CYCLE STRATEGIES TECHNOLOGICAL ALTERNATIVES FOR REDUCING FUEL CYCLE COSTS

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Competitiveness is a key word for the immediate future of the electrical sector throughout Europe. The inevitable liberalization of the electricity market, with the emergence of independent producers and the possibility that major consumers can choose the supply most suited to their needs, poses a series of new challenges to the sector. The fact that some old nuclear power plants in the U.S. have closed because their variable costs could not compete with those offered by small independent suppliers is a severe threat to the economic viability of operation of existing nuclear plants.

ENUSA, as a nuclear fuel designer and manufacturer, is aware of this need to improve the competitiveness of nuclear generation and has been developing several courses of action to help cut fuel cycle costs. One of these courses of action is to reduce as much as possible the enrichment needs of fuel used to satisfy the customer's energy requirements as part of the first phase of the nuclear fuel cycle, and to develop and test advanced structural materials in order to increase fuel burnup and reduce the manufacturing impact on the kWh cost.

However, direct fuel cost is not the only impact that fuel has on economic reactor profitability, nor the most important. Hard-to-quantify aspects such as reduction of rapid neutronic creep in certain components, the ability to reconstruct damaged assemblies, reduction of time and dose owing to waste suppression, etc., all have a direct impact on reactor availability and therefore on the resulting average variable kWh cost, as they reduce the variable operating and maintenance costs.

The advanced PWR product, whose qualitative and quantitative advantages and characteristics are discussed in this paper, brings together in one single product the most advanced characteristics of axial blankets with slightly enriched uranium along with design flexibility and reduced waste of gadolinium as burnable absorber.

PWR PRODUCT DESCRIPTION

In this design, each rod contains two axial zones at the ends of 15 cm. high these sections are filled with solid, slightly enriched (typically 2.6%) uranium pellets, and the rest of the pellets contain fully enriched uranium as defined by the energy needs of this fuel. In the rods containing gadolinium, following each 15 cm. end zone are intermediate 15 cm. zones free of gadolinium. Then, in the central zone with a height of 305 cm., the uranium mixed with gadolinium has an enrichment lower than the maximum defined, and the greater the gadolinium concentration the lower will this enrichment be.

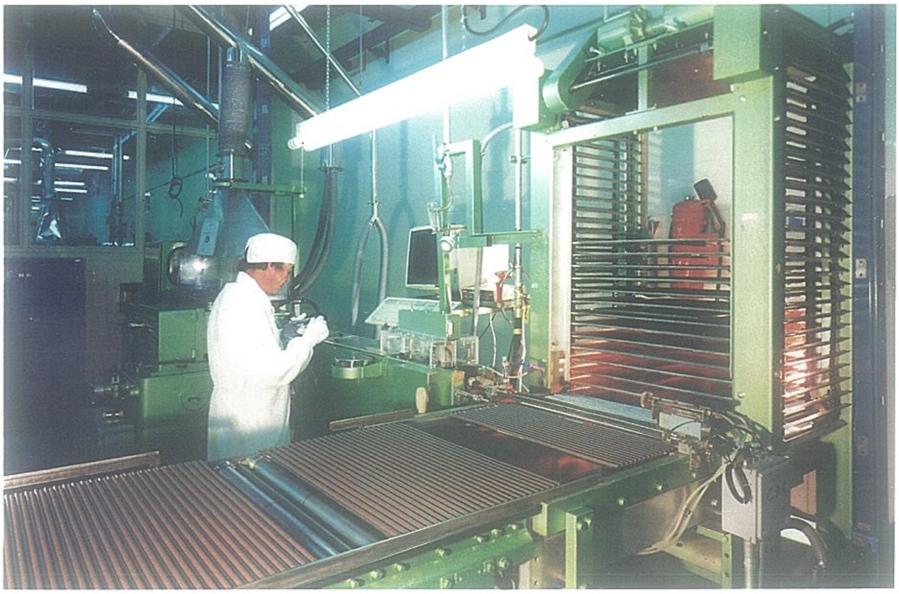
The combination of these advanced characteristics in a new product merits an explanation.

The use of axial blankets is an obvious improvement as it results in a reduction of axial leaks, which leads to a direct savings in excess reactivity required at the end of the cycle and thus in the initial required enrichment. This is demonstrated by the extensive experience with their use in BWR reactors, and in particular the increased height of the upper blanket in General Electric products subsequent to the GE8 due to high leaks in the upper core.

In addition to the above mentioned savings in enrichment and costs, the use of axial blankets has beneficial effects on the neutronic irradiation rates of essential reactor components. Although these are designed with a wide margin for the original design life of 40 years, they can begin to approach limits when reactor life extensions or power uprates are planned. An axial blanket at the upper end reduces fast neutron fluence both in the upper core plate and in the circumferential weld that joins the center sleeve of the vessel to the one that houses the nozzles. On the other hand, the lower axial blanket performs the same service for the lower core plate, an essential component that supports the entire core weight.

The fact that to date axial blankets have not been included in PWR fuel has more to do with the ability of manufacturers to deal with a variety of enrichments and products in a single installation than with the economic magnitude of savings obtained. However, process quality improvements, from automated loading systems to inspection capabilities of the finished product with passive and active scanners, ensure that zero defects are

Pellet inspection after rectification



Final inspection of an XL fuel assembly for the European market.

obtained when dealing with different enrichments.
The reduced power at the ends of the fuel columns has significant effects on power density in the center. In fact, the use of natural uranium axial blankets for developing this product had been rejected due to the negative impact produced on local power factor FQ and especially on the DNB. This could be unacceptable in reactors with limited margins availability. The effect was due to the almost total absence of power in axial blankets, which resulted in a significant power increase in the center of the column, especially early in the fuel's lifetime.
On the other hand, the use of slightly enriched uranium in axial blankets, together with the use of partial length gadolinium, serves to flatten the power and effectively cancel the impact on FQ and especially on DNB.
Studies performed with the state of the art of core analysis methodology demonstrates that there is no clear gain in enrichment owing strictly to the use of full length gadolinium as opposed to discrete absorbents such as WABA's. The same energy results are simply obtained, with a somewhat lower uranium weight, 0.2%, for a higher level of enrichment, 0.005%, but with an identical economic cost.
However, if combined gadolinium is used with the axial blanket, resulting in freedom of radial and axial blanket location, it is possible to fully cancel the harmfull effects stemming from reduced power at the ends of the fuel column. Of course some of the axial power flattening capabilities can also be obtained by using discrete poisons such as the WABA's, but this results in a series of disadvantages that cannot be obviated. On one hand, there are effects on reactivity and thus on energy loss, since the very mechanical structure of the discrete absorbent has a residual absorbent effect at cycle's end along the entire height due to moderator displacement, whereas the equivalent effect for gadolinium, neutron absorption by paired isotopes, only exists along the part of the fuel that contains it. On the other hand, the use of WABA's creates a dependency on the specific design component supply, which could actually turn each component into a prototype, leading to high present and future costs.

QUALITATIVE ADVANTAGES

The advantages gained with gadolinium have to do with flexibility in fuel design, product customization, reduced times and doses due to waste management and therefore increased availability.
With the growing number of requirements for high energy and safety margins in core design after each refueling, the freedom to choose the positions of fuel assemblies in the core becomes a critical aspect. As opposed to WABA's, the use of gadolinium does not condition the location of fresh assemblies in the most favorable positions. Typically the position (6.2) of 3-loop cores, occupied by a control rod, precludes the loading of a fresh assembly with WABA type burnable absorber, whereas the use of this position for a fresh assembly using gadolinium has made it possible to gain up to 6 days of operation in a specific case.
This freedom of positioning is especially important in transition cycles, specifically from 12 to 18 months in which the transition should preferably be performed in the shortest time possible, even in a single cycle, for the purpose of entering the Spring-Autumn refueling system as soon as possible in alternating years so as to reduce the cost of replacement energy and thus the variable average cost of the electric subsystem.
This "rapid transition" requires a major boost in enrichment, typically from 3.6 to 4.2%, which creates strong power gradients inside the core. This requires the use of consumible poisons in most fresh assemblies, which impacts the need for the above mentioned freedom of assembly positioning. In addition, this situation creates new gadolinium enhancement opportunities, as it permits asymmetric arrangements of the poison in the zones near the core periphery in which absorbent is only needed in the most internal quadrant(s), which saves on inserting absorbent in the externals, the power of which will already be quite reduced due to the existence of strong radial leaks.
We should not forget, as this is in itself a major technological leap, the ability of gadolinium to adapt to problem solving or the specific needs of each reactor. In fact, the ability of locating the gadolinium pellets in any radial or axial position inside the assembly makes it possible to address problems of excessive irradiation of an internal component, as the shutdown margin increases if unavailability of a control rod should so require, the axial power distribution flattens if limitations in FQ appear, etc. These possibilities are not new, as they have been successfully experimented with in BWR technology, where initial problems owing to the strong radial and axial heterogeneity of the geometry of these raectors have been more than outweighed by the achievements of applied engineering in solving these limitations. As in other lucky coincidences of life, the efforts made to compensate for one defect have amply overcome the initial reference.
Last but not least, the reduction of times, costs and doses associated with the disappearance of discrete poisons must be mentioned, since this eliminates the need to load and unload them in the assemblies, the need to manage them until they are processed as waste and the considerable risk that in the end they will represent a direct economic penalty.

ENERY AND ECONOMIC COMPARISON

In addition to the above mentioned advantages obtained with the combined use of enriched uranium axial blankets and partial length gadolinium as a burnable absorber, a comparison has been made in strictly quantitative terms to assess the use of this advanced product in terms of the energy obtained and the costs savings in the first part of the fuel cycle.
An analysis has been carried out of the enrichment required and the associated fuel cost in pta/kWh to satisfy the typical energy requirements of a three-loop Westinghouse reactor operating in 18-month cycles and with a very high total use factor of the order of 90%. The advanced product described above, i.e. axial blankets with 2.6% enrichment and 305 cm. long gadolinium, is compared with the currently used product, i.e. uniformly enriched fuel using WABA's as absorbent.
The comparison is made for exactly the same cycle energy, i.e. 490 DEPP, and in terms of average required enrichment and associated cost. The letdown burn obtained, 45000 MWd/tU, is currently considered as optimum and involves loading 64 fresh assemblies in a low leak scheme to gain reactivity and with a hot channel factor of 1.50 without uncertainties
The methodology used in the comparison is state of the art of core analysis, i.e. three-dimensional modelling with power and burnable detail by fuel rod, and using the

neutronic code system APA (ALPHA-/PHOENIX/ANC).
The load schemes are reasonably optimal, and also the number of WABA's or of rods with gadolinium has been reduced to a minimum in order to obtain a rigorous energy and, in particular, economic comparison.
The comparison was made for the equilibrium cycle, in order to overlook previous differences in the burn of assemblies present in the core. This equilibrium was reached by burning three cycles with constant supply.
The results obtained indicate the need for uniform 4.15% enrichment in the study with WABA's to fulfill energy requirements, as opposed to an arithmetic mean enrichment of 4.0908% in the advanced product, obtained with a 335 cm. central zone with 4.26% enrichment and 2.6% enriched axial blankets. 500 absorber rods are required for the WABA solution, as opposed to 392 for the gadolinium solution.
Therefore, an average enrichment savings of 0.592% is obtained. On the other hand, the 4.26% central enrichment is only 0.11% higher than the uniform enrichment for the WABA's, and therefore this does not have any impact on licensing of fresh and spent stores of the major Spanish PWRs (limited to 4.30% and 4.50%).
To evalute the economic savings, the prices of concentrates, enrichment and conversion provided by EURATOM in late 1995 have been used, and financial costs stemming from advance payments during these processes have been accounted for. The manufacturing prices used are representative of the situation being analyzed.
The results show a savings in total kWh cost of almost one cent for the first part of the fuel cycle by using the advanced product. The absolute valor of this savings is one hundred million pesetas for each operated cycle.

FUTURE CYCLE STRATEGIES

The above comparison is perfectly valid for the current situation of 18-month cycle operation. However, as a result of the power uprate process already underway for the major Spanish PWRs, the validity of these conclusions for the post-uprate periods, i.e. with thermal powers of between 2900 and 3010 MW, must be verified.
The studies performed to date indicate that the same requirements regarding days of operation at full power and for 2900 MW thermal power are accomplished by loading exactly the same number of fresh assemblies through the increase of letdown burn up to 4800 MWd/tU. This increase is significant and has a very positive impact on manufacturing costs. At the same time, it is important to consider more advanced cladding and structural materials that are capable of permitting satisfactory fuel operation at these high burn up degrees.
The same as for pre-uprate conditions, an equivalent study has been performed to compare the current product to the advanced product using axial blankets and gadolinium based on the same energy requirements, i.e. 490 DEPP and 2900 thermal MW, and with the same methodology and the same level of detail for the degree of refueling scheme optimization and equilibrium cycle modelling.
In the current product using WABA's as absorbent, cycle energy requirements are fufilled with 4.50% enrichment, whereas with the advanced product an average enrichment of 4.4436% is required that is achieved with a 4.64% central enrichment and 2.6% for axial blankets.
Therefore, the result is an average enrichment savings of 0.0564% and a central enrichment 0.14% higher than when WABA's are used. This does not pose any special problems, and in fact this enrichment is lower than the one used in several North American reactors for operation with 24-month cycles.
An economic evaluation of these results indicates that use of the advanced product provides an economic savings in the first part of the fuel cycle costs of 115 Mpta. per cycle, which means a relative savings of 1.2% with regard to total costs.

EXPERIENCE IN OTHER COUNTRIES

Gadolinium is the predominant neutronic absorber in the European and Japanese markets, whereas it is not as prevalent on the North American PWR market.
ENUSA is presently manufacturing fuel assemblies for the Belgian plant of Doel Unit 4 with 8 gadolinium rods per fuel assembly and a concentration of 8% per assembly. The rest of the Belgian plants that operate 18-month cycles also use gadolinium.
In the French market, the only burnable absorber used is gadolinium, which is required for the new operating strategy of 18-month cycles in the major 1300-1400 MW units. For the Swedish market, ENUSA manufactures fuel assemblies containing eight rods with 5% gadolinium for Ringhals Unit 2. In the Japanese market, the Ohi plant has pioneered testing of assemblies containing 10% gadolinium, and it is the only burnable absorber used in this market.
As indicated hereinabove, axial blankets are being used in all BWR reactors. For PWRs and for the North American market, Westinghouse's experience with axial blankets is significant, with approximately one hundred full regions delivered up to 1994.

CONCLUSIONS

The advanced PWR product is a technological leap in the search for significant improvements in the availability and total variable costs of nuclear generation.
The outstanding advantages are design flexibility, gains in days of cycle operation, solutions to problems concerning core internal components, reduction of lost time and personnel doses due to waste, etc. In purely quantitative fuel terms, detailed studies with state-of-the-art methodology show that the advanced product provides a savings of 0.06% in enrichment, with an economic impact of 100 to 115 Mpta. per cycle for the first part of the fuel cycle.

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View of the skeleton of a fuel assembly from the upper head.