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Contribution of Advanced Fuel Technologies to Improved Nuclear Power Plant Operation

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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.[1] This is being caused by the improvement in the efficiency of fossil-fuelled power generating plants and by stagnating or reduction of fuel prices. In addition, 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 (see Figure 1).[2] Although the cost of nuclear fuel fabrication only amounts to around 10% of the fuel costs, the key to cost savings and efficiency enhancements in the entire nuclear fuel cycle lies in advancement of nuclear fuel technology. Further developments in nuclear fuel technology are therefore focused 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.

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 basis for further fuel cycle cost reduction. Figure 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.

Burnup Increase

The achieved savings in fuel cycle costs through continuous development work have been, for the most part, due to extending 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 fuel is slightly less at 44 MWd/kgHM. The fuel assemblies which 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 (see Figure 3).[3,4]

In the long term it appears feasible for enrichment to increase to 5w/o U-235, that is, taking into account tolerances, 4.95w/o. This enrichment represents a licensing limit in fabrication and could probably only be overcome with considerable effort. This limit would allow an average discharge burnup of approximately 67 MWd/kgHM to be achieved in an annual PWR cycle. Owing to the various enrichment levels in a BWR fuel assembly, an average fuel enrichment of around 4.6w/o is to be considered, leading to an batch average burnup of about 62 MWd/kgHM.

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 normal conditions and accident conditions.

The requirements which 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.[5] 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 possibly slow significantly the future rate of fuel burnup increases.

Cladding Material

It was recognised many years ago that the corrosion resistance of standard Zircaloy is insufficient for the demands of increased burnup. Zircaloy variants with increased corrosion resistance have been developed as well as other Zircaloy-based alternative clad materials. The current Siemens standard PWR clad materials are the Duplex clad and optimised Zircaloy-4. For BWRs Siemens is using LTP2 and the FE-enhanced liner cladding.

Today, the improved corrosion resistance of these clad materials yields 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. In Figure 4 examples of the lead programme for PWR and BWR cladding are shown. 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 which 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, providing a good data base 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, and this was also acknowledged in 1998 by the German reactor safety commission when a status report on high burnup was given to the commission by the German utilities. The report was presented by Siemens.

Fuel Reliability

Higher power ratios and longer in situ time of the fuel assemblies have led to ever increasing demand for the reliable utilisation of reactor fuel. 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, as a global vendor of fuel assemblies with much operating experience, was not directly affected. Nevertheless we have reviewed information gained through our experience with special attention to the design features relevant to fuel assembly bow in two steps. A detailed analysis of the existing experience of control rod clusters drop time measurements and of the fuel assembly design parameters relevant for the sensitivity to fuel assembly bow were evaluated.

The evaluation of the measured 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 of different vendors.

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 (see Figure 5).

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 (see Figure 6). The fretting behaviour of different fuel rod support types has been investigated on the basis of realistic wear characteristics possible in reactor operations. As a first step, an integral fuel assembly test is performed in a test loop. During this test the fuel rod vibration, which results from the given flow through the fuel assembly, is measured and recorded.

As a second step, the simulation of the fuel rod vibration is performed in a single fuel rod test using a segment of the fuel rod to be investigated. The operation conditions can be simulated in an autoclave under high pressure and temperature. For the excitation of the fuel rod, a magnetic system simulates the vibration characteristics which have been measured in the integral fuel assembly test.

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

Advanced Nuclear Fuel GmbH (ANF), the fuel manufacturer of Siemens, is continually working to improve product and process quality. The enhancement of automation along with the implementation of the Statistical Process Control (SPC) is the major task in achieving higher reliability of fuel and efficiency in all phases of the production processes.[6]

Since the systematic introduction of the SPC, ANF has been working on pilot projects which demonstrate the capabilities and achieved benefits. The realisation of the concept, therefore, 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 also used for optimisation of the design.

The implementation of SPC is performed in three phases. First, the manufacturing process is analysed and visualised to determine the process characteristics and the influencing parameters (human resources, machine, material, methods, environment). The current equipment used in manufacturing is checked for its basic capability to deliver data and co-operate with process control. As a second phase, the process is reviewed in order to achieve the quantitative and qualitative correlations between process parameters and product characteristics. Common and well-known methods like FMEA, DOE, etc. are used in this phase. The third phase represents the definition of the control loops (as base input for SPC) and its implementation into the manufacturing process. Examples at ANF are the pellet, spacer, tube, cage and fuel rod fabrication processes. In the future SPC will be applied to the entire scope of the manufacturing process at both ANF GmbH and its sub-suppliers.

Enlargement of Fuel Operation Margins

As a result of the changes in the electricity markets, more and more power plants are operating at higher power levels with an intensified level of low leakage loading. The demands of higher power levels are related to necessary improvements in the fuel element 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 Ultraflow Spacers

To increase the thermal-hydraulic design margins, an advanced spacer design called Ultraflow (see Figure 7) was developed for the BWR Atrium fuel assembly design and qualified with the aid of extensive critical power testing. With the introduction of swirl vanes, which redirect the upstreaming 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.

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 has 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 an increase in power 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

The development of new fuel assembly design methodologies and in-core fuel management methodologies was focused in the past on the continuous improvement of the prediction quality of the design codes used. As understanding of the relevant physical parameters was increased, the design codes for fuel rods, fuel assembly structure, thermal-hydraulics, reactor physics and transient analysis have also been improved. Further code development was also driven by innovative fuel design features like the use of gadolinium, extended use of reprocessed materials (MOX and reprocessed uranium), and advanced low-leakage loading strategies (see Figure 8).

At present, for each technical area involved, a consolidated status has been achieved by these continuous development efforts, which have increased the prediction quality of the codes. As a result, the challenging demands of the last decade for higher power peaking, increased burnup and fuel recycling, have been met with the same level of overall plant safety as before.

While the detailed achievements described for the physical and technological parameters in fuel design and in-core management analysis led to a convincing prediction quality increase, further developments focused on fuel cycle cost reduction are required to apply new methods. Two strategies are currently being pursued:

- intensified application of the statistical design methodology;
- integrated code systems for reactor core design and safety analyses.

Statistical Fuel Rod Design

A successful example of the increased application of statistical design methodologies is its use for fuel rod calculations.[7] The expected fuel rod behaviour can be described more realistically by taking into account the scattering of fuel as-fabricated data and code modelling parameters. A series of calculations using a fuel rod code is normally performed to determine the distributions of the design results and compared with the limits of the corresponding design criteria. For each calculation the important input data, which show a scatter, are varied. Each calculation gives a single value for all investigated items. The superposition of all results of a series of calculation constitutes the distribution.

As a first step, the statistical distribution of the varied input data is determined. The as-fabricated data, such as fuel rod and pellet diameter, plenum and dishing volumes or fuel density, are constructed as Gaussian distributions. Their expected value is equal to the mean value of the tolerances of the fabrication value and the standard deviation is assumed to be one sixth of the tolerance width, based on fabrication experience. The distributions of the modelling parameters (i.e. fission gas release, densification/swelling, cladding creep behaviour, radial relocation, etc.) are based on the validation data base of the fuel rod code. For each model and each measured value, one individual modelling parameter is determined. The superposition of all those parameters is fitted by an appropriate theoretical distribution function to account for the finite sampling size of the validation data base.

On the basis of those distributions and an appropriate set of power histories, Monte Carlo analyses with a fuel rod code are performed. This allows the determination of the resulting distributions with sufficient statistical certainty.

The statistical fuel rod design allows, on the basis consistent treatment of the statistical input data, the realistic description of the fuel rod behaviour under normal and accident operation conditions. By this, the margins for plant operation can be used more efficiently, leading to a benefit for the fuel cycle costs.

Integrated 3-D Code System for Reactor Core Design

The tremendous progress made in computer hardware and software technology — demonstrated, for example, by continuously increasing processing speeds — currently enables large code systems to be directly coupled. This permits the integration of different areas of the analysis such as reactor physics, thermal hydraulics and plant dynamics, with the overall aim of significantly increasing simulation accuracy by eliminating conservatism at the code interfaces.

The new Siemens PWR program system Cascade-3D (Core Analysis and Safety Codes for Advanced Design Evaluation)[8] links some of the most advanced code packages for in-core fuel management and accident analysis.

Consequently, the potential of modern fuel assemblies and in-core fuel management strategies can be better utilised because safety margins, which had been reduced due to conservative methods, are now predicted more accurately. With this innovative code system, the plant operators can now take full advantage of recent progress in fuel assembly design and in-core fuel management.

Higher Reliability and Reduced Fuel Cycle Costs

The global operating experience of Siemens fuel totals 9.55 million fuel rods, representing more than 74 000 fuel assemblies. Siemens has supplied fuel to a total of 105 power reactors in 14 countries in Europe, the Americas and the Far East. This total includes first core and reload fuel for reactors build by Siemens, as well as reload fuel for a large number of reactors built by other suppliers. At the end of 1998, a total of 63 power plants (35 PWR, 28 PWR) operated with Siemens fuel in the core, including 35 power plants (27 PWR, 8 BWR) operating with nearly a full core of Siemens fuel.

As it can be seen in Figure 9, the percentage of reactor cycles operated without any failures has increased significantly for both reactor types since the 1970s, 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 85% of the reactor cycles are operated without any fuel failure. From 54 LWR plants operated with at least 10% Siemens fuel in core in 1998, fuel failures were observed in eight plants (3 BWR, 5 PWR). It has to be pointed out that the fuel failure situation during the last several years was dominated by instances of an increased number of failed rods in only a few reactor cycles.

Especially the Siemens BWR fuel showed outstanding performance, with a combined total of four failed rods, achieving an annual rod failure rate of 0.5×10^{-5} in 1998. 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 1998 was 2.5×10^{-5}, but about 70% of all failures (23 failed rods) occurred in an older PWR fuel assembly design still using Inconel spacers in the active core. This design is no longer delivered.

During the past decades the nuclear fuel cycle costs for a typical LWR have been reduced by almost DM75 million (US$40 million) per year based on ongoing development of the nuclear fuel used. 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 which a burnup potential of 60 MWd/kgHM for PWRs and 50 MWd/kgHM for BWRs has been realised (see Figure 10).

Through further burnup increases the estimated impact of such developments in advanced nuclear fuel technologies on the fuel cycle cost of nuclear plant operation is expected to be a saving of the order of an additional DM20–30 million (US$10–16 million) per year. The exact amount depends mainly on the backend costs and the cost model application (see Figure 11). 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 fuel vendors and the utilities is a prerequisite for the common success.

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Figure 1. Advanced nuclear fuel technologies are the key to cost savings in the entire nuclear fuel cycle (Example: cost situation for a German 1300 MWe plant).

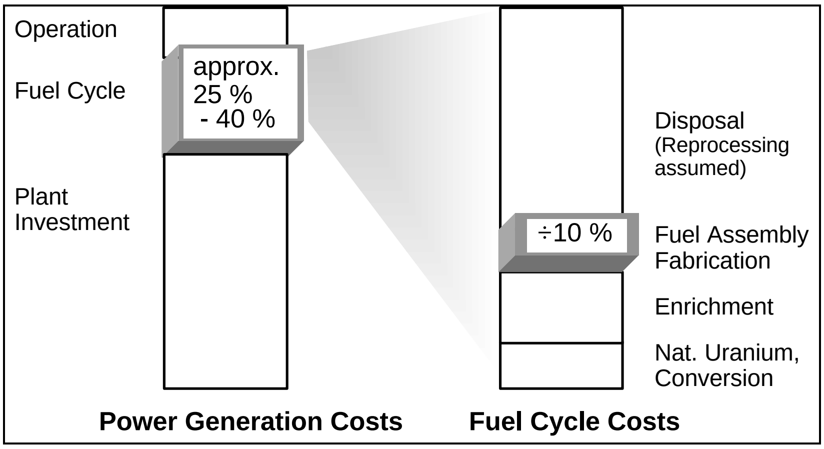


Figure 2. The product lines FOCUS and HTP for PWR and Atrium for BWR are the basis for further fuel cycle cost improvements at Siemens.

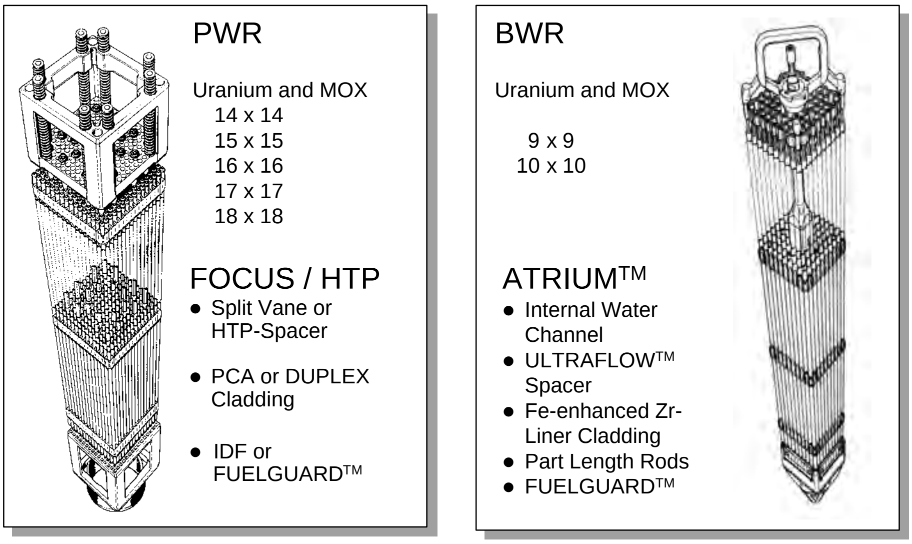


Figure 3. The burnup of the leading batches of Siemens fuel assemblies will continue to increase.

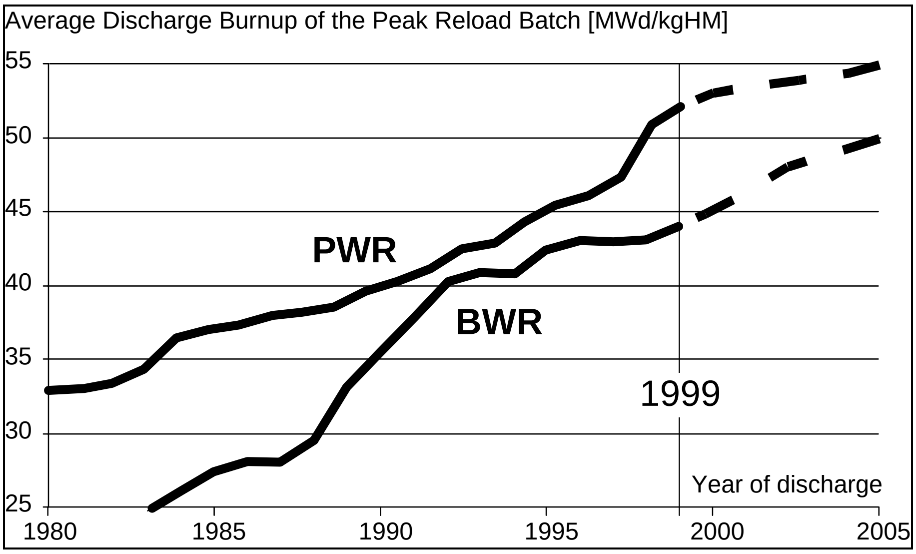


Figure 4. Current and future lead fuel assembly programmes are the basis for the verification of high burnup capability.

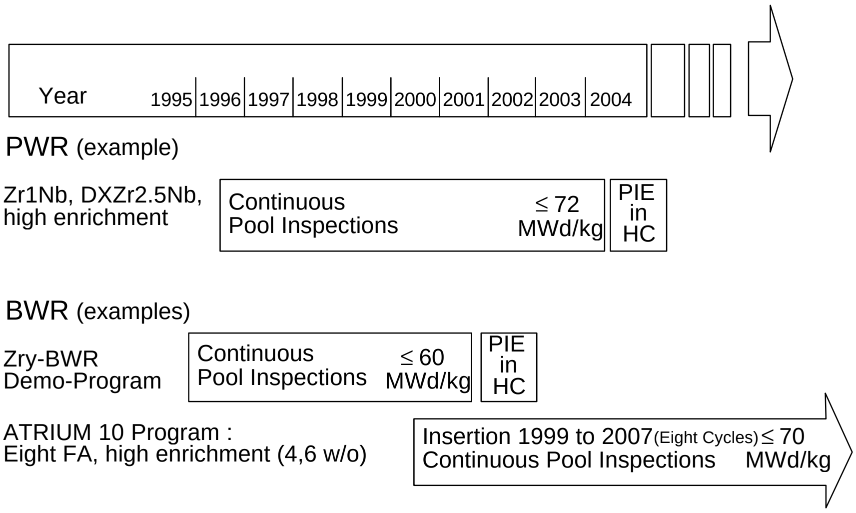


Figure 5. Since the introduction of debris filters the number of fuel failures caused by debris was reduced significantly.

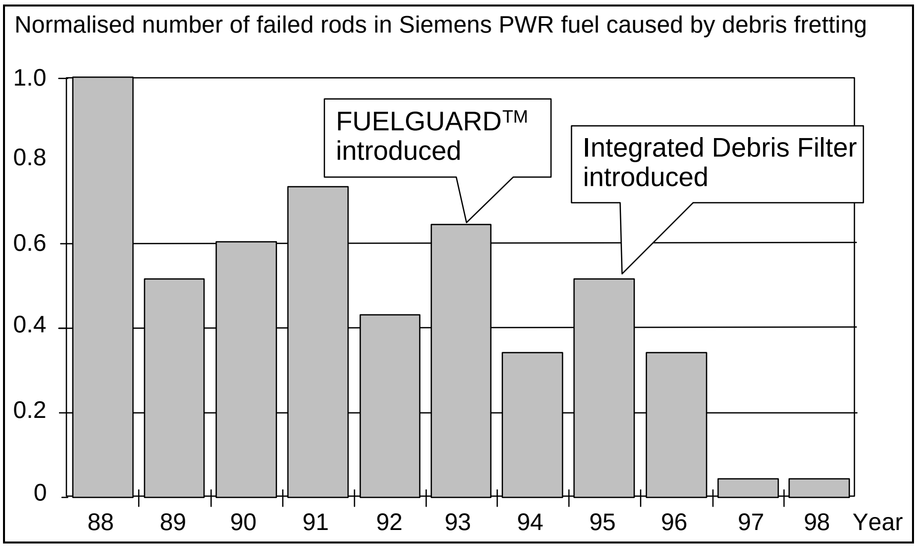


Figure 6. With the new Fretting Test Methodology we gain important new insight in the wear characteristics of fuel rod support.

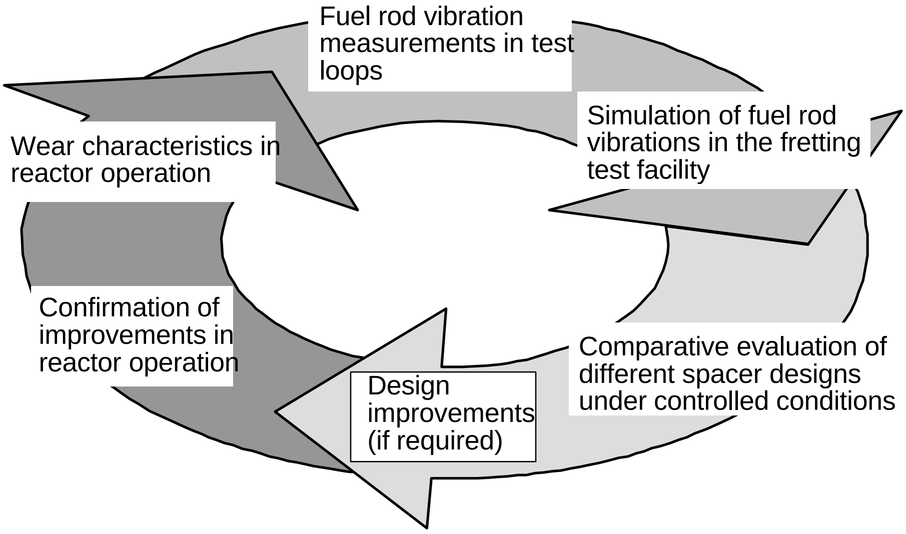
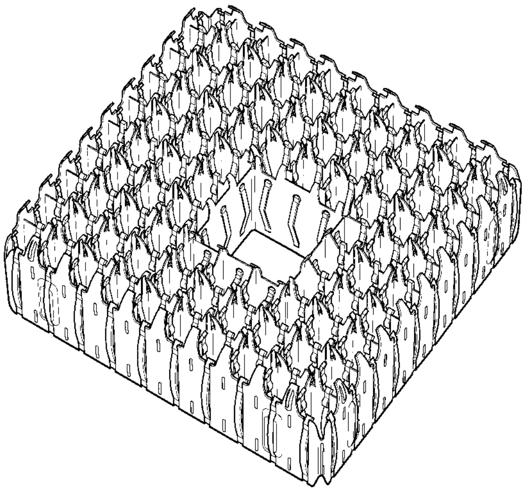
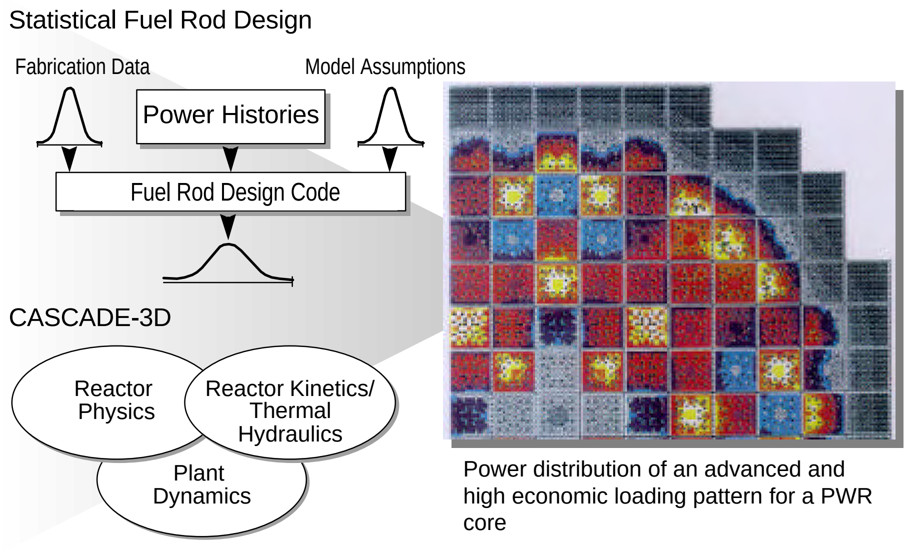


Figure 7. The Siemens Ultraflow spacer for Atrium-10 fuel assemblies can provide high thermal hydraulic margins.



- Swirl vanes and side plate flow vanes increased significantly the achievable critical power level
- An optimized side plate design reduced the pressure drop
- Advanced manufacturing techniques like laser and electron beam welding ensure a reliable and cost effective fabrication

Figure 8. Efficiency enhancements in the nuclear fuel cycle require new methodologies and integrated code systems.



Statistical Fuel Rod Design

CASCADE-3D

Power distribution of an advanced and high economic loading pattern for a PWR core

Figure 9. The operational performance of Siemens PWR and BWR has improved significantly.

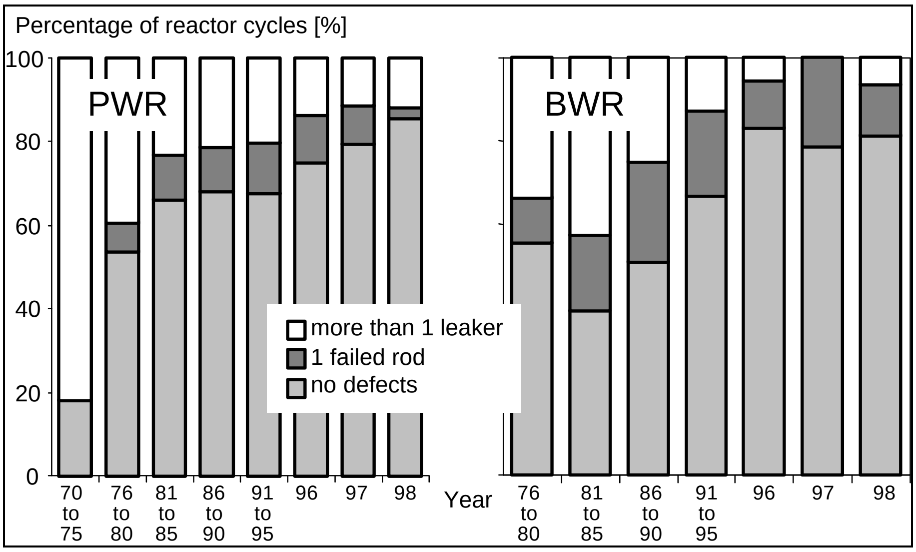


Figure 10. Continuous development has led to annual cost savings in the order of about DM70 million (Example: BWR fuel).

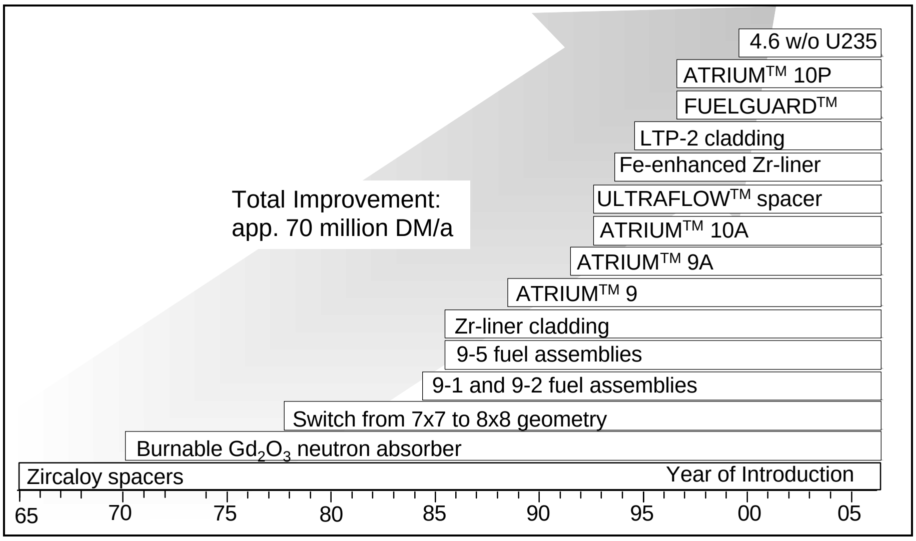


Figure 11. Future savings in fuel cycle costs by increasing burnup are dependent on disposal costs (1300 MWe PWR, annual cycle).