

EFFICIENCY IMPROVEMENT OF NUCLEAR POWER PLANT OPERATION: THE SIGNIFICANT ROLE OF ADVANCED NUCLEAR FUEL TECHNOLOGIES

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ABSTRACT

Due to the increased liberalisation of the power markets, nuclear power generation is being exposed to high cost reduction pressure. In this paper we highlight the role of advanced nuclear fuel technologies to reduce the fuel cycle costs and therefore increase the efficiency of nuclear power plant operation. The key factor is a more efficient utilisation of the fuel and present developments at Siemens are consequently directed at (i) further increase of batch average burnup, (ii) improvement of fuel reliability, (iii) enlargement of fuel operation margins and (iv) improvement of methods for fuel design and core analysis.

As a result, the nuclear fuel cycle costs for a typical LWR have been reduced during the past decades by about US\$ 35 million per year. The estimated impact of further burnup increases on the fuel cycle costs is expected to be an additional saving of US\$10 – 15 million per year. Due to the fact that the fuel will operate closer to design limits, a careful approach is required when introducing advanced fuel features in reload quantities. Trust and co-operation between the fuel vendors and the utilities is a prerequisite for the common success.

INTRODUCTION

For a number of years the power producers' market has been experiencing far-reaching changes worldwide. Increasing liberalisation of the power markets is resulting in fiercer competition in sectors, which were once monopolies for power producers. Existing surplus capacities are compounding this pressure on prices.

Nuclear power generation in particular is being exposed to high cost reduction pressure. This is being caused by the improved efficiency of fossil-fuelled power generating plants and by stagnating decreasing of fuel prices. The cost situation is being further burdened by the high expenditures for licensing, monitoring and the establishment of reserves, and by plant depreciation. Therefore, cost reduction in nuclear power generation is the common goal of the utilities and their suppliers.

Nuclear fuel cycle costs account for 25-40% of the total power generation costs, as illustrated in Fig. 1 (Goll, 1999). Although the cost of nuclear fuel fabrication only amounts to around 10% of the fuel costs, advances in nuclear fuel technology are the key factor to cost savings and efficiency enhancement in the entire nuclear fuel cycle. Further developments in nuclear fuel technology are focused therefore not only on the reduction of fuel fabrication costs but primarily on the by far greater savings potential which can be tapped in the uranium supply sector, and in the management and disposal of

spent fuel. Here, the trend in development is clearly being dictated by the more efficient utilisation of fuel, so that significant savings can be achieved via the contingent volume effect.

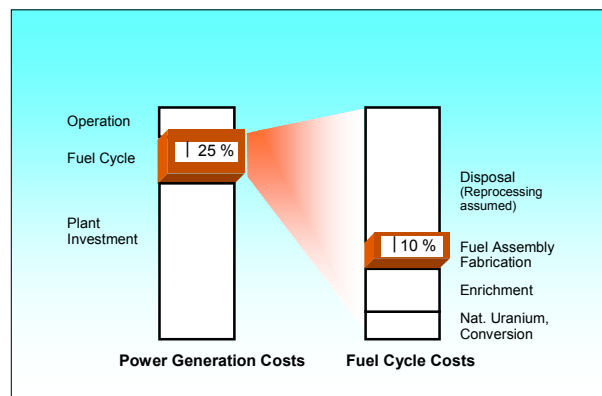


FIGURE 1. Splitting of power generation costs for a German 1300 MWe PWR plant

In this context, further developments must be implemented within the existing boundary conditions. Account should be taken on the fact that, in the last few decades, both plant operation and fuel supply have already been largely optimised. As a result of this optimisation, nuclear fuel has been incorporated into a highly networked

system comprising the requirements for smooth, economical plant operation and safety-related boundary conditions. The economic benefit derived by further technical development within this system has to be verified by addressing all necessary effects. Only in this way can it be ruled out that not only subsystems are optimised.

At Siemens, the HTP (High Thermal Performance) and FOCUS fuel assembly product lines for PWRs and the ATRIUM 10 product line for BWRs are the bases for further fuel cycle cost reduction. Fig. 2 shows these successful fuel assembly types. The modular conceptual design of these product lines allows their insertion in practically all lattice geometries used worldwide for these reactor types.

Present developments focused on the reduction of fuel cycle costs are directed at

- further batch average burnup increase,
- improvement of fuel reliability,
- enlargement of fuel operation margins,
- improvements of methods for fuel design and core analysis.

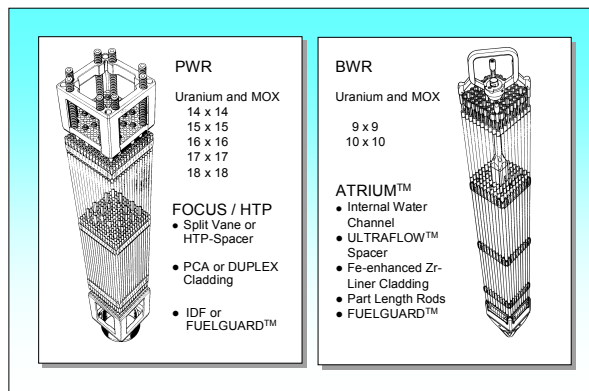


FIGURE 2. The product lines FOCUS and HTP for PWRs and ATRIUM for BWRs

BURNUP INCREASE

Most of the savings in fuel cycle costs have been achieved by the continuous extension of discharge burnup. The average discharge burnup for Siemens fuel assemblies has increased over the last fifteen years to about 52 MWd/kgHM, for the complete discharge PWR batch with the highest burnup. The value for BWR is slightly less at 44 MWd/kgHM. The fuel assemblies that will be discharged over the next several years are either already in operation or are in the detailed planning stage. Therefore reliable predictions can be made regarding the burnup for discharge batch with the highest burnup. This allows a discharge burnup forecast in 2005 of 55 MWd/kgHM for PWRs and 50 MWd/kgHM for BWRs as illustrated in Fig. 3 (Lettau, 1998; Gross, 1998).

In the long term it appears feasible to increase the enrichment up to 5w/o U-235 (i.e. 4.95w/o taking into account tolerances). This enrichment represents a

licensing limit in fabrication and could probably be overcome only with considerable effort. This limit would allow an average discharge burnup of approximately 67 MWd/kgHM for PWRs using annual cycles. Owing to the various enrichment levels in a BWR fuel assembly, an average fuel enrichment of around 4.6 w/o is to be considered, leading to a batch average burnup of about 62 MWd/kgHM.

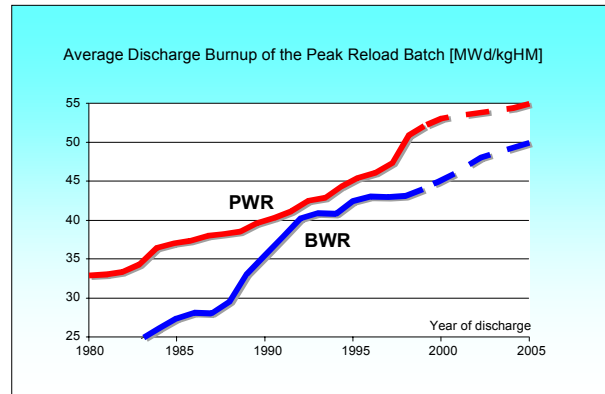


FIGURE 3. Continuous increase of discharge burnup for Siemens fuel assemblies

Taking into account the burnup distribution inside one discharge batch as well as inside a single discharged fuel assembly, maximum fuel rod burnup in the range of about 75 MWd/kgHM for both PWRs and BWRs is expected. The technical challenges posed by this increased burnup are to be treated with detailed investigations of the fuel behaviour under both normal and accident conditions.

The requirements that have to be fulfilled are mainly related to the corrosion and hydrogen pickup of the clad, the high burnup properties of the fuel and the dimensional changes of the fuel assembly structure. Clad materials with increased corrosion resistance have been developed which promise to be appropriate for the discussed burnup range. The high burnup behaviour of the fuel has been extensively investigated and can be described, with good accuracy, in fuel rod computer codes. Advanced statistical design methods have also been developed. Materials with increased corrosion resistance are helpful in controlling the dimensional changes of the fuel assembly structure. In summary, most of the technical questions for the fuel operational behaviour and reliability in the discussed burnup range have been solved or the solutions are foreseeable. This is also acknowledged by regulators.

The main licensing challenges for high burnup fuel are currently seen in the area of accident condition analyses, especially for RIA and LOCA (Gross, 1999). One major open question is, if and how far experimental results for accident conditions can be extrapolated above the burnup covered by experiments. This open question might slow significantly the future rate of fuel burnup increases.

Cladding Material

It was recognised many years ago that the corrosion resistance of standard Zircaloy (Zry) is insufficient for the demands of increased burnup. Zry variants with increased corrosion resistance have been developed as well as other Zry-based alternative clad materials. The current Siemens standard materials for PWR cladding are the DUPLEX and the optimised Zircaloy-4. For BWRs Siemens is using LTP2 and the Fe-enhanced liner cladding. Today, the improved corrosion resistance of these clad materials yield lower corrosion thickness compared to those used several years ago, even though the burnup has significantly increased over this time. Furthermore, alternate clad materials like Zirconium-Niobium alloys have also been developed by Siemens and have been inserted in lead assemblies in several plants. A sound irradiation experience with various operating conditions is a prerequisite for insertion of reload quantities in the future.

Fuel Behaviour

Aiming at higher target burnup, the in-pile fuel performance might affect the major fuel rod design criteria. The requirements for further fuel development are seen as a low fission gas release, good dimensional stability and improved transient behaviour of the fuel.

The behaviour of the fuel at high burnup has been intensively examined experimentally as well as theoretically. The experimental examinations are partly based on the insertion of lead fuel rods that have been irradiated to a burnup up to 105 MWd/kgHM, which is far above the range of normal operation. Hot cell examinations have been completed for a fuel rod burnup of 90 MWd/kgHM, with the peak pellet burnup correspondingly higher. This provides a good database for the validation of our fuel rod code.

In summary it can be stated that high burnup effects are modelled very well in the current version of our fuel rod code. This was also acknowledged in 1998 by the German reactor safety commission on the basis of a status report on high burnup submitted to the commission by the German utilities. The report was presented by Siemens.

FUEL RELIABILITY

Higher power ratios and longer irradiation time of the fuel assemblies have led to ever increasing demand in terms of fuel reliability. Optimum fuel utilisation and the associated cost reduction are possible only if the fuel assemblies can be operated reliably without failures up to their target burnup. To achieve this, the development efforts are focused on:

- the improvement of fuel structure stiffness,
- the design of fuel assemblies with reduced vibration sensitivity and fretting free fuel rod support,
- controlled manufacturing processes.

Fuel Structure Stiffness

During the last few years, control rod drop time problems were reported from different nuclear power plants and different fuel vendors and thus received considerable attention. Subsequent investigations indicated 'C'-shaped and 'S'-shaped bow of fuel assemblies resulting in control rod impediment. Excessive axial forces from hold-down device, flow force and weight, together with design deficiencies, were found to be the root-cause of the problem.

Siemens fuel assemblies were not directly affected. Nevertheless we have reviewed the information gained through our wide operating experience with special attention to the design features relevant to fuel assembly bow. In particular the detailed evaluation of the existing measurements of control rod clusters drop time led to the conclusion that there is no impact as a function of burnup or number of insertion cycles up to 54 MWd/kgHM in German PWRs and for Siemens fuel assemblies in third party plants.

Fretting

Two failure mechanisms occur by fretting: debris fretting, and fretting between fuel rods and the spacer grid support structure. As an important provision in avoiding debris fretting, a debris filter in the fuel assembly bottom end piece is normally implemented for all Siemens HTP, FOCUS and ATRIUM 10 fuel assemblies. This protective measure has contributed significantly to the reduction of the number of fuel failures caused by debris fretting.

In order to understand the interaction between vibration excitation of fuel assemblies and fretting of fuel rods in the spacer grids, Siemens has established a new fretting test methodology illustrated in Fig. 4. The fretting behaviour of different fuel rod support types has been investigated on the basis of realistic wear characteristics possible in reactor operations. First, an integral fuel assembly test is performed in a test loop. The resulting fuel rod vibration is then simulated in a single fuel rod test using a segment of the fuel rod to be investigated.

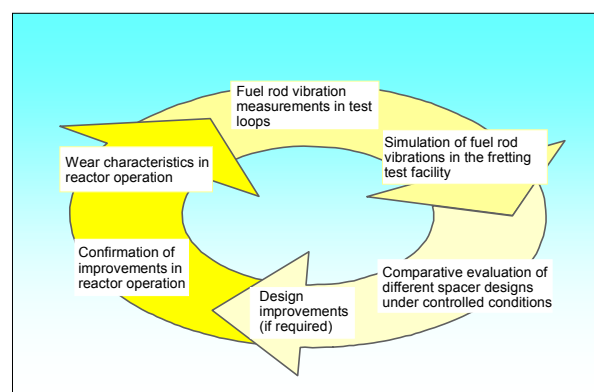


FIGURE 4. The new fretting test methodology

This procedure makes it possible to evaluate and compare the behaviour of different spacer designs under controlled operating conditions. Design improvements can then be derived which improve the fretting behaviour of the fuel rod support.

Statistical Process Control

The continuous improvement of the product and process quality is a permanent issue at Advanced Nuclear Fuel GmbH (ANF), the fuel manufacturer of Siemens. The enhancement of automation along with the implementation of the Statistical Process Control (SPC) is the key factor to achieve higher reliability of fuel and efficiency in all phases of the production processes (Dietrich, 1999).

Since the systematic introduction of the SPC, ANF has been working on pilot projects that demonstrate the capabilities and achieved benefits. The realisation of the concept requires the set-up of new manufacturing devices in order to provide information and data necessary as input for the SPC.

Manufacturing by the SPC requires a detailed knowledge about the different processes to provide the necessary input data for the closed control loops. The feedback of the process/product parameters provides the ability for adjustment of the processes to meet the nominal value of specified product characteristics. The focus of production will be more on review of the process than on the examination and inspection of the product characteristics. The statistical data collected can also be used for optimisation of the design.

Examples of application at ANF are the pellet, spacer, tube, cage and fuel rod fabrication processes. In the future the SPC will be applied to the entire scope of the manufacturing process at both ANF GmbH and its sub-suppliers.

LARGER FUEL OPERATION MARGINS

Due to the cost reduction pressure, more and more power plants now operate at higher power levels and make an extended use of low leakage loading. This requires improvements of the fuel assembly thermal-hydraulic behaviour, especially in the area of spacers. In order to achieve this, the mixing behaviour of the spacer itself must be improved. Additional margins can be gained using additional devices, so called intermediate flow mixers, to achieve the required thermal-hydraulic performance.

Thermal-hydraulic Performance of the ULTRAFLOW Spacers

To increase the thermal-hydraulic design margins, an advanced spacer design called ULTRAFLOW (see Fig. 5) was developed for the ATRIUM 10 fuel assembly design and qualified by means of an extensive critical power testing. With the introduction of swirl vanes, which

redirect the up-streaming water droplets from the centre of the subchannel to the fuel rod surfaces to improve cooling, significant increases have resulted in the achievable critical power level. Through suitable design and fabrication methods, the pressure drop across the spacer was maintained at a low level. Due to the use of low temperature processed Zircaloy material, this spacer fulfils all applicable criteria at high burnups.

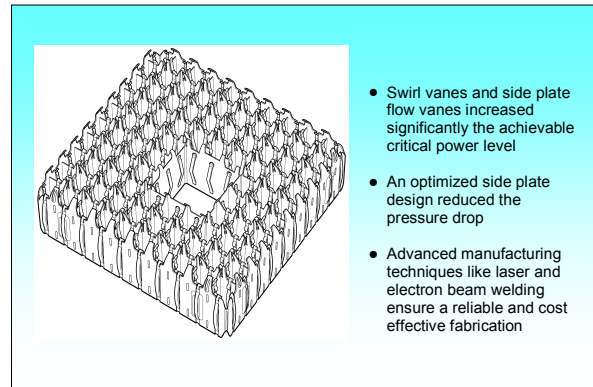


FIGURE 5. The ULTRAFLOW spacer for ATRIUM 10 fuel assemblies

Intermediate Flow Mixers Improve DNB Margins

Intermediate Flow Mixers (IFMs) can be placed at the mid-span of the last three to five spacer spans within the heated length of a PWR fuel assembly in order to increase the coolant mixing through the region most susceptible to departure from nucleate boiling (DNB), thus effectively delaying the onset of DNB. The number of IFMs required is based upon both the thermal-hydraulic customer requirements for DNB performance and hydraulic compatibility.

The HTP/IFM fuel design provides increased thermal margin resulting from improvement in DNB performance while allowing higher radial peaking. The 17x17 and the 15x15 "HTP only" design have been found to have DNB performance comparable or superior to any of the competing state-of-the-art designs. With the addition of three IFM spacers to this base design, the DNB performance has been demonstrated which allows for a power increase of at least 10%. Hence, the addition of IFMs provides substantially increased margin to limits. The DNB performance can be improved, a reduced core neutron leakage can be achieved, the fast neutron flux at the reactor vessel walls can be reduced and therefore the fuel cycle costs are decreased.

METHODS FOR FUEL DESIGN AND IN-CORE FUEL MANAGEMENT

One of the issues resulting from the advances in fuel technology is that the reactor core designs become

increasingly complex with more and more heterogeneity being introduced into the core. Examples of innovative design features are the use of Gadolinium, the extended use of reprocessed materials (MOX and reprocessed Uranium) and advanced low-leakage loading strategies. Taking into account all the requirements – i.e. economic benefit combined with safety-related and licensing aspects –, this gives a crucial role to the methods and codes for fuel design and core analysis. In particular the challenging demands of the last decade for higher power peaking, extended burnup and increased fuel recycling have to be met with the same level of overall plant safety as before.

In developing our new codes for fuel rod and core design, the extension of the application range and the improvement of the prediction accuracy were of primary importance. To focus on fuel cycle cost reduction without sacrificing the accuracy, further developments are driven by the following strategies:

- Integrated code systems for reactor core design and safety analyses,
- Intensified application of the statistical design methodology,

as illustrated in Fig. 6.

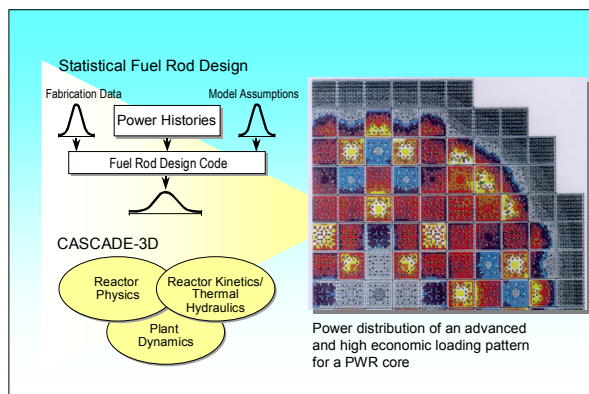


FIGURE 6. New design methodologies and integrated code systems

Integrated 3D Code System

Advances in the fields of computer hardware and software technology – manifested most strikingly by ever-increasing calculation speeds and improvements of the user interfaces – now make it possible for large code systems to be directly coupled to each other. This means that previously separated areas of analysis – such as reactor physics, thermal hydraulics and systems dynamics – can now be integrated with the aim of considerably increasing simulation accuracy by eliminating conservative assumptions at code interfaces.

As an example, the new program system CASCADE-3D (Core Analysis & Safety Codes for Advanced Design Evaluation) links some of Siemens advanced code packages for core design, core monitoring and safety analysis (Van de Velde, 1999). Consequently, by using

CASCADE-3D, the potential of modern fuel assemblies and in-core fuel management strategies can be much better utilised because safety margins, which had been reduced due to conservative methods, are now predicted more accurately.

Statistical Fuel Rod Design

Another important improvement has been achieved by applying statistical methods to fuel rod design calculations (Heins, 1999). The expected fuel rod behaviour – under both normal and accident conditions – can be described more realistically by taking into account the scattering of fuel as-fabricated data and code modelling parameters. This approach allows, for example, the determination of the LOCA fuel failure fraction with a reasonable degree of conservatism and higher prediction accuracy by explicitly taking into account the individual power histories of all fuel rods in the core. This has become possible thanks to the integration of the coupled fuel rod design and LOCA codes into CASCADE-3D.

HIGHER RELIABILITY AND REDUCED FUEL CYCLE COSTS

The global operating experience of Siemens fuel totals 9.96 million fuel rods, which represents more than 77000 fuel assemblies. Siemens has supplied fuel to a total of 107 power reactors in 14 countries in Europe, the Americas and Far East. This total includes first core and reload fuel for reactors built by Siemens as well as reload fuel for a large number of reactors built by other suppliers. At the end of 1999, a total of 63 power plants (34 PWRs, 29 BWRs) operated with Siemens fuel in the core, including 35 power plants (27 PWRs, 8 BWRs) operating with nearly full core of Siemens fuel.

As it can be seen in Fig. 7, the percentage of reactor cycles operated without any failures has increased significantly for both reactor type since the seventies, although the demands on the fuel have been intensified by higher fuel assembly power and longer irradiation times in the reactor. For both reactor types about 80% of the reactor cycle are operated without any fuel failure. From 54 LWR plants operated with at least 10% Siemens fuel in core in 1999, fuel failures were observed in three BWR plants and height PWR plants. It has to be pointed out that the fuel failure situation during the last several years was dominated by incidences with an increased number of failed rods in only a few reactor cycles.

Especially the Siemens BWR fuel showed outstanding performance and achieved with a combined total of 4 failed rods an annual rod failure rate of 0.6×10^{-5} in 1999. Moreover, since 1993, the annual fuel failure rate is scattering in the range $0.5-1.0 \times 10^{-5}$. For PWR plants the annual failure rate in 1999 was 1.5×10^{-5} , but more than half of all failures (18 failed rods) occurred in one plant. The root cause of those failures is still under investigation.

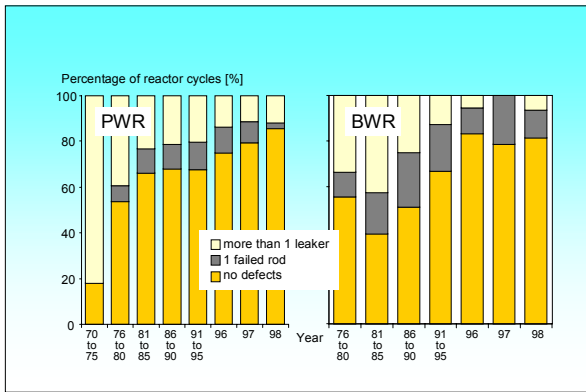


FIGURE 7. Significant improvement of Siemens PWR and BWR operational performance

Conclusion and Outlook

During the past decades the nuclear fuel cycle costs for a typical LWR have been reduced by about US\$35

million per year thanks to the continuous advances in nuclear fuel technology (see Fig. 8). Highlights of this development are the replacement of Inconel with Zircaloy as spacer and guide tube material, the transition to low-leakage core loads on the basis of the development of Gadolinium absorbers, and the Siemens advanced product lines FOCUS and HTP for PWRs, and ATRIUM 10 for BWRs, with a burnup potential of 60 and 50 MWd/kgHM, respectively.

The estimated impact of further burnup increases on the fuel cycle costs of nuclear plant operation is expected to be an additional saving of about US\$10-16 million per year. The exact amount depends mainly on the backend costs and the cost model application (see Fig. 9). Due to the fact that the fuel will operate closer to design limits, a careful approach is required when introducing advanced fuel features in reload quantities. A trustful co-operation between fuel vendors and the utilities is a prerequisite for the common success.

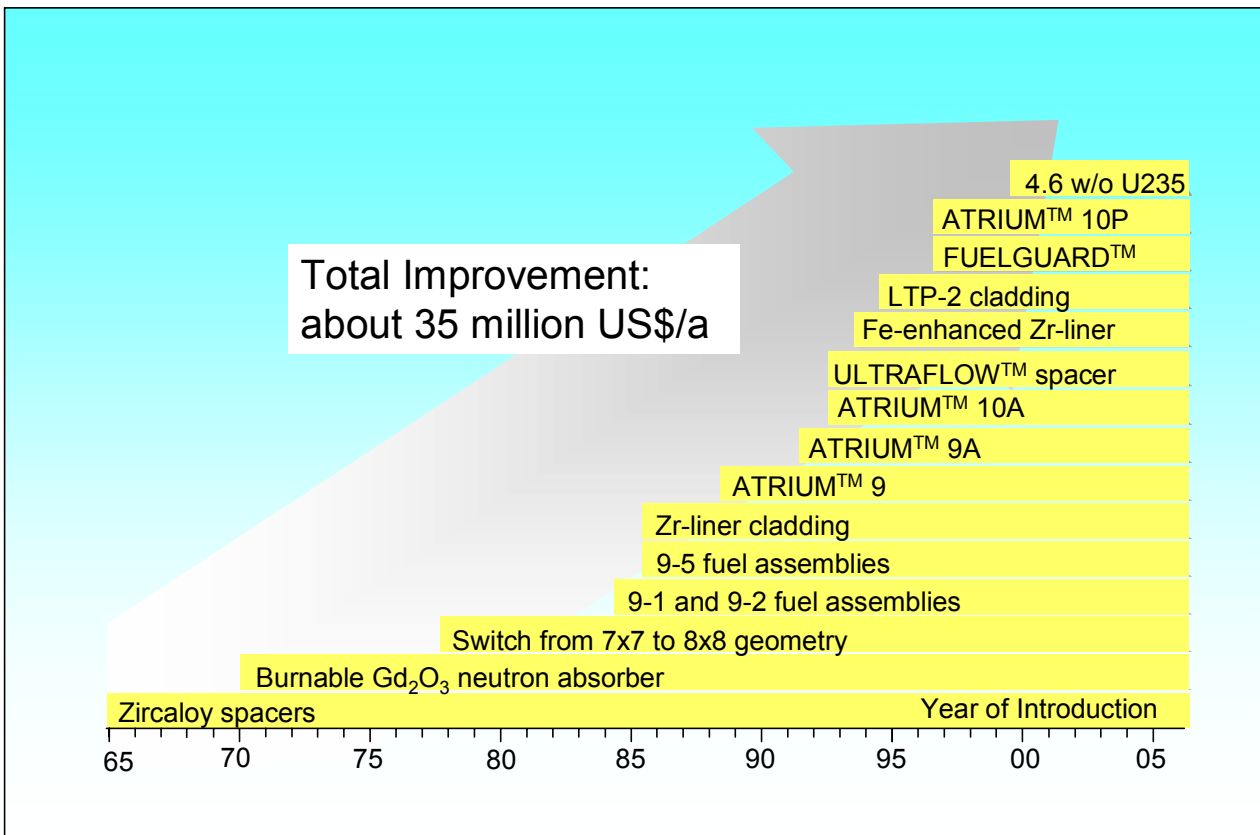


FIGURE 8. Continuous advances in fuel technology led to annual cost savings of about US\$ 35 million (example: BWR fuel)

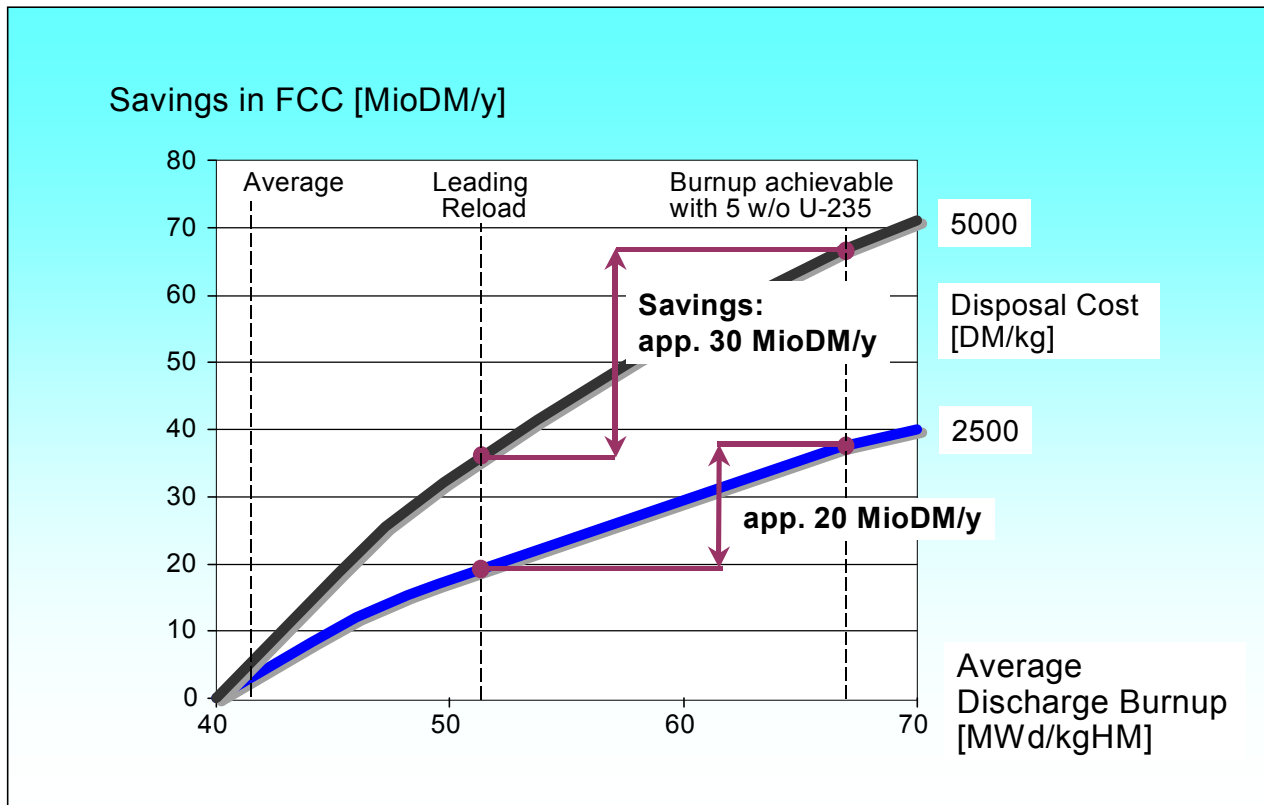


FIGURE 9. Future savings in fuel cycle costs by increasing burnup (example: 1300 MWe PWR, annual cycle)

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