Very high fuel burn-ups in light water reactors

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Historically, average fuel discharge burn-ups in light water reactors (LWRs) have steadily increased with time as technological developments have advanced. The practical limit is currently in the region of 50 gigawatt days per tonne of initial heavy metal (GWd/t). The main driving force behind this increase has been to reduce fuel cycle costs and to benefit from the increased operational flexibility that high burn-ups allow. The question is whether this trend will continue, or whether there are scientific and technological limits to LWR fuel burn-ups.

An NEA expert group has performed a technical assessment of very high burn-up fuel cycles in current light water reactors (LWRs), spanning a discharge fuel burn-up in the range between 60 GWd/t and about 100 GWd/t. The study assessed the impacts for the fuel cycle, for reactor operation and safety, and for fuel cycle economics. This article summarises the findings of the recently published NEA report[1].

Front-end of the fuel cycle

The single most important requirement to reach very high burn-ups is the need to relax the present 5.0% fuel enrichment limit that applies to current fuel fabrication plants and also to fresh fuel transport. This limitation is especially penalising for boiling water reactors (BWRs), since they use a heterogeneous enrichment distribution and the highest enriched fuel rods must be below the 5.0% limit.

The highest average fuel burn-up attainable within the 5.0% enrichment limit is approximately 65 GWd/t and this would have to be extended to about 8.0% to reach a burn-up of 100 GWd/t in pressurised water reactors (PWRs). However, to reach this burn-up, the maximum fuel rod enrichment in BWR assemblies will need to be higher (up to about 10%), because of the heterogeneous enrichment distribution used to counteract local flux peaking. Figure 1 illustrates the linear relation between initial enrichment and average discharge burn-up for various PWR fuel cycles; this clearly points to a maximum burn-up of 65 GWd/t at the 5.0% enrichment ceiling and correspondingly lower for BWRs, since the average enrichment will necessarily be lower than 5%. The increased fuel enrichments needed for higher burn-ups will significantly impact fuel fabrication plants as well as fuel transport.

Fuel management strategies and their impact on reactor core design and safety

The NEA study considered the implications of very high fuel burn-ups on in-core fuel management, as well as core design and the safety characteristics of a reactor. Although the particular details vary depending on reactor type (PWR, VVER or BWR), a VVER-440 reactor was used as an example to illustrate the following two fuel management strategies investigated:

- The first approach was to decrease the reload fraction, leaving the cycle length and reactor power unchanged. For example, the reload fraction could be reduced from one-third to one-quarter, so that the fuel residence time increases from three to four cycles. For a fixed cycle length, the discharge burn-up increases in inverse proportion to the reload fraction.

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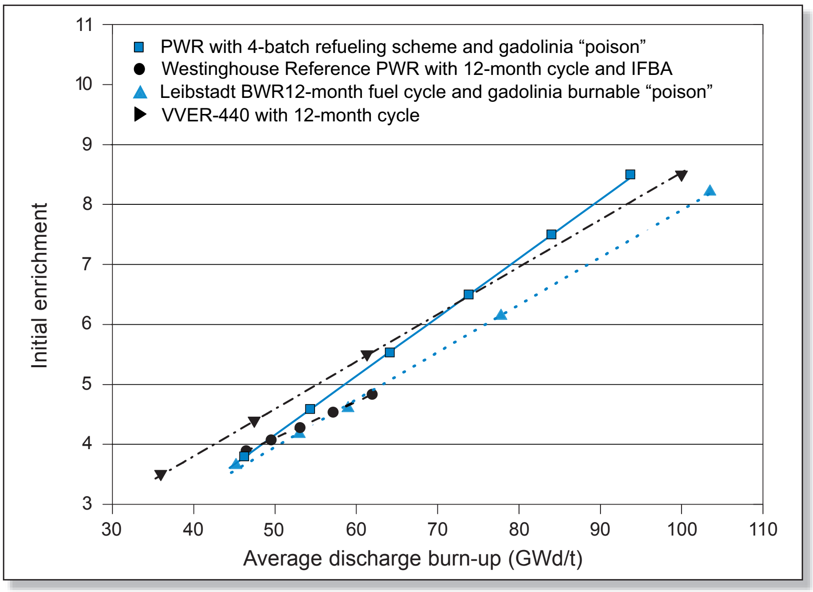
Figure 1. **Relation between initial fuel enrichment (percentage ^{235}U), as a function of average discharge burn-up**



- The other approach of increasing the cycle length while keeping the reload fraction constant could potentially provide a larger economic benefit. Assuming refuelling outage times to be the same, longer cycles imply higher capacity factors and therefore higher income from electricity generation. With this approach, the discharge burn-up increases in direct proportion to the cycle length.

Irrespective of the approach chosen, increasing the discharge burn-up requires higher initial enrichments. Because of the higher initial enrichment, both approaches significantly affect in-core fuel management and care is needed to ensure that the in-core parameters, particularly power peaking factors, reactivity feedback coefficients and shutdown margins remain within acceptable ranges. Higher discharge burn-ups can also be attained by uprating reactor power. If the reload fraction and the time elapsed during a cycle is kept the same, the burn-up increases in proportion to the uprating.

As regards core design and safety aspects for higher average burn-ups, when using high average ^{235}U enrichments in the core, it has been shown that:

- The moderator temperature coefficient becomes more negative.
- The boron coefficient becomes smaller in magnitude.
- There is a reduction in the control rod reactivity worths, causing a reduction in the shutdown margins.

These slightly unfavourable trends for nuclear design and safety parameters at very high burn-ups are mostly manageable, but work on experimental validation, as well as on the validation of nuclear data libraries and core design methods, needs to be extended to very high burn-ups.

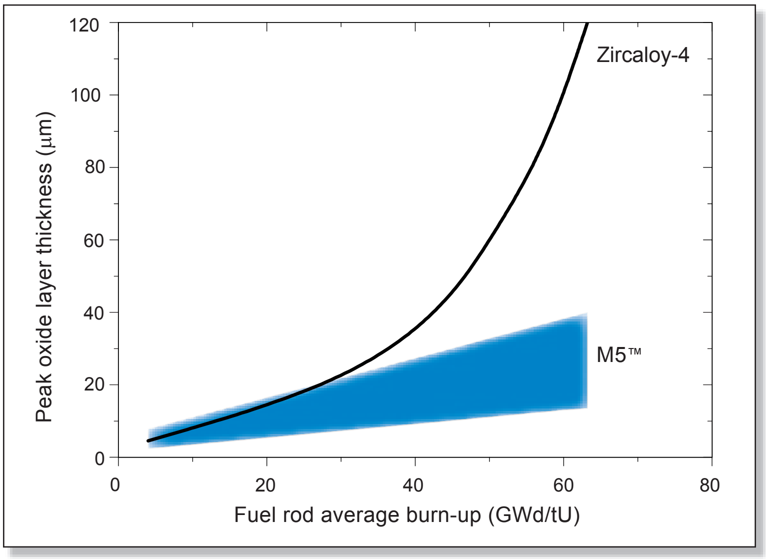
Concerning the irradiation of the reactor pressure vessel, it has been noted that low leakage loading patterns have been very effective in reducing pressure vessel fluences. However, at very high burn-ups there may be constraints in applying this pattern because of radial power peaking effects.

Issues related to reactor operation and thermo-mechanical performance of the fuel

The impact of very high burn-ups on reactor thermal hydraulics and issues related to the thermo-mechanical performance of the fuel has also been reviewed. In the case of thermal hydraulics, there is a need to develop a better understanding of the effects of corrosion, crud build-up and core axial and radial power distributions on the critical heat flux at higher burn-up, and to obtain measurements for high burn-up cladding. The accuracy of current steady state and transient temperature models needs to be verified at higher burn-ups and adaptations of assembly designs may be required.

All fuel thermo-mechanical behavioural aspects are affected at higher burn-ups, notably fuel pellet

Figure 2: **Maximum corrosion depth in M5 alloy compared to Zircaloy 4**



restructuring, gas release, cladding corrosion and dimensional stability. For example, recently developed cladding alloys have demonstrated considerable improvements in high burn-up corrosion resistance, as illustrated in Figure 2. As current fuel behaviour experience will no longer be valid at very high burn-ups, fuel behaviour codes will need to be extensively validated, possibly with new theoretical methods and costly irradiation trials to demonstrate satisfactory performance.

Back-end of the fuel cycle

The higher decay heat outputs and neutron emissions of very high burn-up fuels, due to an increased minor actinide inventory, have unfavourable implications for criticality assessments and spent fuel management, including transport, storage and reprocessing.

The isotopic compositions of uranium and plutonium degrade with higher burn-up, with possible repercussions for reprocessing plants that may necessitate changes of design and/or operating procedures. For example, the inventory of ^{232}U in irradiated fuel shows a steep increase with burn-up. This has an impact on the personnel dose in fuel fabrication operations, as the decay chain of ^{232}U contains an isotope (^{208}Tl) which emits very intense gamma rays.

The isotopic composition of plutonium recovered from very high burn-up fuels will be of a poorer fissile quality. This has particular implications for plutonium recycling as mixed-oxide (MOX) fuel in thermal reactors because a higher initial plutonium concentration will be necessary if the fissile quality is poor. Moreover, MOX fuels are restricted by a 12% total plutonium content to ensure that the void coefficient of the MOX assemblies does not become positive. The maximum average discharge burn-up attainable within this 12% plutonium limit is approximately 75 GWd/t, depending on the isotopic composition of the plutonium used. This is a potential future limitation on MOX recycling, which could possibly be circumvented using innovative designs.

An additional factor is the incorporation of high-level waste in glass, which in current plants is limited by neutron emissions. At very high burn-ups, the increased inventory of ^{244}Cm may reduce incorporation rates and lead to increased volumes of vitrified waste.

Although the radiotoxicity of the irradiated fuel, in sieverts per tonne of heavy metal (Sv/tHM), increases with higher burn-up, this does not account for the fact that each tonne of fuel generates a higher energy output at high burn-ups. The net effect is that the radiotoxicity of spent fuel is practically independent of burn-up when expressed in sievert per terajoule of electricity produced.

Interim storage of spent fuel is potentially an area where very high burn-up fuel could be very advantageous for a utility. A doubling of discharge burn-up would halve the volume of spent fuel accumulated over the lifetime of an LWR. However, the higher decay heat output and neutron emissions of high burn-up fuels will need longer cooling times. Hence, a doubling of the burn-up does not necessarily lead to a doubling of effective storage capacity, because the fewer number of assemblies discharged per year is offset by the increased cooling time.

There is a lack of knowledge as to whether the direct disposal of very high burn-up fuels in a geological repository may have an adverse impact on the subsequent long-term integrity and leach rates from the waste packages. The implications for any conditioning process to which spent fuel may be subjected prior to disposal are also unknown.

Economics

Although there may be some countries in which back-end concepts and strategies are already established and where flexibility for increasing burn-ups may be limited, for the majority of LWR utilities the motivation for adopting very high burn-up cycles is potentially very strong. In some circumstances, very high burn-ups may reduce fuel cycle costs and this is very important for utilities; fuel cycle economics is an area where a utility can directly influence costs and many utilities, particularly those operating in a competitive market, are under very strong cost-competitive pressures.

For many utilities, direct fuel cycle cost reductions may play a secondary role to reducing spent fuel arisings. Many utilities operate with rigid operating constraints, such as limited spent fuel storage capacity, that need careful management to maximise their plant's operational lifetime. For utilities in this position, potential reductions in spent fuel arisings with very high burn-ups may be the key to maximising generating revenue over their plant's lifetime and may therefore equate to a very large economic benefit. Very high burn-ups also allow a utility increased flexibility in choosing an optimal combination of cycle length and refuelling fraction, potentially yielding significant economic and operational benefits.

For very high average discharge burn-ups in the range of 60 to 100 GWd/t, the fuel cycle cost assessment has not shown a clear-cut economic incentive. The case for continued increase in burn-ups is only clear with an undiscounted economic model, and then only under the assumption that back-end unit costs do not rise too steeply with burn-up. Discounted economic models show a benefit from increased burn-ups only with an optimistic relation between initial enrichment and average discharge burn-up (in which the cycle length is constant and the refuelling fraction decreases), and with back-end unit costs that are independent of burn-up. Since there is no single economic model that applies to all utilities, depending on the local circumstances, some countries or utilities may see a benefit in very high burn-ups while others may not.

Conclusions

Attaining very high burn-ups will necessitate technological developments in almost every aspect of the fuel cycle. Most of these are considered achievable if there is sufficient incentive to go to higher burn-ups. Future progress towards very high burn-ups can be expected to be made in small incremental steps, just as has happened historically. However, there are several technological barriers to very high burn-ups. The most significant is the 5% criticality limit that currently applies in fuel fabrication plants. Relaxing this limit is not just a technological issue, but will also require significant investment decisions by fuel fabricators. The successful relaxation of this limit to, say, 6 or 7% may determine the highest practical average discharge burn-ups that will eventually be attainable.

Other technological areas where further development will be required for very high burn-ups include fuel assembly design, fuel assembly materials, in-core reactor physics behaviour and fuel thermo-mechanical behaviour. There are also implications for the back-end of the fuel cycle. Where a once-through fuel cycle is chosen, there may be implications from the higher decay heat output and neutron output of irradiated fuel assemblies on transport and/or interim storage. For a reprocessing cycle, the elevated decay heat and neutron outputs are likely to have significant technological ramifications. More specific recommendations regarding future technological directions are given in the NEA report.

The economics part of the study has highlighted a complicated situation, where some utilities might see definite cost benefits with very high burn-ups, and others seeing a less clear benefit. The economics versus burn-up dependence is in a very fine balance, with opposing effects almost cancelling each other out. In these circumstances, small differences specific to individual utilities can tip the balance against or in favour of high burn-ups. At this stage, it has not been possible to make any definitive conclusions and it will be necessary to see how fuel vendors and other fuel cycle service providers respond commercially to utility demand for higher burn-ups. ■

Note

1. NEA (2006), *Very High Burn-ups in Light Water Reactors,* OECD/NEA, Paris.