The Uranium Institute

Twenty-Third Annual Symposium
10–11 September 1998: London

Perspectives on LWR Fuel Development

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Developments in LWR fuel design have for many years served the utilities in their efforts to reduce operating costs while maintaining high reliability and safety standards. The priorities have shifted over the years and are expected to continue to do so. The external and internal factors driving these developments will not stop changing.

Currently, deregulation of the electricity markets in Europe and the USA is driving electricity utilities to reduce operating costs. The fuel cycle cost is significant, ranging from 0.4 to 1.3 US cents / kWh depending mainly on the back end alternative (reprocessing or direct disposal) chosen. The different components of total fuel cycle costs (FCC) are approximately illustrated in Figure 1. The fact that back end costs are excluded from the direct disposal route does not mean that the costs are zero, but rather that they are paid for per kWh produced, and it is thus not possible to reduce them by developments in fuel design.

The fuel suppliers are contributing to cost savings through the development of improved and more cost efficient products, aimed at reduced requirements for uranium feed, enrichment, or waste handling and disposal. This process is illustrated for ABB BWR fuel in Figure 2. However, the need for further fuel development has become increasingly obvious due to the changes in electricity

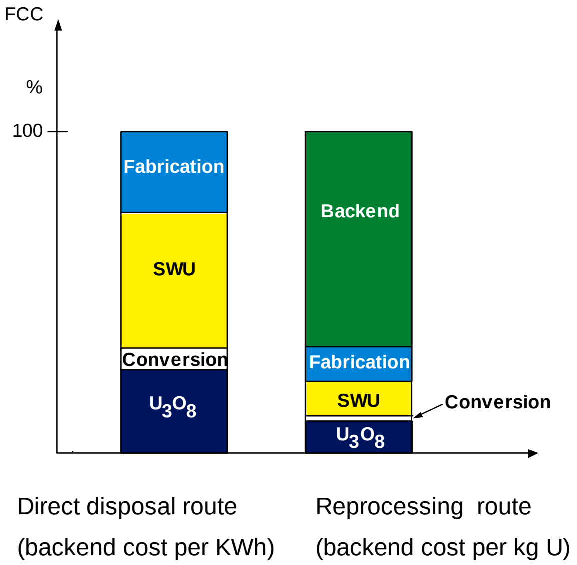


Figure 1. Components of fuel cycle cost which can potentially be reduced by fuel design developments.

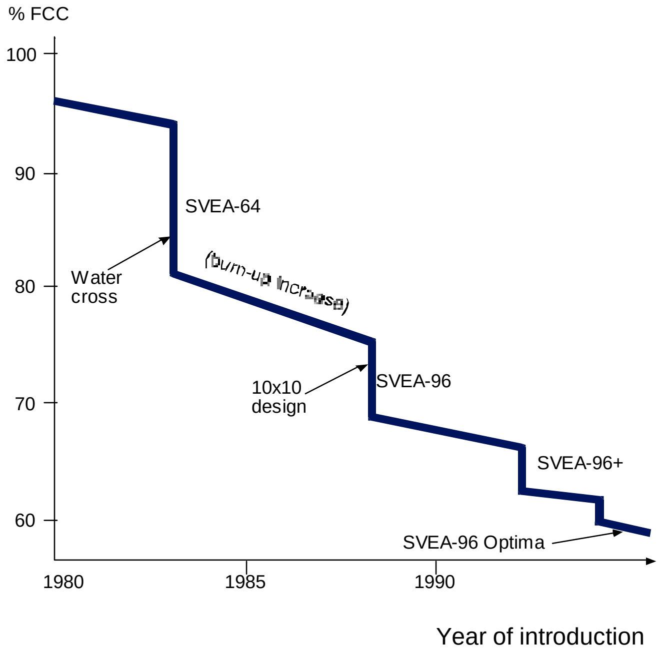
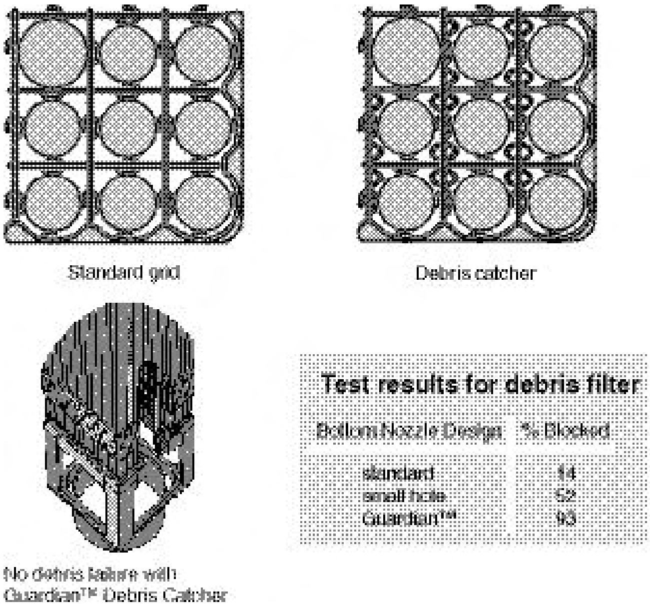


Figure 2. Total fuel cycle cost reduction through introduction of improved ABB BWR fuel designs.



Test results for debris filter

Bottom Nozzle Design	% Blocked
standard	14
small hole	52
Guardian™	93

Figure 3. The Guardian debris filter design for ABB PWR fuel.

markets that are currently taking place.

Another obvious way of reducing costs for utilities is to reduce prices for fuel fabrication services. In Europe as well as in the USA there is a significant overcapacity for fuel fabrication. Factories for fuel fabrication are capital intensive and the fixed cost may range up to 50% of the total fabrication cost. As the fuel fabrication cost contains the cost for product development, there is a risk that fuel suppliers may be forced to reduce their development expenditure due to the price pressure on their services.

The understanding that fuel product development is aimed at reducing electricity prices, and not primarily at reducing the cost of fuel fabrication services has, however, been the driving force behind the development efforts of ABB. Cost-cutting efforts are nevertheless in focus for many development programmes at ABB. The recent and future developments which ABB is undertaking to meet the challenges of deregulated electricity markets are discussed below.

Fuel Reliability

Fuel reliability is deemed as the most important characteristic of fuel by most utilities. In order to sustain a high fuel reliability, of less than one failed fuel rod in 10 reactor operating years (corresponding to about one failed fuel rod in one million rods), which is the present goal of ABB, an efficient root cause analysis programme has to be sustained. Each failed rod is normally inspected in the pool of the reactor or in a hot cell. The cost of such an investigation is considerable. One single hot cell examination may easily cost US$1 million, or 10% of the cost of fabricating a reload for a reactor.

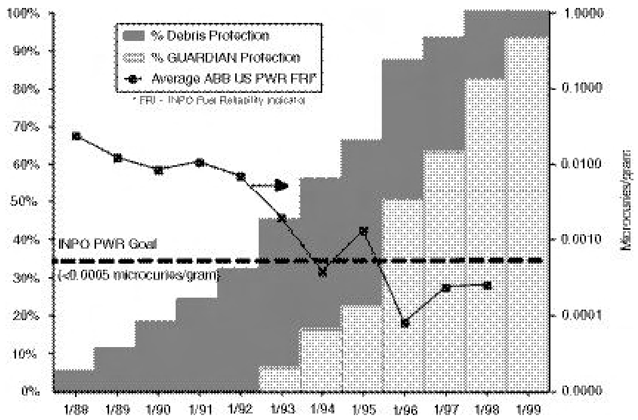


Figure 4. Improvement of ABB PWR fuel reliability upon introduction of the Guardian debris filter.

Today the totally dominating failure cause for ABB fuel is related to debris entering the reactor core from other systems, such as the turbine in a BWR or a steam generator in a PWR, after a maintenance shut down. Therefore present ABB fuel designs are equipped with filters at the inlet of the fuel assemblies. However, a totally "debris-tight" filter is not desirable, especially in BWR fuel bundles. BWR fuel bundles have channels to prevent cross-flow of coolant and steam, and thus the risk of a complete sealing off of a filter during adverse conditions can not be tolerated. On PWR fuel a very efficient filter is the ABB Guardian (Figure 3), the introduction of which has contributed to a great improvement in fuel reliability (Figure 4).

For BWR fuel, ABB Atom has applied a defence-in-depth strategy in its development. This includes, in addition to a robust debris filter, the development of fuel resistant to secondary degradation failures. It is known that once a primary pinhole has occurred on any operating fuel pin and water enters through it, secondary degradation starts. Such secondary degradation in a single pin may release significant amounts of radioactive products into the primary system of the reactor, even though the primary failure itself would only would release totally insignificant quantities. ABB Atom has therefore developed a fuel design, now under testing, in which such secondary degradation will not occur.

The evolution of fuel designs has, however, resulted in surprises in the area of fuel reliability. For PWR fuel, current problems such as bundle bow, cladding corrosion and fluid elastic vibration instabilities are examples. For BWR fuel, various

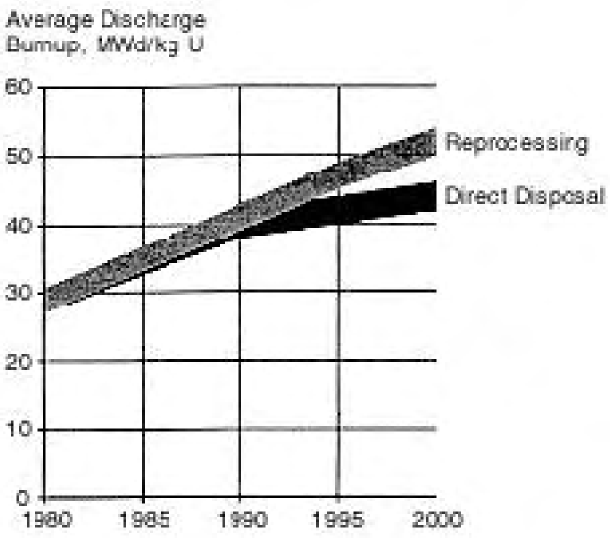


Figure 5. The evolution of design discharge burnup of BWR fuel in Europe.

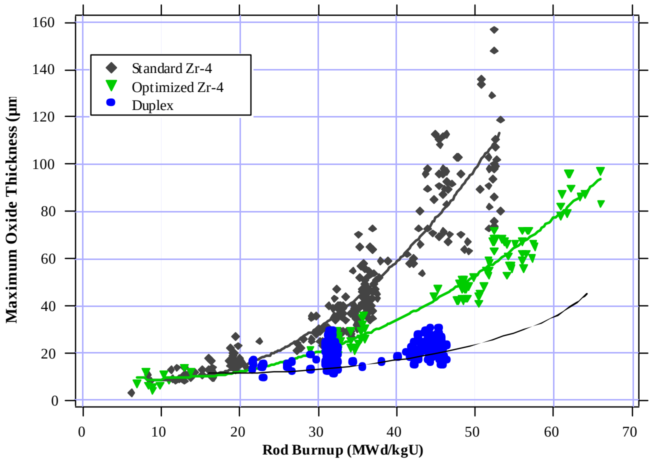


Figure 6. Corrosion of three different ABB PWR clad materials.

types of cladding corrosion phenomena caused by newly introduced regimes of water coolant chemistry are corresponding examples. Thus, a continued fuel failure root cause analysis programme will probably continue to be needed in the future. As the traditional source of financing (i.e. the fuel fabrication price) of such investigations is currently shrinking, the industry needs to find other business solutions.

Increased Burnup

In several countries the back end cost for fuel is proportional to the amount of fuel consumed in a reactor, instead of the amount of electricity produced by the reactor. This back end cost may be more than 50% of the total fuel cycle cost. An obvious way of reducing cost is therefore to increase the discharge burnup of the fuel by higher enrichment. This gradual increase of design burnup has been going on for several years (Figure 5).

A higher discharge burnup means a longer residence time in the reactor, and thus material limitations need to be observed. Improved materials such as Optimised Zircaloy and Duplex claddings have therefore been introduced. The corrosion of these materials compared with standard Zircaloy cladding is shown in Figure 6.

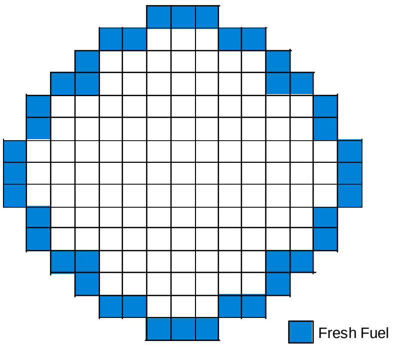
Another consequence of increased discharge burnup is that the reload batches become smaller (as each assembly stays longer in the core of the reactor). The number of fresh, highly reactive fuel bundles in the core is thereby reduced. To reduce the reactivity of these assemblies, in order to keep the specified shut down margin, burnable absorbers are traditionally used. With fewer fresh assemblies containing these burnable absorbers, an even dispersion in the core is more difficult to achieve.

Thus, other means of reducing local high reactivity need to be developed. Such a design, the SVEA-96 Optima, has recently been introduced by ABB Atom for BWR reactors. In this design some of the fuel rods in the assembly have been shortened and been given a larger rod diameter. By this design a discharge burnup of more than 55 MWd / kgU is achievable while still not exceeding the 5% U-235 enrichment level to which most licences in transportation and fabrication in the nuclear industry are limited. Licensing activities for fuel with this burnup are in progress.

Improved Fuel Utilisation

Improved fuel utilisation can be achieved by improved core loading through low leakage loading patterns (LLLPs). The traditional way of doing this is to load the oldest and most burnt-up fuel (which has the lowest reactivity) at the core periphery, thereby improving the neutron economy. Most of the power will then be generated at the centre of the core. In Figure 7 such a loading pattern for a 900 MWe PWR is illustrated, as well as a less economical out-in loading pattern (OILP).

A consequence of LLLPs is that the fuel needs to be able to sustain a higher power. The higher enriched fuel for higher burnup is a further reason for this requirement. In BWRs the critical power ratio (CPR) is therefore improved. Figure 8 illustrates the improvements in CPR achieved by the new BWR designs introduced by ABB Atom


Out In Loading Pattern (OILP)

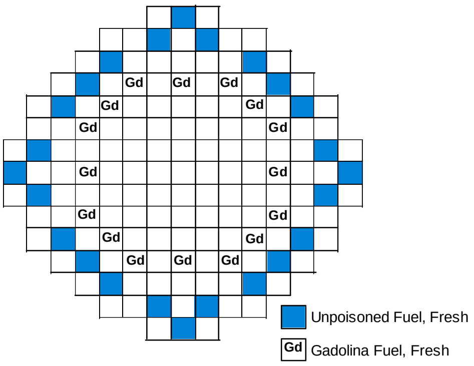

Low Leakage Loading Pattern (LLLP)

Figure 7. Two fuel loading patterns used in 900 MWe PWRs.

over the years. A 10% improved CPR can be translated into 2% less fuel consumption or a corresponding reduction in enrichment.

LLLPs also require that other safety margins, such as those imposed by the criteria for loss of coolant accidents (LOCAs) and shut down margin, are maintained. The thermal limitation in a PWR is the "departure from nucleate boiling" (DNB). Modern ABB fuel in the USA and Europe is designed for superior DNB performance. Most PWRs are limited in local power of the core by the LOCA criteria. This currently limits the power peaking allowed.

The methods originally used to analyse LOCAs were regulated by the US Nuclear Regulatory Commission (NRC) in 10CFR50 Appendix K to provide sufficient margins. Since the late 1980s the NRC has allowed more realistic methods to be used in such analysis, provided that the basis and methods can be verified against experiments. Therefore software development is being done in order to increase the allowed power peaking factors and consequently to allow more efficient loading patterns.

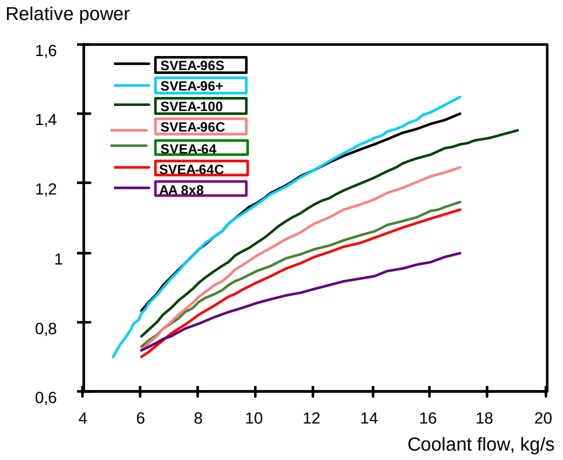


Figure 8. Improvements in critical power ratio (CPR) for different ABB BWR fuel designs.

Each new fuel design needs to be verified for thermal capability (CPR or DNB) in a range of operational modes and power distributions. In recent years, ABB Atom has made a significant investment in a new facility for doing such tests.

While there is a natural limit for how much the fuel cycle cost can be reduced by increasing burnup (due to the 5% enrichment limit), still better loading patterns may be found, provided fuel with suitably increased enrichment properties is available. The drive for further development in this area is evident. Experience is that new fuel designs are readily accepted by the utilities, as illustrated by Figure 9.

Plant Uprating, Long Cycles and Flexibility

One of the most efficient ways to improve the competitiveness of nuclear power is to uprate the reactors. Figure 10 illustrates the uprating performed on ABB-built BWRs and PWRs.

For the fuel, an uprating means that the core must produce more power. With less emphasis on low leakage loading (discussed above), the core may simply be designed so that the extra power is produced at locations close to the core periphery, sacrificing some neutron economy. For a fuel designer this translates into the same requirements as discussed in connection with LLLPs.

Moving to longer cycles is another way to improve plant capacity factors. This mode of operation is particularly challenging for the reactivity control system. The development of burnable absorbers included in the fuel has given the flexibility needed. Within the ABB group two different burnable absorbers are in use, the traditional gadolinium (Gd) for both BWRs and PWRs, and erbium (Er) for PWRs. The latter has

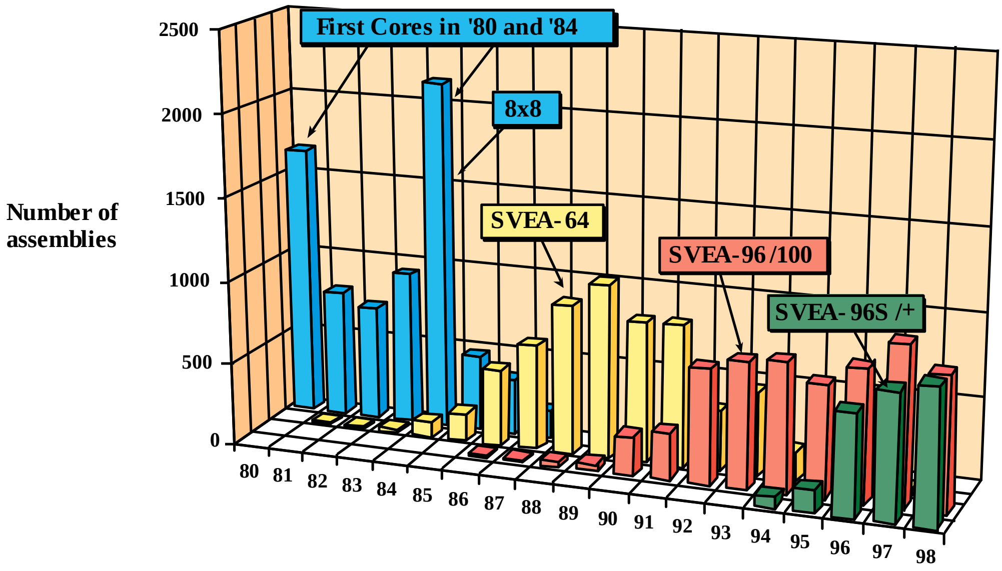


Figure 9. Deliveries of different types of BWR fuel by ABB, showing the introduction of new designs.

been introduced in the USA for PWRs operating on very long (two year) cycles. Erbium has a lower absorption cross-section than gadolinium, as is illustrated in Figure 11.

The cross-section of Er is temperature dependent, giving a higher neutron absorption at higher neutron temperatures. This helps in PWR core designs as it provides a contribution to the requirement of having a negative moderator temperature coefficient. Er also has the advantage of not impacting the peaking factors as much as Gd. On the other hand, Gd gives less penalty from non-burning or slow-burning isotopes, the existence of which requires extra enrichment of U-235. The burnable absorber design can thus be refined even more, depending on specifics of cycle length, burnup and power peaking restrictions. This can add up to a significant saving in total fuel cycle costs.

Flexibility can mean different things to different utilities. One type of flexibility is in cycle length. If, for some reason, it becomes desirable to shorten an ongoing cycle, and at the same time to prolong the upcoming cycle (for instance, in order to have reloading during the normal season the following year), core design work may become difficult (see Figure 12). The reason is that the reload for the upcoming refuelling, which will now be used for a long cycle, will contain too few fresh fuel assemblies and as a consequence too

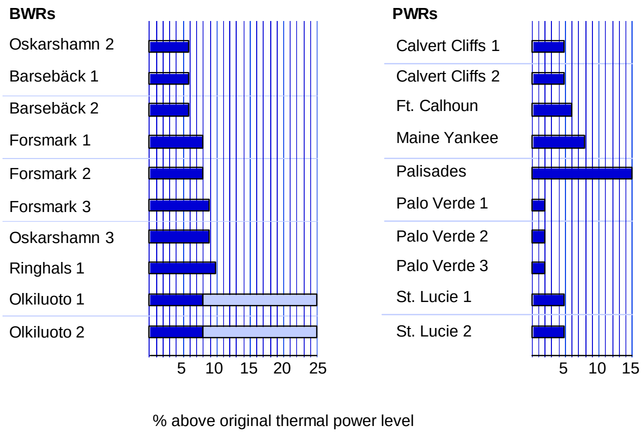


Figure 10. Power uprating performed at ABB-built reactors (including that still in progress at Olkiluoto, shaded) (% above original thermal power level).

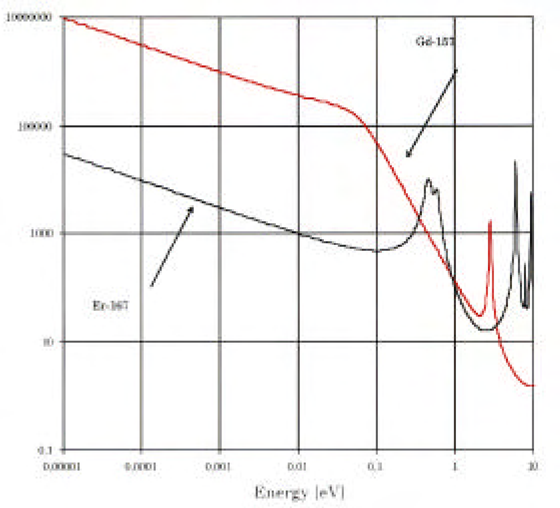


Figure 11. Nuclear absorption cross-sections of erbium (Er) and gadolinium (Gd).

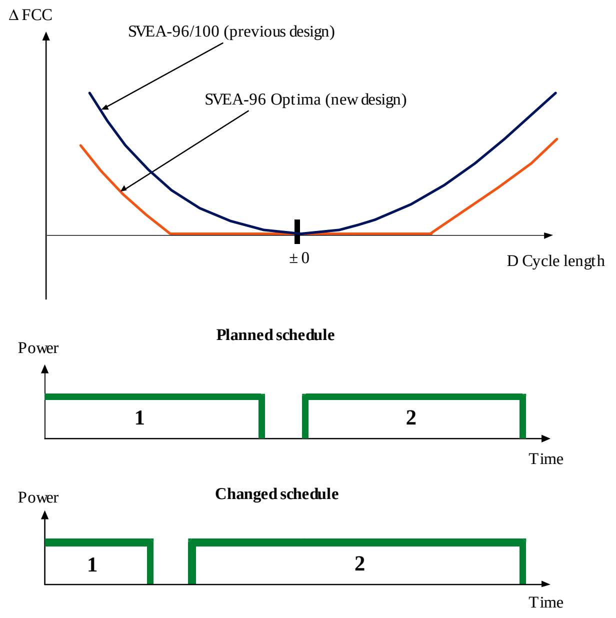


Figure 12. Illustration of cycle length flexibility. The upper figure illustrates impact on fuel cycle cost (FCC). The lower pictures illustrate the originally scheduled and changed cycle lengths.

few gadolinium rods. Therefore it may be difficult to maintain the shut down margin in the core design. Figure 12 illustrates this phenomenon and the difference between two ABB BWR fuel designs.

Another flexibility is load following requirements, i.e. the ability to follow the demand for electricity on the grid. This requirement leads to a fuel product that has to withstand rapid power changes. ABB has for that purpose developed so-called “liner fuel” in which the cladding inner surface has a liner that protects the cladding from rupture during the chemical and mechanical loads applied to it by the expanding fuel pellets during power increases. This has been standard for many years in BWRs and is being considered also for PWR applications.

In a deregulated electricity market it can be foreseen that even more flexibility will be required in the fuel. Utilities may want to operate nuclear power plants in the same manner as gas fired or hydro plants, and produce power when the demand and prices are high. It is foreseen that further development may be needed in the area of improved flexibility.

Conclusions

Fuel design development is an efficient tool in supporting utilities ’efforts to reduce operating costs. Although nuclear fuel designs have undergone tremendous improvement during the past 30 years, there is still a large development potential. The price for fabricating fuel assemblies is only 10–25% of the total fuel cycle cost, but determines the requirements for uranium feed and enrichment, and the amount of waste produced. Thus, it is vital for the nuclear industry that the current fierce competition in the fuel fabrication market does not lead to a halt in fuel development, but to a recognition that continued development efforts involving suppliers and nuclear utilities is in the best interests of the industry.