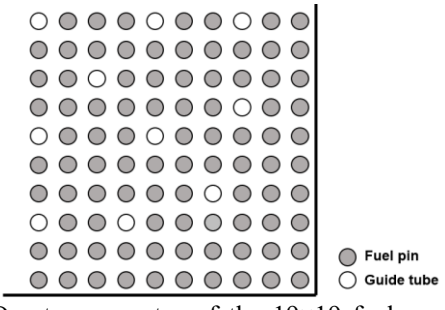


Fig. 1. Quarter geometry of the 19×19 fuel assembly used in the lattice calculation, comprising 332 fuel rods, 28 guide tubes, and a central instrumentation tube.

Fig. 2 presents the reactivity-limited burnup, defined here as the burnup at which k_{inf} falls to 1.0, as a function of pellet diameter and enrichment, three representative enrichments being shown. Because the assembly pitch is

fixed, the pellet diameter on the horizontal axis is in one-to-one correspondence with the H/HM ratio, as indicated on the upper axis. The pellet diameter that maximizes the reactivity-limited burnup shifts only slightly with enrichment, from 0.65 cm at 4.5 wt% to 0.63 cm at 6.5 wt%, corresponding to an increase in the optimum H/HM ratio from 4.5 to 4.9. The shift is toward a wetter lattice, since the higher fuel absorption makes the thermal utilization less sensitive to the moderator content, but it is small compared with the breadth of the maximum, over which the burnup varies by less than a few percent.

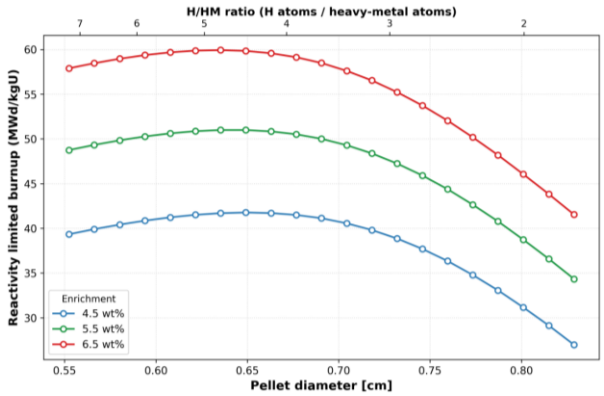


Fig. 2. Reactivity-limited burnup as a function of pellet diameter, shown for three representative enrichments. The upper axis gives the corresponding H/HM ratio.

This optimum, however, does not maximize the energy extracted from a single loading. Since the energy produced per assembly is the product of the reactivity-limited burnup and the heavy-metal loading, and the latter increases with the square of the pellet diameter, the two optima do not coincide. Assuming an axially uniform burnup over an active fuel length of 3.81 m, which corresponds to that of the APR1400, the energy per assembly shown in **Fig. 3** peaks at approximately 0.76 cm, well beyond the 0.63–0.65 cm range that maximizes burnup. The maximum burnup therefore does not imply the maximum energy extraction.

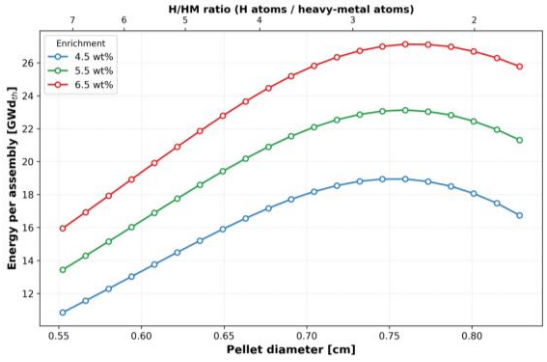


Fig. 3. Thermal energy produced per assembly as a function of pellet diameter and enrichment, evaluated for an active fuel length of 3.81 m under the assumption of an axially uniform burnup.

Figs. 4(a) and **4(b)** show, respectively, the separative work and the front-end fuel cost required per unit of thermal energy produced, evaluated with NuEcon. The latter comprises ore, conversion, enrichment, and fabrication. The fabrication cost is assumed to be charged on a per-assembly basis; since the number of rods per assembly is fixed by the lattice, it is taken to be identical for all geometries considered here. It therefore enters **Fig. 4(b)** as a fixed charge per assembly divided by the energy produced, and thus favors the larger pellet diameters that extract more energy from a single loading. A uranium ore price of 130 \$/kgU and a separative work cost of 120 \$/SWU were assumed. The solid black lines are iso-energy contours, denoting the combinations of enrichment and pellet diameter that yield equal energy production per assembly.

The shape of these contours follows directly from **Fig. 3**. For a given target energy, reducing the pellet diameter reduces the heavy-metal loading and must be compensated by a higher enrichment, so that the required enrichment falls as the diameter is increased. This compensation ceases at the diameter that maximizes the energy per assembly, near 0.76 cm; beyond it a further increase in diameter no longer adds energy, and the required enrichment rises again. Each contour therefore turns back on itself near 0.76 cm, and the two branches on either side of this turning point represent two distinct geometries that deliver the same energy per assembly.

The two quantities are not minimized at the same point on a given contour. Along the 18 GWd$_{th}$ contour, for example, the separative work per unit energy in **Fig. 4(a)** is smallest at the low-enrichment end of the contour, near 4.5 wt% and 0.70 cm, whereas the front-end cost in **Fig. 4(b)** is smallest at 5.0 wt% and 0.65 cm. The fabrication charge, being fixed per assembly, is constant along a contour and does not displace the minimum; the ore charge does, since the feed required per unit energy is itself minimized at a higher enrichment than the separative work is.

Tracing the minimum cost along each contour shows that the preferred combination changes with the target energy: for a target of 18 GWd$_{th}$ per assembly the cost is minimized near 0.65 cm and 5.0 wt%, whereas for 26 GWd$_{th}$ the minimum shifts to 0.67 cm and 7.0 wt%. These results indicate, first, that the geometry maximizing burnup is not the geometry giving the best economics, and second, that the preferred geometry must therefore be selected together with the intended cycle strategy rather than in isolation.

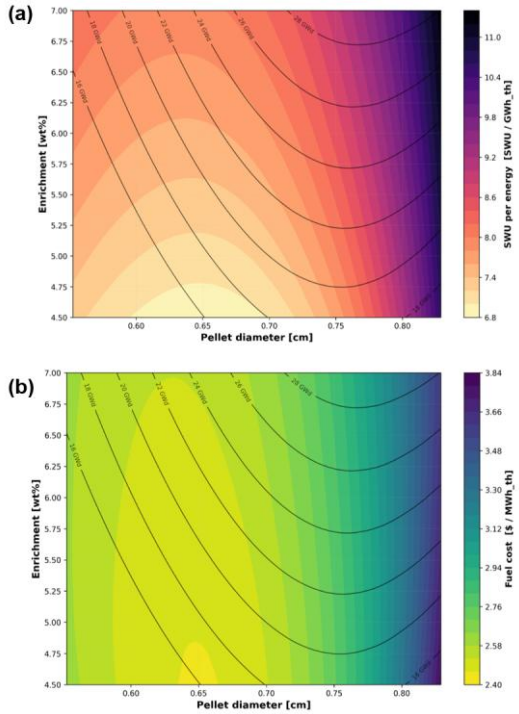


Fig. 4. (a) Separative work and (b) front-end fuel cost, comprising ore, conversion, enrichment, and fabrication, per unit thermal energy produced as a function of pellet diameter and enrichment. Solid black lines are iso-energy contours labeled in GWd_{th} per assembly.

3.2. Full-core coupled neutronics and fuel performance analysis

To evaluate the core and fuel performance attainable with the finer lattice, a 24-month cycle core was designed using 19×19 assemblies and compared with the 24-month 16×16 core of the APR1400 [7], taken here as the reference. The 19×19 core was constrained to retain the same number of assemblies and the same total thermal power as the reference core, and the pellet diameter was selected so that the total uranium loading is likewise preserved. The pellet diameter obtained under this constraint does not coincide with the fuel-cost optimum identified in the preceding section; it was adopted deliberately so that the two cores differ only in the lattice arrangement and not in fuel inventory or core rating, which allows the effect of the lattice refinement itself to be isolated.

The loading pattern of the reference core was retained for the 19×19 core, and the peaking factor limits and the target cycle length were confirmed to be satisfied for both cores. Pin-wise power histories were then reconstructed and supplied to GIFT for the 8,964 rods of the 19×19 core belonging to the unique assembly types that constitute the loading pattern; because the remaining assemblies are equivalent by symmetry, this set covers the full range of rod power histories present in the core. The same procedure was applied to the reference core. The results presented below are envelopes taken over all of these rods at each time step, so that each curve represents the most limiting rod for the corresponding parameter at that instant.

Fig. 5 compares the limiting fuel parameters of the two cores. Distributing the same core power over a larger number of rods lowers the maximum linear heat generation rate throughout the cycle (Fig. 5(a)), and the reduced rod power in turn lowers the maximum fuel centerline temperature by a substantial margin (Fig. 5(b)). This reduction propagates favorably to the remaining parameters. Since fission gas release is strongly temperature-dependent, the lower fuel temperature suppresses gas release and thereby reduces the maximum rod internal pressure (Fig. 5(c)). The smaller thermal expansion of the pellet also delays gap closure and mitigates the cladding hoop stress arising from pellet–cladding mechanical interaction; the transient peak that appears at the power ramp following refueling is markedly lower in the 19×19 core than in the reference core (Fig. 5(d)).

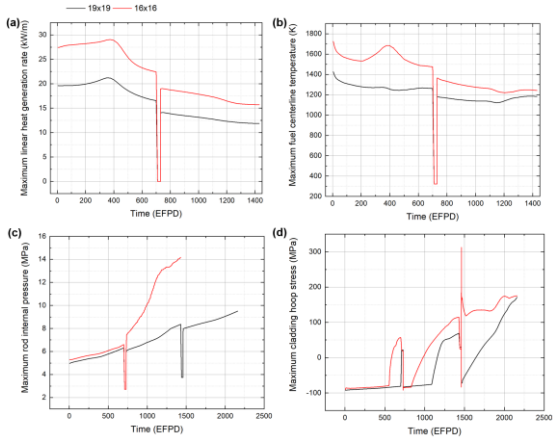


Fig. 5. Comparison of the maximum (a) linear heat generation rate, (b) fuel centerline temperature, (c) rod internal pressure, and (d) cladding hoop stress between the 19×19 core and the reference 24-month 16×16 core.

4. Conclusions

The design implications of adopting a 19×19 lattice in a PWR were examined from two perspectives: the rod geometry that optimizes fuel economy, and the fuel performance of the resulting thinner rod. At the lattice level, the figures of merit chosen determines the preferred geometry, and the figures of merit considered here do not share a common optimum. The pellet diameter maximizing the reactivity-limited burnup lies at 0.63–0.65 cm over the enrichment range considered and shifts only weakly with enrichment, the shift being small relative to the breadth of the maximum. The energy produced per assembly, by contrast, continues to increase up to approximately 0.76 cm, because the heavy-metal loading grows with the square of the pellet diameter and therefore faster than the burnup declines. The front-end fuel cost per unit energy introduces a third optimum that migrates along the iso-energy contours, from 0.65 cm and 5.0 wt% at a target of 18 GWd_{th} per assembly to 0.67 cm and 7.0 wt% at 26 GWd_{th}. The rod

geometry of a finer lattice therefore cannot be selected on neutronic grounds alone: the target energy to be extracted from a single loading determines which enrichment and which geometry are preferred, so that different target energies call for different combinations of the two.

At the core level, a 24-month cycle 19×19 core retaining the assembly count, thermal power, and uranium loading of the reference 16×16 core was evaluated, so that the two cores differ only in the lattice arrangement. Distributing the same power over more rods lowers the LHGR throughout the cycle and hence the fuel centerline temperature by a substantial margin. The lower temperature suppresses fission gas release, so that the maximum rod internal pressure of the 19×19 core remains below that of the reference core over the entire residence time. The smaller thermal expansion of the pellet also delays gap closure and markedly lowers the transient hoop-stress peak that accompanies the power ramp after refueling, although the hoop stress of the two cores approaches a comparable level toward the end of the residence time. For the parameters examined here, the finer lattice therefore does not degrade the fuel behavior in normal operation relative to the reference core.

Acknowledgement

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