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Framatome ANP extended burnup experience and views on LWR fuels

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> *" Those who believe in progress*
> *run the risk of being born too early"*
> *Oscar Wilde*

In every sense of the term, nuclear fuel forms the core of nuclear power plants. Although there are many equipment items important for their safety function or for their participation in NPP availability, the fuel, in essence renewable, is one of the key elements which have to be acted upon if utilities are to be helped to fulfil their mission of generating power in total safety and supplying the kWh to their customers at the best price.

Nuclear fuel is also the core business of the Framatome-ANP Fuel Business Group: pooling and rationalizing the available skills - technical, cultural and human - supplied by each of the partners forms a challenge [1] which it is up to each and every one to meet in a cooperative spirit.

Where Are We Coming From?

Since the end of the seventies, when most of the installed generating capacity came on stream in Europe and the USA, the management of LWR cores has radically changed due to a number of advances in the nuclear fuel field. These fuel enhancements have been made possible by huge R&D programmes and by perfecting the analytical methods implemented to support the new fuel designs before obtaining their qualification through in-reactor experience feedback.

For a utility which intends to generate power during a given period - typically between 12 and 24 months - the most economical answer is to find a trade off between loading the smallest possible number of assemblies enriched in U235 to the highest possible value, and the lowest dispersion of the resulting burnups when the assemblies are discharged. Of course, other significant parameters such as outage duration and back end costs have also to be considered.

Figure 1, specific to a 900 MWe PWR but valid in principle for any other unit, illustrates the entire range which has been covered by the utilities: with the same origin (52 assemblies enriched at 3% U235 for 12-month cycles), the fuel managements practised in 2000 in most of the European PWRs were still situated, owing to the French NPPs, in the 3.7%-4.2% band (***Figure 2***), with cycle lengths between 12 and 18 months; outside EDF, European units already operate at the limit of their respective authorized enrichments (4.5%-4.7%) and in the USA, 40% of PWRs operate in 20-24 month cycles, using assemblies enriched between 4.6% and 4.95%.

The rise over the 1980-2000 period in the average burnups reached by the discharged fuels is supplied per world region for the PWR ***(Figure 3a)*** and the BWR ***(Figure 3b)***. Three to five years hence, assemblies with average burnups of 50-52GWd/t will be discharged in large numbers, with peaks at more than 55GWd/t. It is important to observe that, given the qualification timeframe, the design of these assemblies had to be undertaken as early as the first half of the 1990s: this means that at the very least, fifteen or so years elapse between the first engineering office sketches and the supply of energy by cores fully loaded with the new fuel assembly.

Figure 1 primarily shows that the existence of enrichment limits is a major constraint to continuing the fuel cycle cost improvement from the in-reactor fuel management standpoint. At the present rate of reload enrichment increase, the level of 5% U235 will be the general rule around 2010-2015 in all reactors which already have - or will have - authorization. Five years later, discharging will take place of the first reloads made up of assemblies designed and dimensioned for this purpose, at 60-63GWd/t average and 70-73 GWd/t maximum assembly burnups.

Brief Outline of Fuel Assembly Upgrades

If we take as a reference the UO_2 fuel assembly (PWR or BWR) as it was, coming from the USA at the start of European nuclear development, we note that a first wave of three major upgrades, improved with time, rapidly enriched the original concept, not only for UO_2 but also for MOX or REPU fuels.

- Nozzle **removability**: this new feature soon became necessary when the first assembly damage occurred during handling; today, beyond the technological solutions found, the optimum solution remains to conduct the restoration of assembly during outages, requiring fast action and zero waste. This expectation has found a response in the top nozzle quick disconnect system of the **HTP** and **ALLIANCE** fuel assemblies.

- The use of **Zircaloy**, a less neutron-absorbing material than the original stainless steel or Inconel, now in general use for the fuel rods, guide thimbles and mixing grids. Various versions of this material, both in texture, chemical composition (through tin content adjustment) and in form (duplex, coating of a corrosion-resistant outer liner, for Siemens-designed hot reactors) have had to be developed to recover margins continuously eaten into by operating conditions.

- The fitting of an **anti-debris device** at the bottom of the assembly to protect the rods from attack by any loose parts. We now have several devices at Framatome-

ANP: **Fuelguard**, **IDF** and **Trapper**, similar in principle and effectiveness (***Figure 4***).

A second wave of fuel upgrades came into being when the time came to enhance fuel assembly core management through "low leakage" loading patterns, with the aim of improving the overall neutron balance. This category covers several enhancements.

- The use of **burnable poisons** to provide fine control of the power generated by the fresh fuel rod bundle. Although many variants have been perfected - discrete poisons (clusters outside the assembly) or lumped poisons (co-milled with Uranium or deposited on the outside of the pellets) - Framatome-ANP has always stayed faithful to the UO_2-Gd_2O_3 mixed oxide, which is readily adjustable by content.

- The improvement of the **mixing capacity of the grids**, in order to get the most out of the relaxation of the $F_{?H}$ and F_Q-LOCA factors arising from the updated safety analyses. Owing to its threefold task of providing coolant mixing, restraining the fuel rod bundle and contributing to mechanical strength, the grid is the area with greatest innovation potential for the designer. The **HTP grid**, commissioned in 1988, is a significant example of this: its main feature is strip doublets which produce curved internal flow channels and which also serve as spring elements to firmly hold the rods in radial alignment. Similarly, one can point to the **Mark-BW grid**, which is characterized in particular by its well-known unlocking-locking key used during rod loading, but above all by its outstanding critical heat flux performance which has been reproduced with the **ALLIANCE grid.**

- The search for **advanced materials** intended to ultimately replace Zircaloy, whose in-service results indicate that it is reaching its technological limits. On a pre-emptive basis, Framatome decided to undertake from the mid-eighties a series of huge programmes for the research, selection and qualification of new alloys using our entire Company resources while calling upon those of the CEA and university laboratories: the **M5** solid-wall alloy, boasting extremely high irradiation performance ***(Figure 5)***, is now, and will be for many years, the reference commercial alloy for the claddings and structures of Framatome-ANP PWR products almost everywhere in the world; for the Siemens-designed plants, considered hottest, we have alloy **DX-D4,** which is the most accomplished version of the Duplex alloys [2].

- On the fringe of the development work just referred to, the occurrence – fortunately rare – of in-service incidents is a strong incentive to improve fuel products. For example, what utility, having experienced the RCCA incomplete insertion incident, has not appreciated all the advantages of the **Monobloc**™ guide thimble equipping our AFA 3G and ALLIANCE fuel assemblies?

- In the BWR fuel field, the motivations behind assembly upgrading are the same as for the PWR: establishing wider margins to design limits for enhancing operating reliability and exploiting an appropriate amount of them in order to optimise cost-effectiveness. However, the near-absence of any constraint other than that dictated by the support of the fuel channel outer envelope allows the near-continuous flow of new features. The history of the successive versions of our BWR assemblies illustrates this trend.

- The transition from the 8x8 fuel assembly used in the late 1970s to the 9x9 fuel assembly (at the beginning of the 1980s) with a central water rod brings a 20% reduction in average linear heat generation rate, and increases the margin to the critical power ratio.
- The replacement of the innermost rods with additional water rods, then with an internal water channel of square cross section (1992) as the first **ATRIUM** design, produces a very flat thermal neutron flux distribution, and thus, by permitting a more homogeneous distribution of U235 enrichments in the fuel rods, leads to better fuel utilization.
- The introduction of the **Ultraflow** spacers with swirl vanes has increased margin to critical power and that of the **Fuelguard** anti-debris device has contributed to prevent debris-related damage; the implementation of part-length fuel rods for improving shut down reactivity margin and reducing the 2-phase pressure drop, as well as of natural Uranium blankets, axial gadolinium loading and enrichment zoning, have improved fuel utilization.
- In the mid-1980s, when PCI was the root cause of the majority of BWR fuel failures, cladding with pure Zirconium inner liner was introduced. The development and testing of improved cladding materials continued, resulting in the introduction of Zy-2 cladding with an iron-enhanced Zirconium liner.

- Beyond these intrinsic product improvements, fuel utilization can also be made more efficient by optimizing the NSSS-fuel combination. To do this, Framatome-ANP's Engineering Group has devised US-3D, a three-dimensional system for continuous monitoring of reactor core power distribution, consisting of fixed neutron instrumentation based on rhodium self-powered neutron detectors installed in the core and giving permanent access to local fuel duty conditions. The available operating margins to authorized limits are thus on permanent display to the operator.

To wrap up this outline of fuel technological upgrades [3], let us reiterate how much the anticipation of market needs is paramount: it is difficult to know how to undertake and manage heavy, high-cost R&D programmes so that they come to fruition at just the right time. If they come to fruition too late, there will be an inevitable loss of market share; if too early, there will be the risk of poor sales. To protect itself from risks like these, Framatome-ANP's policy has always been to foster partnerships with the utilities.

Framatome-ANP's High Burnup Experience at a Glance *(Figures 6)*

Framatome-ANP benefits from experience built up for nearly forty years, with the fuel families developed by Framatome and Siemens: 95,000 PWR and 45,000 BWR fuel assemblies have been supplied throughout Europe, the Americas, Asia and South-Africa.

- Concerning PWR fuel, more than 830 of our assemblies have reached burnups between 50 GWd/tU and 65 GWd/tU. This experience in high burnups has been gained through many different core management strategies, from 12 to 24 month cycle length, and from 1/6 to 1/2 core reload size ratio.

- For BWR fuel, thanks to the implementation of 9x9 then 10x10 designs, the average burnups have been increased from 25 GWd/tU at the middle of the 1980s to more than 40GWd/tU at the end of 2000, with four Atrium-10A LTAs discharged at 71 GWd/tU representing by far the highest value in LWRs world-wide. There are altogether 43 BWR fuel assemblies with a burnup higher than 50 GWd/tU, and 13 complete reloads have reached an averaged batch burnup higher than 40 GWd/tU.

- Since the first MOX fuel loading in 1966 in Germany, more than 2700 MOX fuel assemblies (mainly of AFA 2G, Focus and Atrium types) have been irradiated in 36 European LWRs. Today, most of the MOX batches are discharged at burnups of around 45GWd/tHM reached after four annual cycles of irradiation, with some individual elements irradiated up to 54-55GWd/tHM. Our experience includes MOX rods with plutonium fissile concentration amounts up to 4.8 w/o (about 7.1 w/o Pu). This extensive MOX European experience shows that no technical problem resulting from the MOX fuel has ever been encountered, and the reliability of our MOX fuels is as good as for our UO2 fuels [4].

- Duplex claddings were developed especially for the very demanding Siemens PWR to further leverage the proven mechanical characteristics of Zircaloy-4 and significantly improve corrosion behaviour. Industrialised since 1989, Duplex cladding tubes have been irradiated, successfully reaching maximum assembly burnup of 62 GWd/tU. In addition, LTAs with 5% U enriched fuel rods are going to be inserted in 2001 in the Gösgen NPP for irradiation during at least 5 annual cycles [5].

- More recently, the M5 alloy, a ternary Zr-1.0Nb-O, has been industrialised to fully equip our products. This results from the extensive irradiation programs implemented in 28 commercial PWRs world-wide, that have successfully shown its impressive benefits at extended burnup relative to corrosion (20 µm at 70 GWd/MTU), hydriding, creep and growth behaviour (=0.7%). A rod burnup value of 78 GWd/MTU is planned to be reached in early 2002 after the completion of a seventh irradiation cycle in progress in a Framatome reactor.

- For BWR, the Zy-2 LTP cladding material, produced using a special Low-Temperature-Process, has been found to exhibit an optimum resistance to both nodular and uniform corrosion. As a countermeasure against PCI, Fe-enhanced inner liner was developed to prevent secondary damage. As of today, irradiation experience has been cumulated on more than 500,000 Zy-2 LTP fuel rods including up to 62 GWd/MTU with positive results.

What Track Record?… For What Prospects?

Generally speaking, as contributors to nuclear power generation, we all have reason to feel proud of our collective track record.

- All things considered, nuclear power generation remains economically competitive. The plants have reached maturity, for many the costs are written off, and their operation is fully controlled. In the USA, where plant closures were feared, there are clear signs that this will not happen: rather there are examples of buyout of individual plants by consortia, the extension of operating licences to 60 years, projects for power uprating and for the resumption of work at the construction sites most advanced at the time of interruption. In Asia, despite a slowdown due to the last economic crisis, new units are being commissioned and new jobsites opened.

- Nuclear energy is environment-friendly: it meets the growth needs intrinsic to any human society and ensures breathable air for future generations. The findings of the “Dilemma” report of European Union DG XVII [6], which assesses the consequences of the Kyoto protocol, are clear-cut: typically, for France ***(Figure 7)***, only a scenario based on strong nuclear maintained at around 70% of power generation needs will enable it to meet its commitments up to 2025. Turning to waste, we observe that, for example, if today's assemblies had kept their original irradiation capacity of 33 GWd/t, EDF would need almost an extra 500 tonnes or 1000 assemblies per annum to generate its usual production level of 400TWh. Further, the reprocessability of all our products, which enables the residual energy material (plutonium) to be recovered for recycling, along with their capacity for interim storage, justify the application of the label "Green Fuel" to nuclear fuel.

All of this means that Framatome-ANP's track record on the fuel front speaks for itself, we have a hand stuffed with aces:

- reliable, high-performance fuel products: AFA 3G, HTP, Mark-BW, Atrium fuel assemblies, M5 and Duplex materials, which allow us to meet the range of market needs, even including some local specific requirements (Focus assembly for Siemens reactors, Mark-B assembly for B&W reactors), and are able to accommodate MOX or REPU,
- fully-integrated fabrication facilities which cover the whole spectrum of assembly manufacturing operations,
- a comprehensive array of services and associated equipment, served by qualified professionals.

The result is that with 40% of the market share, we are the foremost vendor of LWR fuel world-wide ***(Figure 8)***. The objective we have set ourselves, *at the very least*, is to hold on to this advantageous position.

In the areas of skills and industrial resources, Framatome-ANP now possess extensive facilities in Belgium, France, Germany and USA, which we intend to adapt to our needs but also to streamline, with the aim of achieving better efficiency.

As soon as Framatome-ANP was created in January 2001, we embarked upon a large-scale restructuring operation, FIT2WIN, aimed at characterizing and gauging best practices and individual skills at identifying redundancies. By combining the recommendations made by the mixed analysis groups with the strategic interests of the market and our shareholders, we should be in a position by end 2001 to settle upon the organizational structure which best meets the global objective of cutting our operating costs.

In the fuel-specific areas of design, R&D and fabrication, we have a substantial progress margin, particularly in the PWR field, to streamline our organization and working practices: sales force, engineering, etc. There is the strong expectation that in the short term the use of alloy M5 can be extended to the assemblies of the German market, and that the HTP grid can reinforce any other assembly skeleton. We have at Framatome-ANP, in the **ALLIANCE** assembly, developed and built by Franco-American teams, a PWR assembly capable of reaching burnups of at least 70 GWd/t, thus meeting the needs of the most economic fuel managements that can be contemplated with 5%-enriched Uranium. Its in-core qualification has been ongoing in European NPPs since 1999 and in American NPPs since 2000. It is destined to be the reference fuel for the future EPRs. With the products of the **ATRIUM** family, we also have a BWR fuel assembly capable of getting the best out of the 5% enrichment. Its advanced variant Atrium-12 is the reference product of the SWR-1000 reactor.

Conclusion

Mention has been made several times of the 5% enrichment limit which is the source of the 70-75 GWd/t burnups. On the assembly designer's time scale, this limit is close to being reached and the right fuels for this situation are already at hand. The question which will then arise is whether to maintain the R&D effort in the future, bearing in mind that this effort is central to the accomplishing of fuel performance gains whose impact is felt well beyond fabrication costs. It is in our power to achieve more, but if we are to aim for more without raising the number of "*those who believe in progress run the risk of being born too early*", we shall soon need to receive from utilities tangible signs about the future and signs which go beyond benevolent neutrality.

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[5] W Beck, G Meier, *"Fuel and core design for 5 cycles exposure with high enriched fuel in the Gösgen nuclear power plant"*. Topfuel 2001. Stockholm. May 27-30, 2001.

[6] Commission of the European Communities Directorate General XVII *"DILEMMA STUDY: Study of the Contribution of Nuclear Power to the Reduction of Carbon Dioxide Emissions from Electricity Generation"*. July 1999.

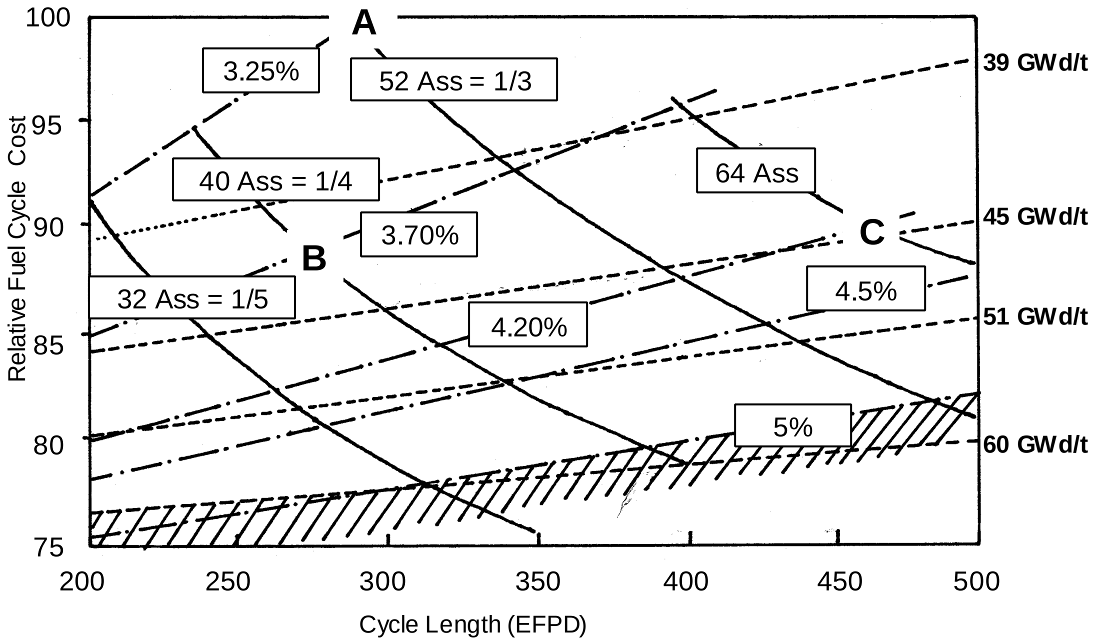

Figure 1: *Relative fuel cycle cost*

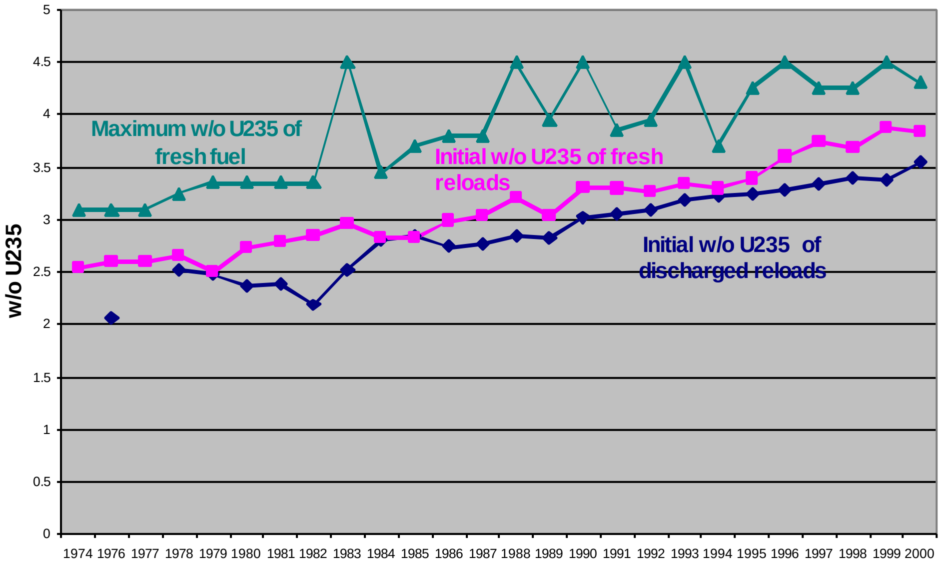

Figure 2: *w/o U235 evolution over the 1980-2000 period*

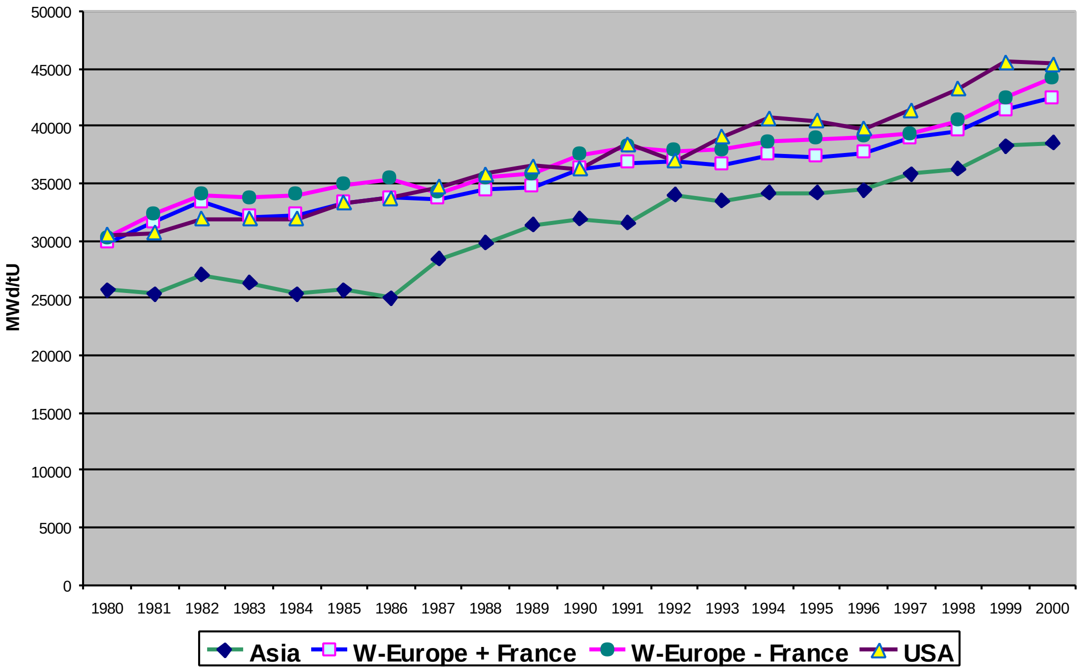

Figure 3a: *Regional discharge burnup comparison over the 1980-2000 period (PWR)*

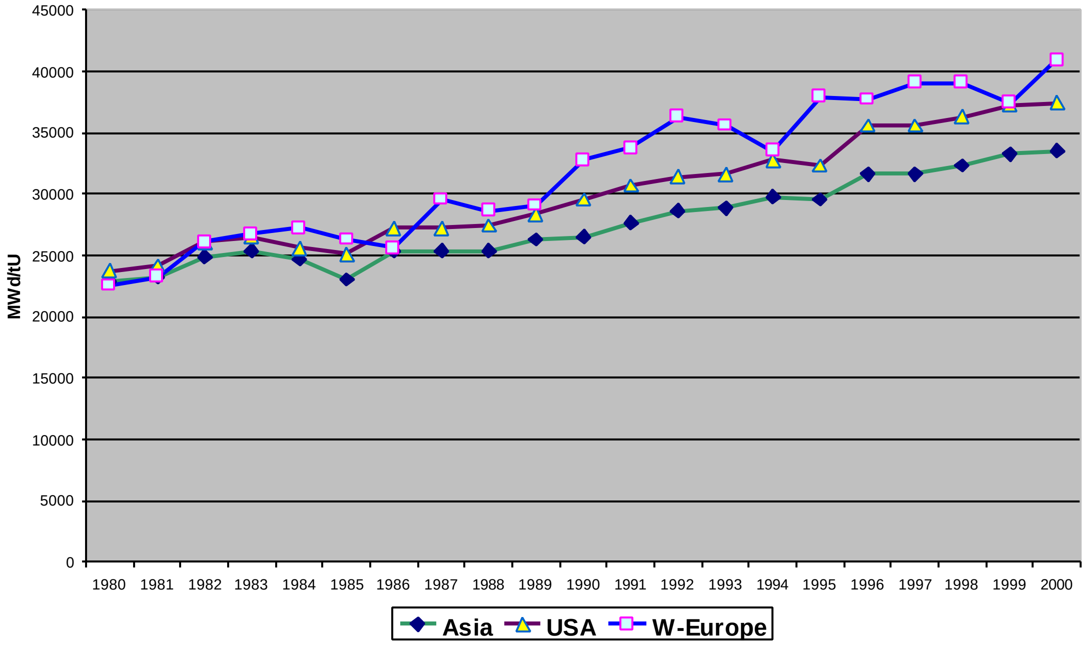

Figure 3b: *Regional discharge burnup comparison over the 1980-2000 period*

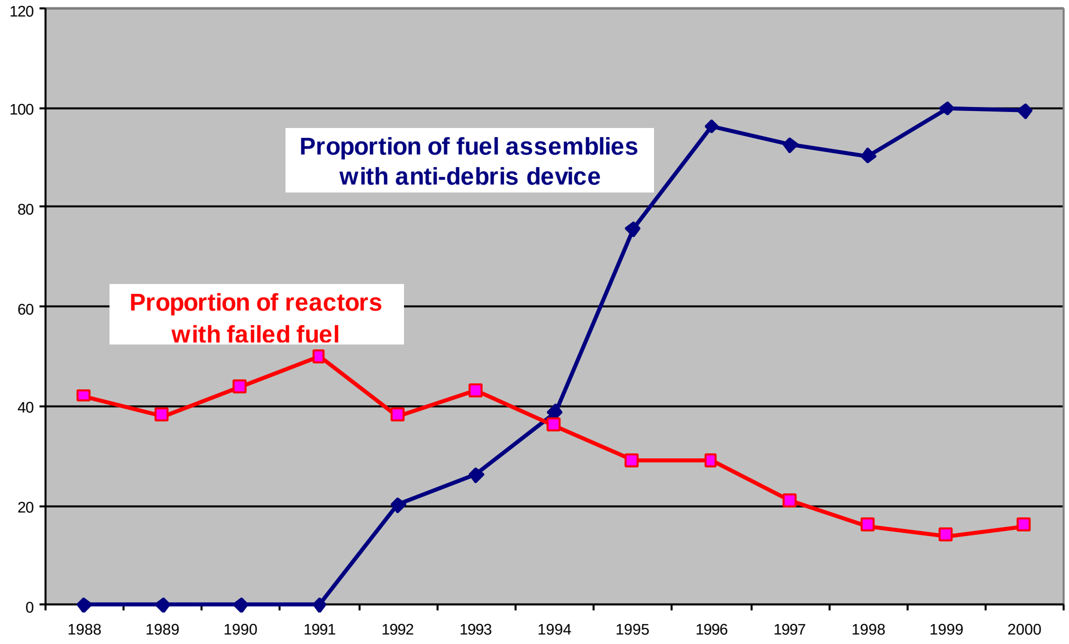

Figure 4: *Fuel failure reduction (%) following the introduction of anti-debris device*

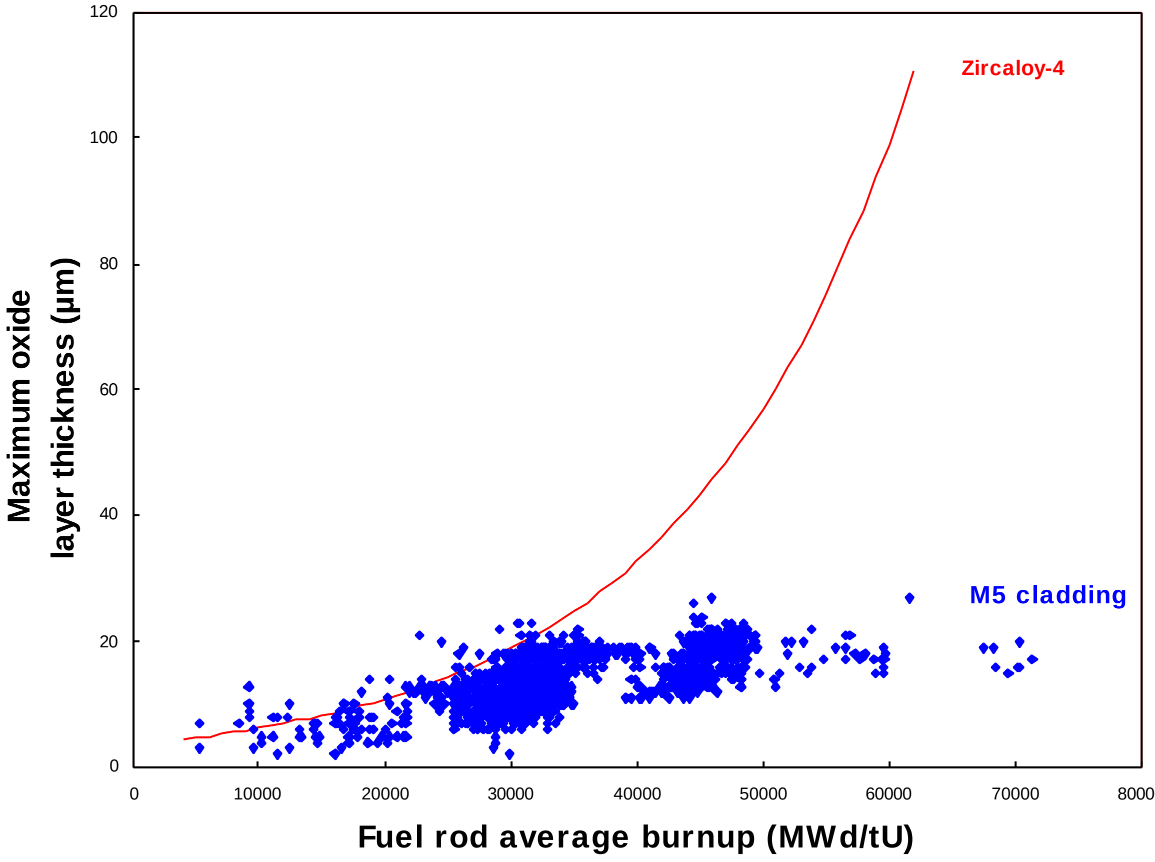

Figure 5: *Corrosion behaviour of M5™ compared to Zircaloy*

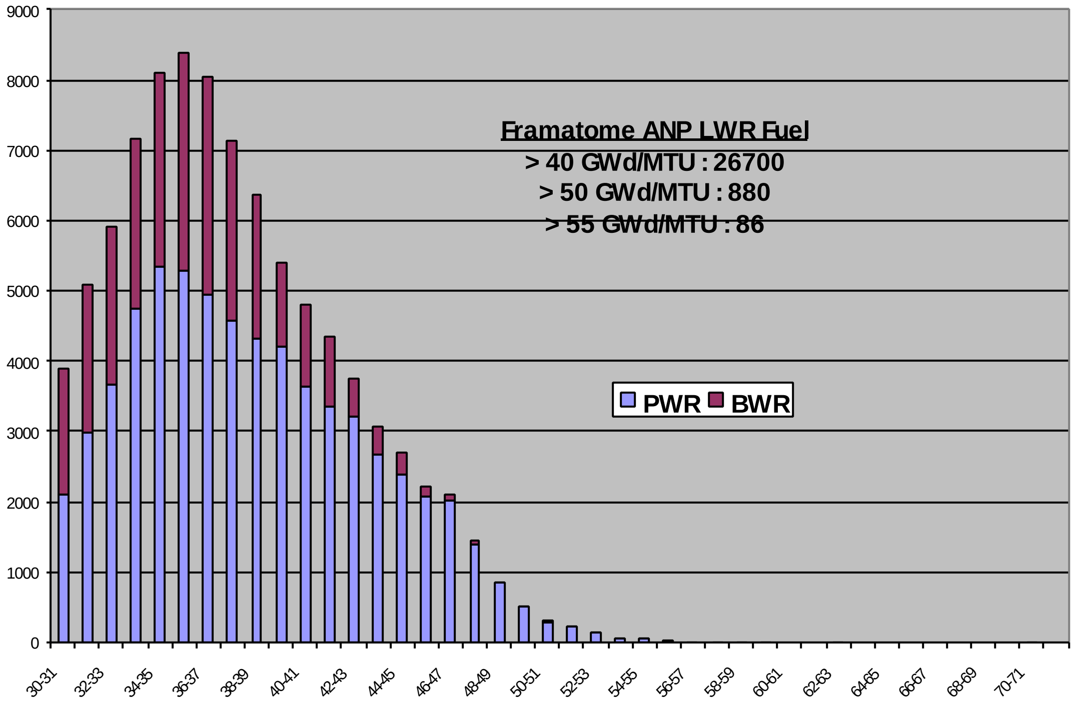

Figure 6a: *Framatome ANP High Burnup Experience (PWR & BWR)*

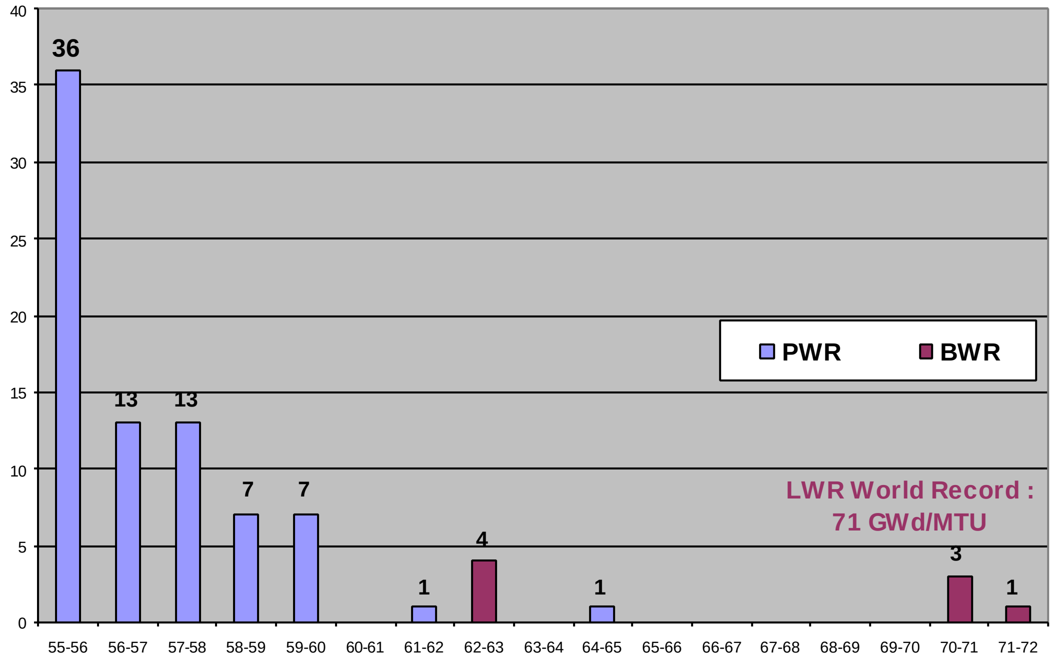

Figure 6b: *Framatome ANP High Burnup Experience*

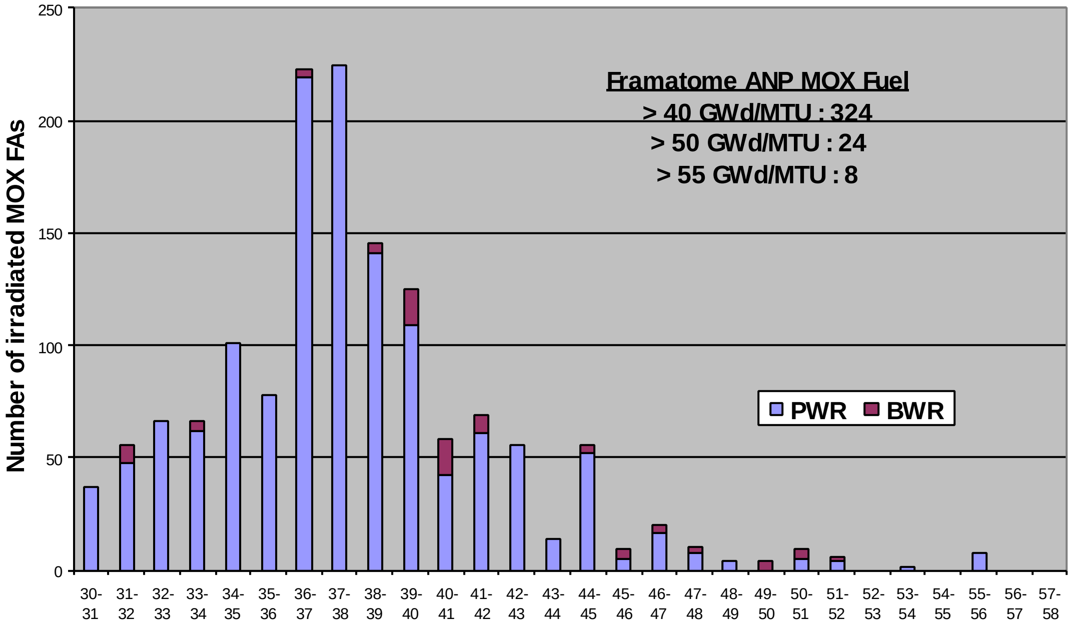

Figure 6c: *Framatome ANP MOX High Burnup Experience (PWR & BWR)*

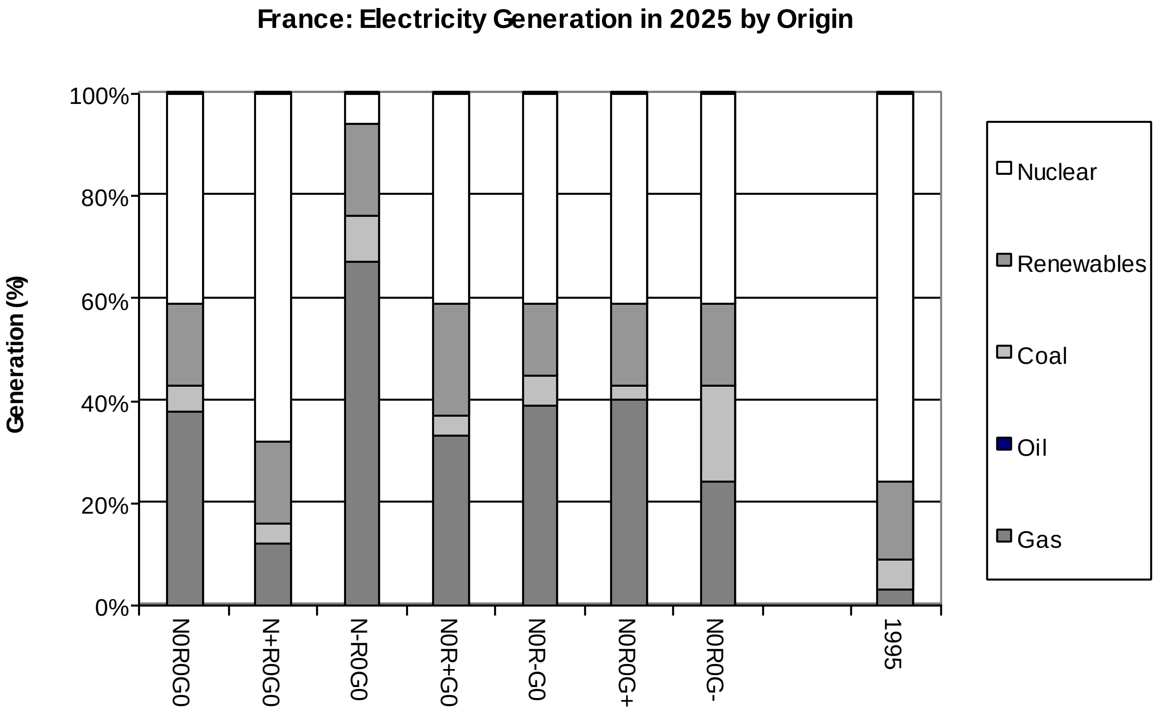

Figure 7a: *Kyoto Protocol*

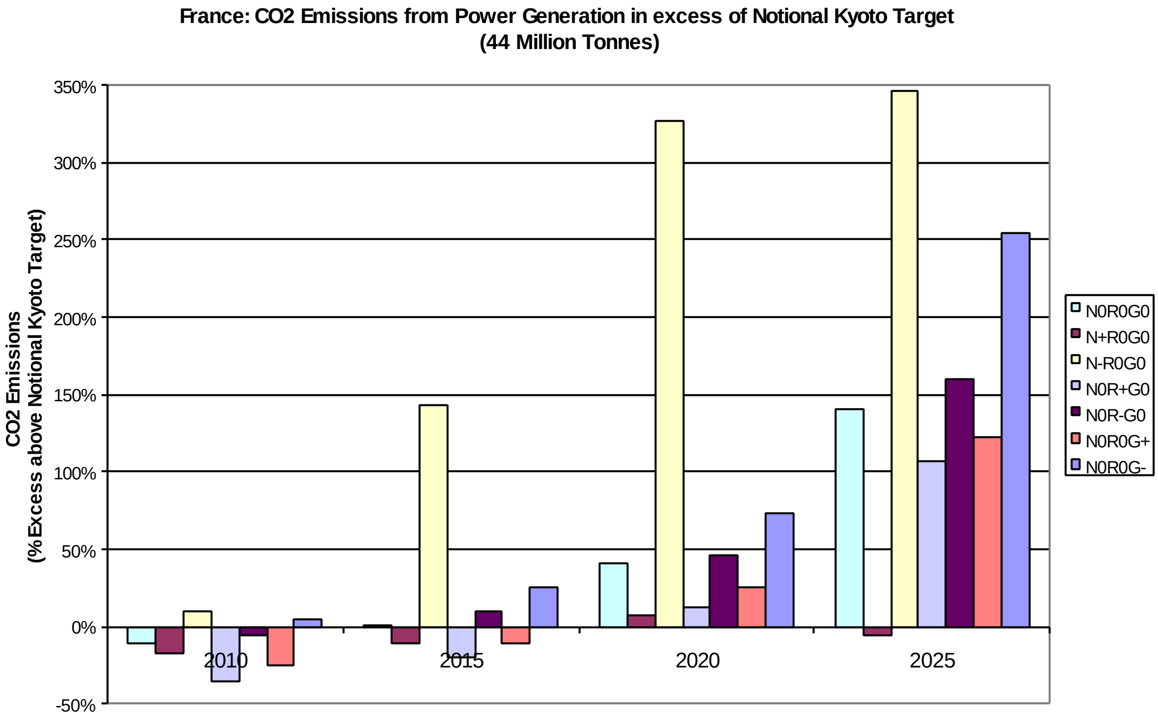

Figure 7b: *Kyoto Protocol*

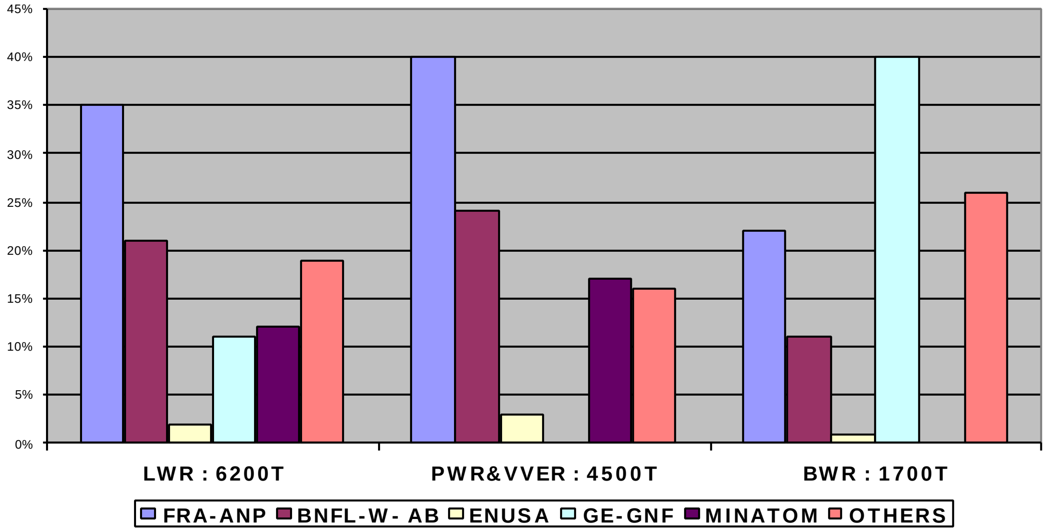

Figure 8: *Fuel market shares (1998-2000)*