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Optimum Overall Economy Through Advanced Fuel Designs

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Fuel assemblies represent the connecting link between the fuel cycle and the nuclear power plant. By improving energy output, efficiency, operational flexibility and the reliability of the fuel assemblies, both the fuel cycle costs and other aspects of power generating costs can be improved. Thus, investment in fuel assembly development, enhancement of in-core fuel management codes and methods as well as improvement of fuel assembly manufacturing processes and technologies feature a substantial economic effectiveness.

Economic analysis by calculating specific fuel cycle costs

In order to be able to evaluate the economic impact of technical measures or commercial factors associated with nuclear fuel, the specific - that is energy related - fuel cycle costs are calculated.

The methods applied for such calculations must consider a large number of technical and commercial parameters, because nuclear fuel is essentially characterized by a large number of technical and chemical processing steps, physical correlations and by the fact that the costs are spread over relatively long periods of time.

The purpose of fuel cycle cost calculations is to allocate all income and all expenses associated with a specified quantity of fuel to one measuring unit. The resulting specific fuel cycle costs (referred to in the following as fuel cycle costs) are consequently defined as the price at which each generated kilowatt hour is to be sold in order to recover all expenses related to the fuel quantity involved (*Figure 1*).

Fuel cycle costs can be calculated using a number of different approaches depending on the case in question. The choice of a particular method depends essentially on the section of the time scale being considered, that is whether fuel cycle costs have to be calculated for the entire amortization period of the nuclear power plant, for a number of transition cycles or for an equilibrium cycle. In addition, it may depend on the required depth of analysis or the available input data.

One commonly used approach for fuel cycle cost calculations is the 'present worth method' (*Figure 2*). Since the costs that are due at various points in time can only be accurately compared with each other by taking into account the corresponding interest effects, all costs and income must be based on, that is discounted to, a common reference date. The integration of interest and discounting factors into the above basic formula immediately results in the arithmetical formula for calculating the fuel cycle costs according to the present worth method.

Significance of the fuel cycle cost structure for the economic incentive of technical developments: main focus – burnup extension

Depending on the economic boundary conditions, in most countries the development of fuel cycle costs has been characterized by a steady and considerable decrease over the past decade or more. This development has been brought about to a significant extent by the further technical development of fuel assembly design and in-core fuel management, as well as by developments in the fabrication processes. An essential development goal has been the extension of the discharge burnup by an increase in U235 enrichment.

The magnitude of the impact of technical development measures on fuel cycle costs depends on the structure of the fuel cycle costs, i.e. the specific cost shares of natural uranium, separative work, fuel assembly fabrication and fuel assembly disposal. When the relative shares of disposal costs and fuel assembly fabrication costs is high and the cost is related to the amount of the fuel, technical measures which increase the specific energy output of the fuel, i.e. an increase of the discharge burnup, result in high economic benefits. This is demonstrated in *Figure 3*.

The figure shows the structure of fuel cycle costs as a function of discharge burnup, varied in the range of 30 to 70 MWd/kgU. The figure is based on present commercial boundary conditions, and the cost for fuel assembly disposal is assessed at 1250 €/kgU. The dotted line indicates the burnup reached today on an average by discharged Framatome ANP PWR fuel assemblies (BWR burnups are somewhat lower).

The splitting of the fuel cycle costs into its individual cost components makes the driving forces for the decline of fuel cycle costs over the burnup range evident. By far the biggest contribution in this example results from the specific disposal costs, a much smaller contribution results from the specific fuel assembly fabrication cost. The specific cost for the natural uranium needed for the respective fuel assembly design behaves practically neutrally, whereas the separative work cost component is the only component showing a slight rise when burnup is increased.

With respect to the total fuel cycle costs, the figure shows a decrease of nearly 50% over the entire burnup range considered. As one percent reduction of the fuel cycle costs corresponds, depending on the commercial boundary conditions, to up to one million € per 1300 MWe reactor/year. This represents an enormous saving in fuel cycle costs.

MOX fuel assemblies assume a special position in terms of the evaluation of the effect of the discharge burnup on the fuel cycle costs. The structure of the fuel cycle costs of MOX fuel assemblies is dominated by the costs of fuel assembly disposal and fabrication, i.e. by those cost components which bring about a decrease in the fuel cycle costs when the burnup is raised. This is why MOX fuel assemblies are subject to an even more pronounced reduction in the fuel cycle costs than uranium fuel assemblies when the burnup is increased.

Relevance of the boundary conditions: differentiated requirements of the markets

As has been shown, the economic incentives of burnup increase are strongly influenced by the approach to the disposal costs, or, more specifically, by the absolute level as well as by the dimension of the disposal cost and, in addition, by the level of discharge burnup achieved. The influence of these parameters on the total fuel cycle costs is shown in *Figure 4*.

To demonstrate the magnitude of the influence of the different approaches to disposal costs given in different countries, three cases of disposal costs are considered here: 2500 €/kgU, as an assessment of, for example, present German conditions; 1250 €/kgU, as an assessment of disposal costs, for example in France; and disposal costs related to energy produced, as for example, practiced in the USA. Again, the burnup varies from 30 to 70 MWd/kgU.

When looking back from the burnup level of 45 MWd/kgU, reached on average by PWR fuel assemblies discharged at present, an increase of the discharge burnup has resulted in considerable reductions of the fuel cycle costs in all the disposal scenarios considered.

When considering discharge burnups above 45 MWd/kgU, in cases where the disposal costs are related to the weight unit of uranium, there is still a very significant potential for further reduction of the fuel cycle costs, within the burnup range considered.

Regarding the case of disposal costs quoted in currency per KWh, the fuel cycle cost curve flattens significantly in the range of high burnups. In this case also, the appearance of a fuel cycle cost minimum below 70 MWd/kgU is possible, e.g. depending on the actual level of interest rate.

Today, practically all over the world an enrichment limit of 5% U235 is applicable to nuclear fuel cycle facilities. When considering a 1300 MWe PWR operated in a 12-month cycle, this enrichment value corresponds roughly to a burnup of 65-70 MWd/kgU. In any case, this enrichment limit will impose additional technical and economic costs, as well as licensing effort and licensing risks, to an enrichment increase beyond this value. Therefore, consolidation of burnup extension, which may last for more than one decade, is expected at 5% enrichment.

Apart from the fuel cycle cost aspects, logistic considerations may also play an important part with respect to burnup extension. For example, to ease bottlenecks

at the back end, the fuel cycle strategy to be pursued may in certain cases be dominated by logistic necessities.

Reacting to the market requirements, from a very early point in time, Framatome ANP has invested in new advances and has developed technologies aimed at exploiting the large economic potential of burnup increase [1]. As the leading manufacturer of LWR fuel in the world, this has been based on extensive operating experience comprising today about 95 000 PWR and 45 000 BWR fuel assemblies, inserted in NPPs in Europe, USA, Asia, South Africa and South America. With regard to the peak pellet burnup, our experience already exceeds 100 MWd/kgU, and, with regard to complete reloads, values of 53 MWd/kgU.

Reduction in fuel cycle costs by improvement in fuel utilization

The economic improvements achieved by burnup extension through increasing the U235 enrichment have been supplemented with a whole range of measures geared towards improving the fuel utilization by enhancement of the neutron economy [2]. These measures comprise the introduction of part low leakage, the consequent use of low neutron absorbing rate materials in the fuel assembly structure, transition to Gd₂O₃ designs so as to realise full low leakage core loadings and, as more recently, implementation of super low leakage and transition to the low gadolinium concept where technically feasible.

In total, these development measures resulted in a saving in U235 enrichment of about 0.35% U235. On the basis of a constant burnup (calculating the respective economic effects of the natural uranium and separative work savings) and based on the actual prices of natural uranium and separative work, this results in fuel cycle cost savings of about 2.5 million € per 1300 MWe reactor/year.

In the case where the improvement of the fuel utilization by enhancement of the neutron economy is transferred into an increase of the discharge burnup – which is being done wherever possible – the resulting economic effects can be considerably higher. This fact will be of increased interest when the 5% enrichment limit is reached, i.e. under this border condition, improvement of neutron economy will gain substantially in economic importance.

Optimization of the cycle length

Fuel cycle costs may also depend on plant operation since, for example, a change in the cycle length affects fuel utilization. An extension of the cycle length has a negative impact on fuel utilization and therefore results basically in a rise of the fuel cycle costs. However, since extension of the cycle length aims at improvement of the load factor, it can actually make plant operation more cost effective.

Depending on the licensing situation, and if the unloading of the entire core is not demanded by special constraints, the method of In-core Shuffling can provide a means to reduce outage times, even independently of the cycle length. When applying this method, the fuel assemblies not to be unloaded are moved directly to their final position in the core. Thus, given the respective boundary conditions, by applying this method, the load factor can be improved without adverse effects

resulting from the fuel cycle costs. The economic effects resulting from plant operation have in any case to be evaluated against the fuel cycle cost effects, taking into account also the specific boundary conditions of a power plant park and power system requirements.

Advanced high efficiency fuel assembly designs and integrated high capacity fuel management methods to meet the differentiated challenges of the markets

Reacting to the complex challenges of the markets in a way that aims at the best overall economy of the fuel cycle requires highly sophisticated products developed on the basis of broad long-term experience [3]. By following this line, Framatome ANP is in a position to offer integrated concepts and a leading technique. *Figure 5* shows examples of technical features in the field of PWR fuel assemblies which are characteristic:

- Spacer grids with optimized swirl vanes provide enhanced thermal-hydraulic performance, which is being used e.g. for advanced fuel concepts or power upgrading of the NPP. The innovative HTP spacer design combines in a single component coolant flow mixing by curved flow channels and fuel rod support by line-contact, which ensures a large contact area and thus optimum resistance to grid-to-rod fretting.
- The one-piece MONOBLOC™ guide thimble consists of an enlarged thicker tube, including a dash-pot area. Associated with the excellent corrosion and hydriding behaviour of the M5™ alloy, the MONOBLOC™ geometry provides an excellent resistance against fuel assembly bow at high burnups. Effective protection against debris is being obtained with the high efficiency bottom nozzles TRAPPER™ and FUELGUARD™ characterized by low pressure drop coefficient upgrading thermal-hydraulic performance and, in the case of FUELGUARD™, by innovative curved ribs for debris retention.
- The advanced cladding material M5™, a ternary alloy of zirconium, niobium and oxygen, provides high margins with respect to corrosion and hydriding under high demanding duty, thus meeting important criteria for achieving high burnups. In addition, this alloy exhibits lower growth and lower irradiation creep by a factor of 2 to 3 compared to low tin content optimized zircaloy 4.

Our advanced fuel designs AFA 3G, HTP X5 and ALLIANCE feature combinations of these superior components according to the needs of the customers. Some of the features, like MONOBLOC™ guide tubes made of M5™, already implemented in the AFA 3G All M5 design, have been maintained in our new generation PWR fuel assembly ALLIANCE. Monometallic structural grids made of M5™, providing increased thermal-hydraulic performance by implementation of large vanes, have been introduced. ALLIANCE is designed to reach discharge burnups of at least 70 MWd/kgU.

In the case of BWR fuel assemblies (*Figure 6*), characterized by a radial gradation of the U235 rod enrichments, fuel utilization has been considerably increased by implementation of an internal water channel structure. In addition, a further increase in fuel utilization has been effected by fine tuning the distribution of the U235 enrichment, sophisticated implementation of the burnable absorber gadolinium, as well as the use of part-length fuel rods which, at the same time,

improve the thermal-hydraulic stability behaviour of the reactor. The ULTRAFLOW™ spacer concentrates the coolant flow to fuel rod surfaces, thus improving dryout performance and increasing the respective margins. For effective debris retention in BWR fuel assemblies the FUELGUARD™ or the Small-Hole debris filters are available.

For both PWR and BWR, high performance fuel assemblies based on the above technique have been developed for the recycling of uranium (ERU fuel assemblies) and plutonium (MOX fuel assemblies) separated by reprocessing from discharged fuel elements which can provide for a further increase of fuel utilization and, accordingly, further conservation of resources.

As an adverse effect of the implementation of the broad spectrum of innovative features to improve economy and also of the insertion of MOX and ERU fuel assemblies in LWRs, heterogeneity in the core increased. In addition, the increased variety in cycle lengths, introduced to accommodate grid-specific demands and economic boundary conditions in order to reduce power generating costs, imposed considerable challenges to fuel management codes and methods. In response to this, integrated high capacity methods, enabling, for example, the consideration of safety-related physical, thermal-hydraulic as well as mechanical data on an individual fuel rod basis in the core, have been developed and put into practice. By this means, very precise analyses and predictions became possible, enabling the best use of margins and responding in an optimized way to increased needs.

The objective target: optimum long-term overall economy and sustainability

The pre-requisite for all further development is to ensure the maximum possible degree of reliability of the fuel assemblies. As a result of this basic strategy, and despite the considerable reduction of the fuel cycle costs achieved in the past, which has also been associated with more demanding conditions for fuel assemblies and in-core fuel management, the fuel failure rates have been reduced.

Today, fuel failure rates of the Framatome ANP PWR fuel assemblies have been decreased to around 1×10^{-5} (*Figure 7*). Low failure rates are not only a prerequisite for obtaining a high plant availability and load factor, but also contribute to minimizing radiation exposure. While the load factor directly affects the specific power generating costs, and can thus have a correspondingly large impact on the overall plant economics, radiation minimisation additionally contributes to important environmental goals. In order to assure optimum overall economy in the long run, further developments must not only enable short-term economic savings, but must additionally be recognized as a long-term strategic task within the framework of sustainable development, i.e. they must be aligned with the target of combining economic, ecological and social requirements.

Improvement of the fuel utilisation has also contributed to this. While reducing fuel cycle costs by improving fuel utilisation, a significant ecological contribution has also been achieved at the same time (*Figure 8*).

As enhancement of the neutron economy results in savings of natural uranium and separative work, this is directly associated with savings of resources and energy.

This applies not only to measures such as reductions in neutron absorption in structural components, reductions in neutron leakage and optimisation of the moderation efficiency, as discussed above, but, to a certain extent, also to burnup extension, as an increase of the burnup also improves the neutron economy in the core and the burnup dispersion of the discharged fuel assemblies.

The effects of all this are substantial. Altogether, the development measures carried out by Framatome ANP have led to a reduction in the specific demand (that is, the demand related to the unit of produced electricity) of both natural uranium and separative work by about 15%, thus saving valuable resources.

In comparison with fossil power plants, the share of the fuel costs in the total power generating costs of a nuclear power plant accounts only for a relatively small percentage [4] (*Figure 9*). The figure shows a typical example of the power generating cost structure of nuclear power plants in operation. About 20% can be taken as a representative figure for the share of the fuel cycle costs. The component of the fuel cycle costs which accounts for the resource natural uranium is less than 3% of the power generating costs, that is smaller again by about one order of magnitude, while the remainder of the fuel cycle cost components are based on technical processes which are subject to further technical development, and therefore to possible further economic improvement.

This is to be compared with a fuel share in the power generating costs of fossil plants of about 40% in the case of hard-coal-fired steampower plant or up to about 70% in the case of combined-cycle plants. Therefore, nuclear power plants are much less sensitive to future price fluctuations for primary energy sources and feature a particularly long-term stability of their generating costs.

Summary and conclusions

Optimum overall economy has to combine short-term and long-term economic effects and must also stay abreast of the requirements of sustainable development. Thus, in the long term, optimum overall economy is best assured by an integral strategic approach incorporating economy, ecology and social aspects. This applies especially in the complex area of energy production.

As also presented in a recent OECD study [5], trends in the development of the nuclear fuel cycle are aimed towards the target of improving, in one way or another, the economic, environmental and social aspects of nuclear energy. In addition, according to the OECD study, an evaluation of the sustainability of nuclear power, carried out on the basis of a large number of criteria for sustainable development, showed the high relative potential of nuclear power. Similar views are also described in other sources [6].

Design and development, fabrication and insertion of fuel assemblies are, on the one hand, characterised by a relatively small share of the power generating costs of altogether only about 3% and, on the other hand, by a large impact on the total power generating cost. Thus, further development in the field of fuel assemblies, directed as indicated above, comprises a potentially high economic efficiency and contributes to the sustainable development of energy production.

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$$\sum Costs^* = \sum Benefits^*$$

where:

$$benefits = [FCC] \cdot [produced\ energy]$$

$$\Rightarrow FCC = \frac{\sum Costs^*}{\sum Energy^*}$$

* present worth

Figure 1: Determination of FCC means to combine all relevant cost elements to one measuring unit – the specific FCC

$$FCC = \frac{\sum Costs^*}{\sum Energy^*} = \frac{\sum_{Time} C(t) \cdot q^{-(t-t_0)}}{\sum_{Time} E(t) \cdot q^{-(t-t_0)}} \quad * \text{ present worth}$$

where:

$$q = 1 + \frac{i}{100}$$

$E(t)$ Energy produced in the period of time under consideration
 $C(t)$ All costs related to the produced energy
 i Interest rate
 $t-t_0$ Terms of discount
 FCC Specific fuel cycle costs

Figure 2: One of the most commonly used approaches is the present worth method

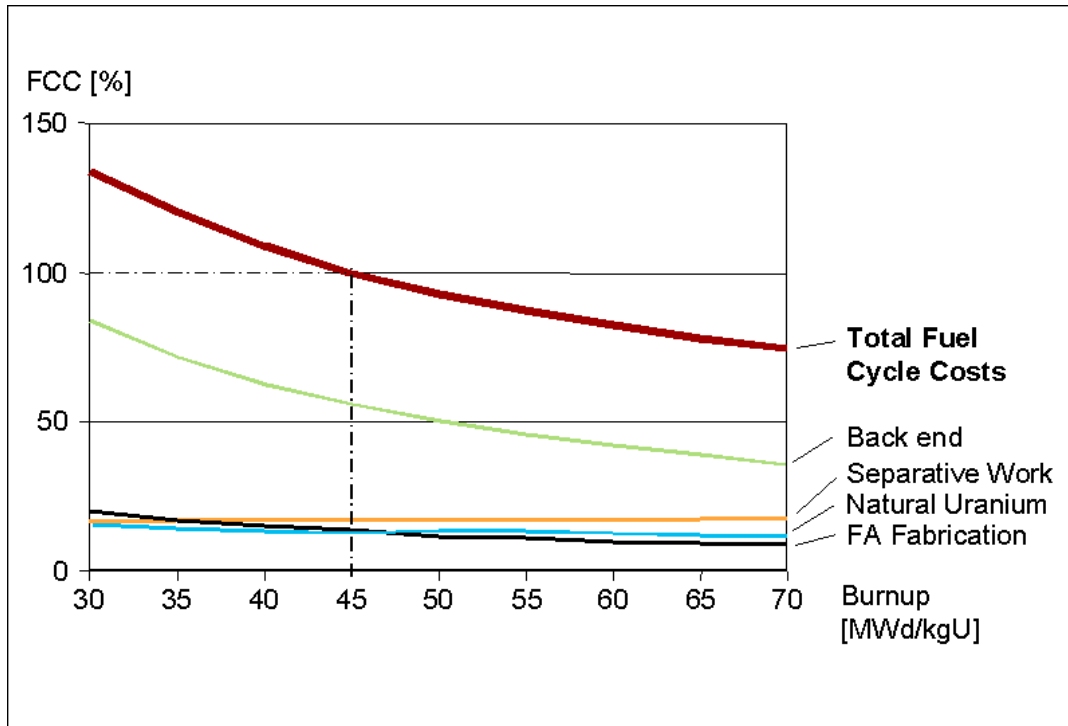


Figure 3: Effect of the Individual Cost Components of the FCC on the FCC-Curve over the Discharge Burnup

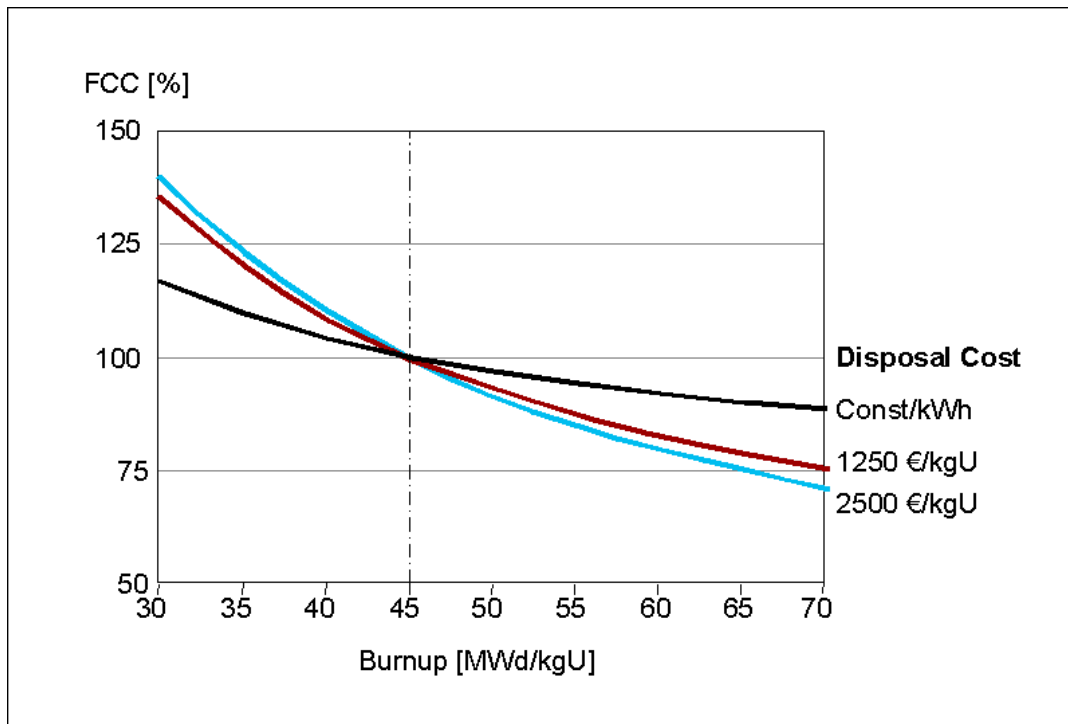


Figure 4: Important Parameters Influencing the Economic Effect of Burnup Increase

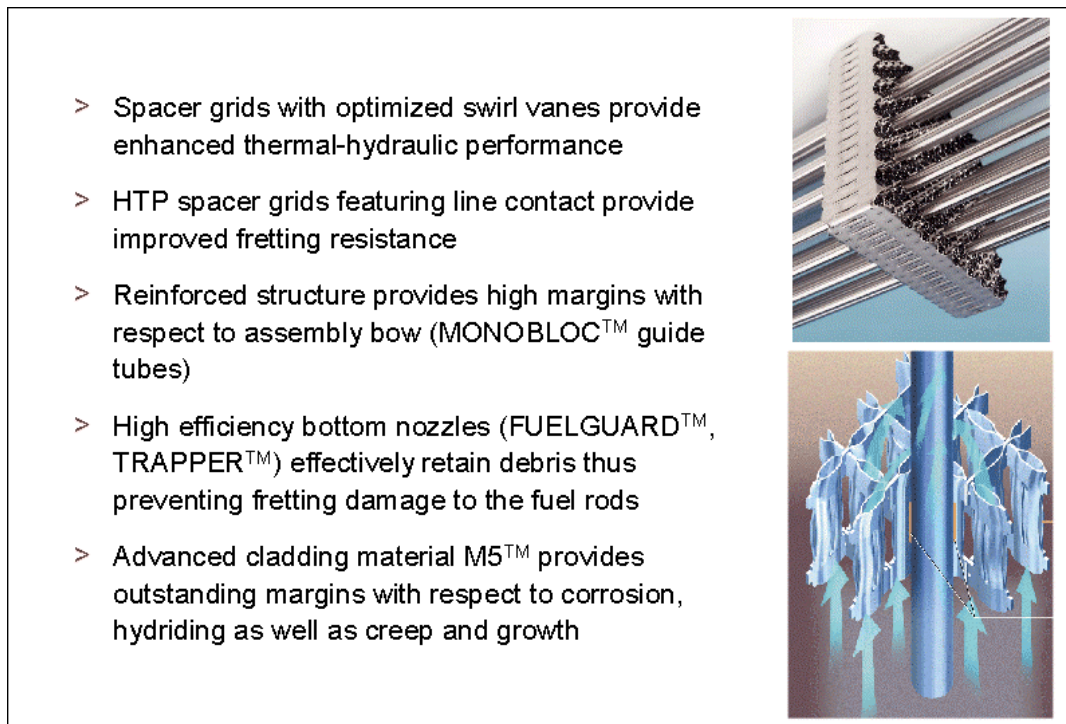


Figure 5: Challenges of the Market Converted into High Performance PWR Products

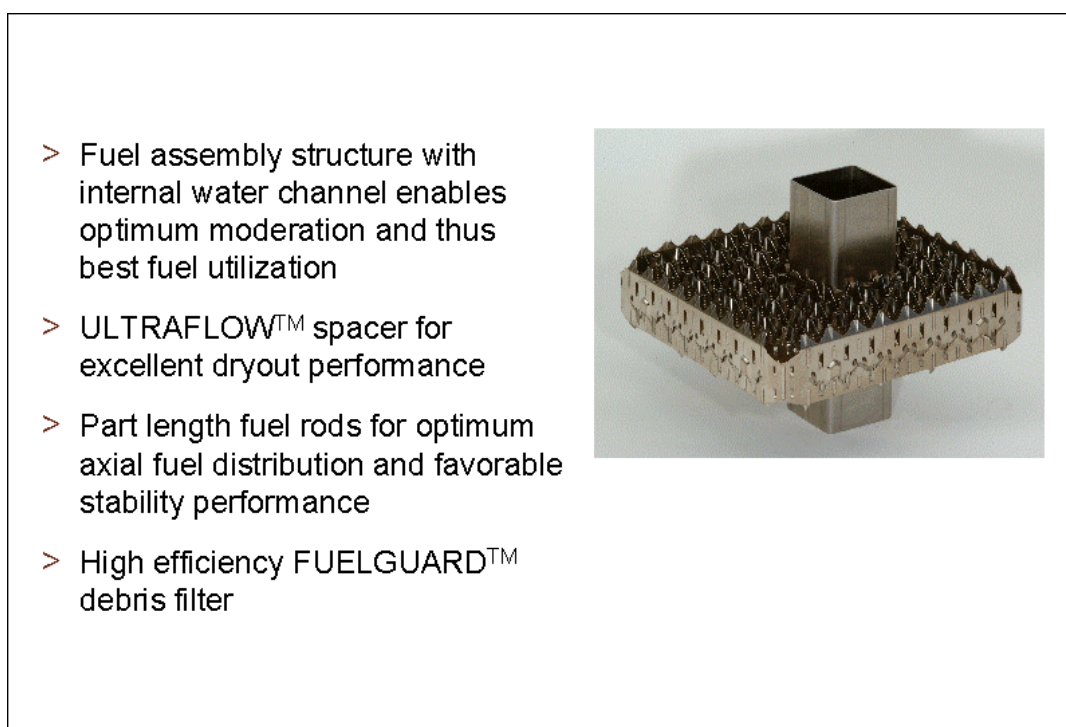


Figure 6: Challenges of the Market Converted into High Performance BWR Products

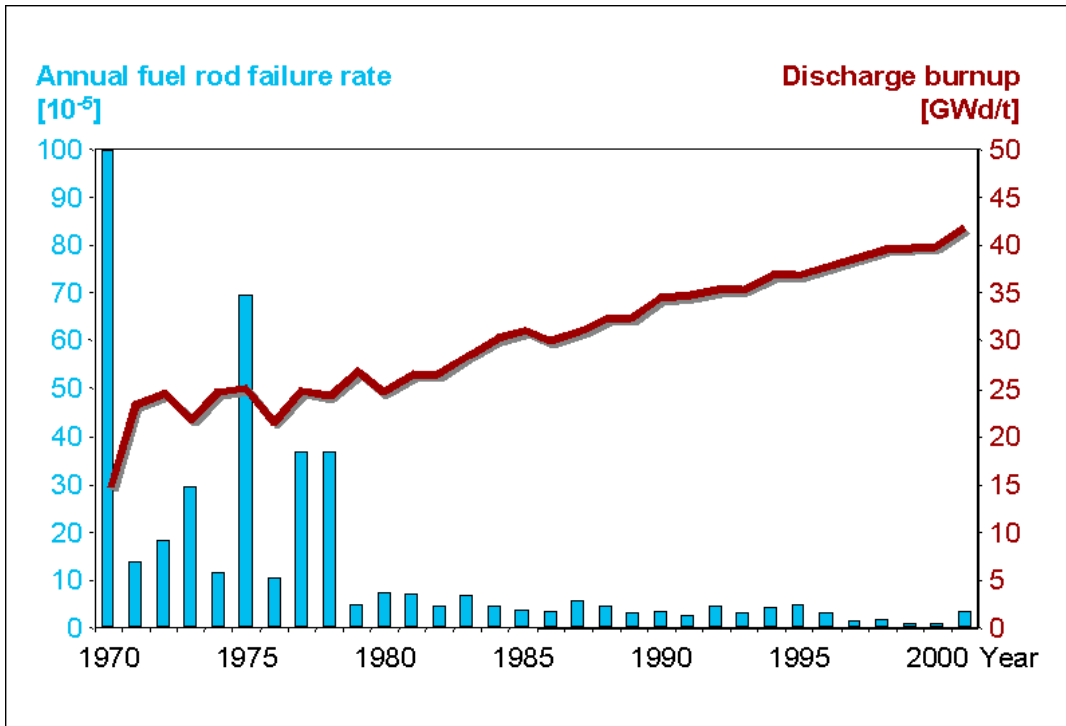


Figure 7: Reduction of FRAMATOME ANP PWR Fuel Rod Failure Rates Despite Steadily Increasing Discharge Burnup

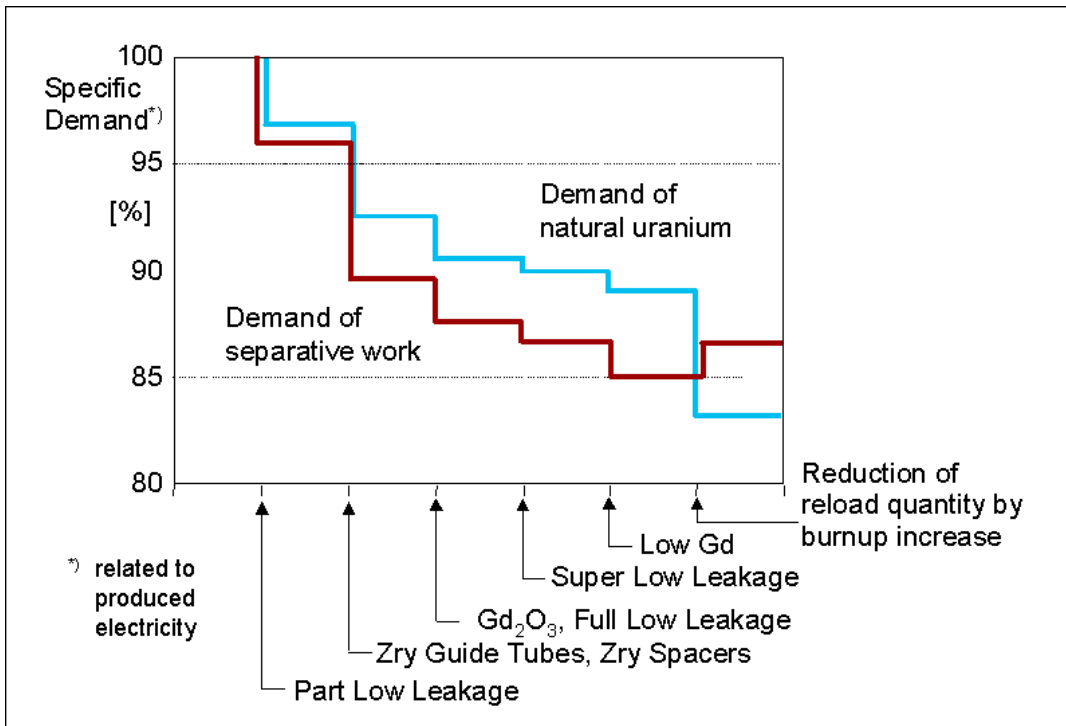


Figure 8: Effect of Fuel Assembly Development on Resource Conservation

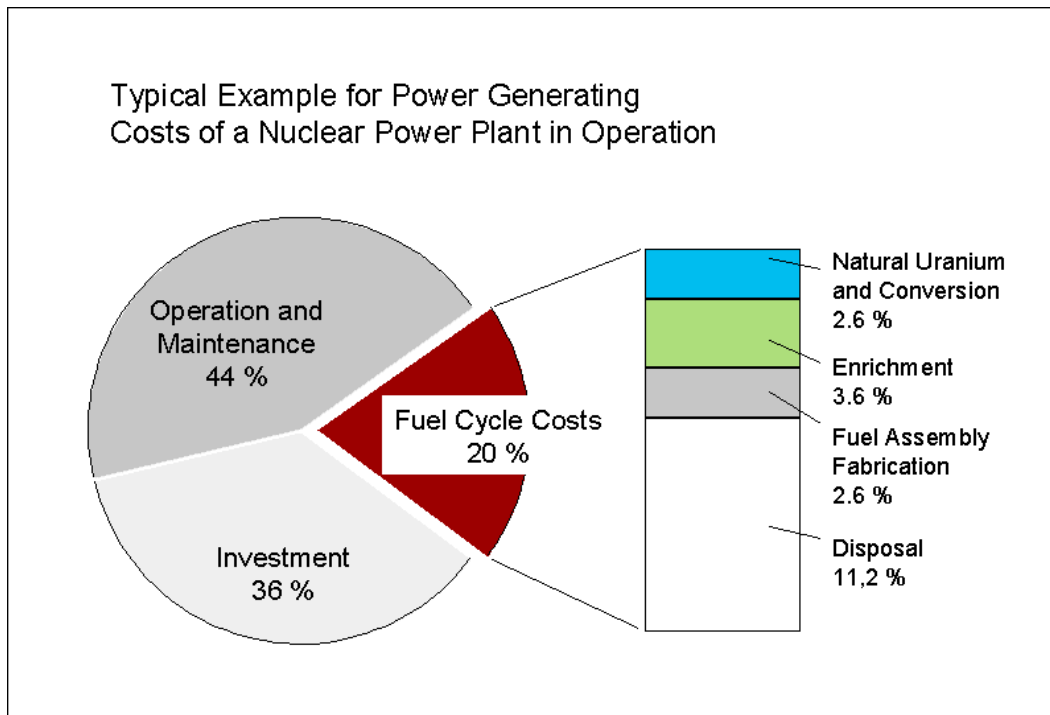


Figure 9: Power Generating Costs of NPP:
Low Dependence from Natural Resources