Current Trends in Nuclear Fuel for Power Reactors

A. Introduction

1. Since 1986 growth in nuclear capacity around the world has averaged 1.5% per year. Growth in nuclear electricity generation has been almost twice as fast, at 2.9% per year (IAEA 1986-2006). Much of that increase is due to improved performance and increased capacity factors of existing plant, which have been aided by, among other things, improvements to the performance and reliability of nuclear fuel.

2. Nuclear fuel is at the heart of a nuclear reactor, and the safe and economic behaviour of this fuel is a key factor in the continuing long term development of nuclear power. This was recognised early, with the key issues determining the economic drivers for fuel development summarized, for example, in 1977 in Oak Ridge National Laboratory's report, "A Survey of Nuclear Fuel Cycle Economics 1970 – 1985" (Prince et al. 1977). It was originally anticipated that there would be a first stage involving pool storage of spent fuel, a second stage where reprocessing would lead to the use of plutonium bearing (MOX) fuels in light water reactors and finally the use of fast breeder reactors. The timescales anticipated are now seen to have been extremely optimistic, and the economics are no longer so clearly driving towards reprocessing and fast reactors. However, the drivers of uranium availability and the costs of enrichment, fuel manufacture and waste management that were identified in 1977 are still valid today, and they have ensured continuous development and improvement in nuclear fuel.

B. Nuclear Fuel Types

3. The vast majority of nuclear fuel used today consists of uranium dioxide pellets contained in a sealed tube of zirconium alloy to make a fuel rod. There are many variations in the way the rods are supported in assemblies or bundles for use in the reactor, and improvements in both the fuel rod and assembly structure have been continuous. Table 1 lists typical features of the fuel used in power producing reactors today.

TABLE 1. Fuel Features

Reactor type	Fuel material	Fuel rod cladding[1]	Typical Assembly	Enrichment
AGR	UO_2	Stainless steel	Circular array of pins in graphite sleeve	2 - 4%
BWR	UO_2	Zircaloy-2	Square array	Up to 4.95%

[1] Zircaloy-2 and -4 are alloys of zirconium with about 1.5% tin as the main alloying element. Magnox alloy is magnesium with about 1% aluminium or zirconium. Both E110 and E635 are alloys of zirconium with about 1% niobium.

Magnox	U metal	Magnox alloy	-	Natural
RBMK	UO_2	E110, E635	Circular array	Up to 2.8%
PHWR	UO_2	Zircaloy-4	Circular bundle	Natural
PWR	UO_2	Zircaloy-4	Square array	Up to 4.95%
WWER	UO_2	E110, E635	Hexagonal array	Up to 4.95%

C. Economics

4. The most important determinant of nuclear power's future is cost-competitiveness compared with alternatives. Nuclear power plants have a 'front-loaded' cost structure, i.e. they are expensive to build and comparatively cheap to operate. There is, therefore, a strong economic incentive to maximise the utilisation of the asset. This means fewer unplanned outages and, for plants with batch reloading, longer operational cycles and shorter outages. The load factor of modern nuclear plants with batch reloading is often over 95%, and two year fuel cycles are becoming common. For plants with on-load refuelling capabilities, maximising utilization of the asset has meant longer fuel dwell (i.e. increasing the total time a fuel element spends in the reactor). For all power plants there is also a need to minimise waste arisings, due to limited on-site storage facilities and the cost of waste removal and treatment.

5. For nuclear fuel, this has meant a need to endure longer operational periods and to demonstrate increased reliability. Fuel failure in operation is expensive for an operator, particularly if it limits output or increases outage durations. Figure 1 shows how average cycle length, measured as effective full power days (EFPD) has evolved for BWR and PWR plants in the USA.

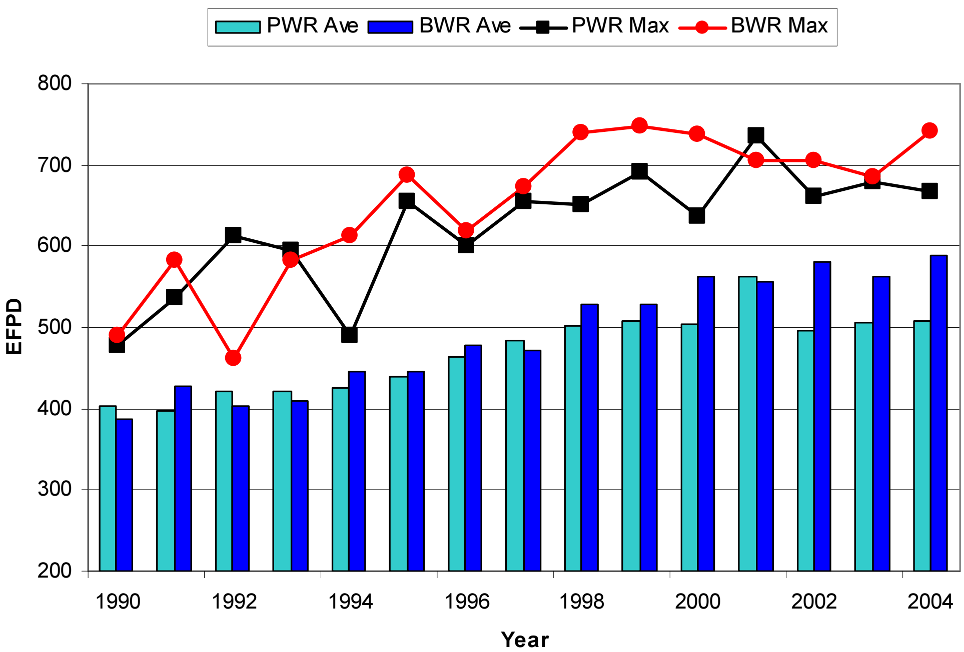

Figure 1. Increasing average cycle lengths for fuel elements in PWRs and BWRs in the USA.

6. The cost of nuclear fuel is small compared with the cost of a nuclear power plant. But fuel is still expensive, prompting continuing efforts to increase performance. Increasing the energy obtained from fuel incurs both additional costs and savings, with costs coming from the need to add additional enrichment and the management of the high burnup waste material, and savings coming from the need to manufacture and dispose of fewer fuel assemblies. The balance of these costs and savings to date has favoured an increase in fuel burnup, although economic studies suggest that the additional costs for further burnup increases may not be so favourable.

7. The effect of these drivers has been an increase in the average burnup of the fuel used in all reactor types. The burnup, measured in gigawatts days per tonne of heavy metal (GWd/tU), is a measure of the energy extracted from a given weight of fuel. Figure 2, which presents the trends of fuel burnup since 1970, shows that the average burnup of light water reactor types has doubled. To achieve this increase in burnup, the main change has been to increase the enrichment of the fuel, typically from 2.5%U-235 to around 4.5%U-235, with a current maximum of 4.95%U-235. Additional changes, as described below, have also been made to fuel materials and their manufacture to ensure reliability over the extended times spent in the reactor.

8. The increase in burnup has been least marked in the reactor types that use natural uranium as fuel, and whilst the few remaining Magnox reactors are all near final closure, the PHWR vendors and reactor operators are starting to investigate the use of slightly enriched uranium, which will give them the opportunity to double or triple average burnup.

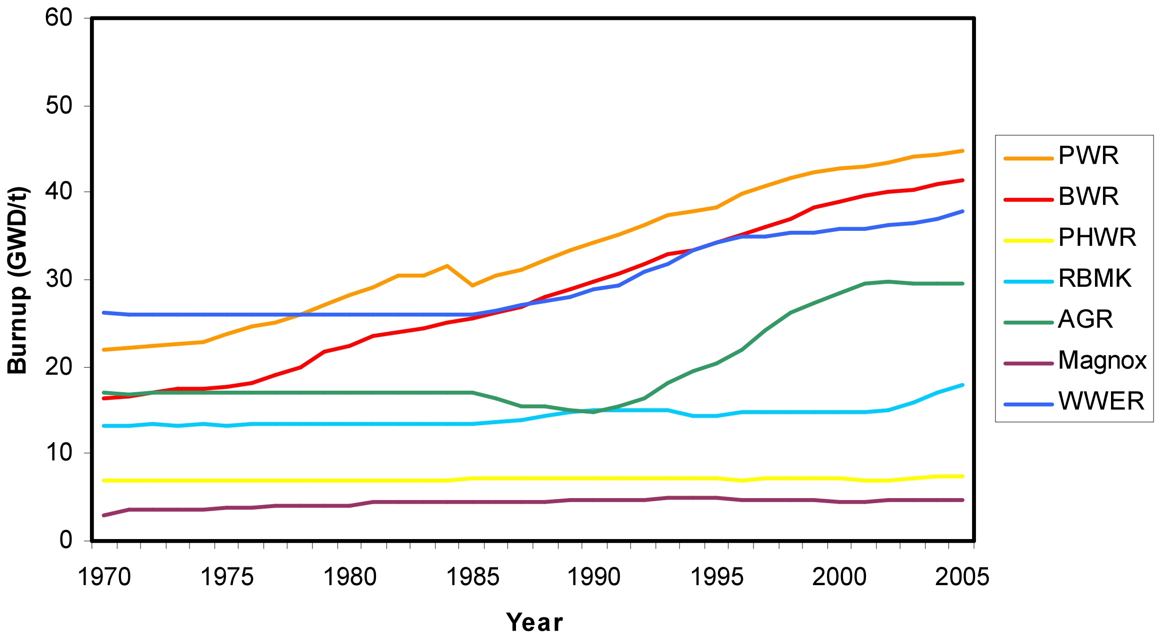

Figure 2. Trends in fuel burnup for different types of reactors

D. Safety

9. Because nuclear fuel is the source of the vast majority of the radioactivity produced by a nuclear power plant, it is imperative that the design and manufacture of the fuel is sufficiently robust not only to allow it to operate normally without incident, but also to withstand any transient or accident that could occur in the plant in a manner that can ensure that safety is not compromised. This is ensured through a licensing process that oversees, not only operation, but also that the design and manufacture of nuclear fuel is carried out to extremely high standards, and that design requirements are codified and performance is demonstrated experimentally.

10. In the 1970s there was a large programme of experimental work to demonstrate how fuel would behave under transient and accident conditions, and safety criteria were defined that provided limits on operation such that fuel would not allow an unacceptable release of radioactivity. The intent was that for normal operation and frequent transient conditions, the fuel cladding would not fail, and that under severe accident conditions any fuel failure would be able to be contained and controlled by the plant safety systems. Examples were the testing of fuel under transient high power conditions (power ramps) or under severe loss of coolant accident (LOCA) conditions. As burnup has increased it has been necessary to demonstrate that changes in design or materials do not challenge the limits set by these safety criteria.

11. The need to demonstrate compliance with the safety requirements means that improvements to fuel design and operation are carefully considered and implemented incrementally, with experimental demonstration, typically through the use of 'lead test assemblies', following extensive testing and research. The incremental approach to burnup extension has been a feature of nuclear fuel development as limitations on burnup extension have been identified and overcome.

E. Modern Design Features

12. It was noted above that the main change required in nuclear fuel to obtain high burnup is an increase in fuel enrichment, but that alone is not sufficient. Nuclear fuel operates in a demanding environment of high radiation fields, high temperatures and high coolant flow. Early fuel designs were adequate for the initial low burnups, where the time that the fuel was in the reactor was limited, but as burnup has increased it has been necessary to improve the fuel in the many ways, described in this section. All must take into account the fact that material properties change with time under the intense radiation fields in the reactor.

13. Modern nuclear fuel is the result of a huge investment in research, experimental testing and operational experience. Changes are introduced to improve safety or performance margins or perhaps to overcome a design problem. Some of the more recent challenges faced by fuel designers are described below:

E.1. Clad Oxidation

14. One of the limits on PWR fuel behaviour is a constraint on the amount of oxide formed on the fuel cladding during operation. A limited amount of oxide is acceptable and even protects the underlying metal from further corrosion. A limit of 100 microns is generally applied, and if the oxide is allowed to grow above this, the protective oxide layer breaks down. This limit is reached with

standard zircaloy-4 cladding at an average burnup of around 45GWd/tU, so a programme of clad improvement has been under way for several years. At first, variations in the composition of zircaloy-4 were tried, and increased oxidation resistance was seen with alloys containing less tin as an alloying component. More recently new alloys have been introduced containing 1%Nb as an alloying component, and this has led to a major reduction in oxidation of the cladding during operation, so that the 100 micron limit is not expected to be reached even at the target burnup of 100GWd/tU.

15. Introduction of these new alloys is slow, however, and reflects the great care taken in introducing new materials into nuclear fuel. The reasons are due to the necessary testing of the new materials in a reactor. For example, testing new fuel types under transient conditions at extended burnup is necessary to demonstrate acceptable behaviour in abnormal conditions and to define limits to failure. Such tests are very expensive and take many years to carry out. It takes typically six years for a lead test assembly of a new fuel variant to reach the extended burnup necessary before experimental testing can even start.

E.2. Water Chemistry

16. The relationship between the fuel cladding and water chemistry is very important; changes in the water can profoundly influence fuel oxidation rates and the migration of corrosion products from the steam generators to the fuel, where they can deposit as crud. A consequence of using fuel with higher enrichments and longer cycles is that the distribution of power in a reactor core becomes less uniform, and the local power within an assembly can rise. This has led to deposition of crud from the coolant at high power locations, causing power distortions and even fuel failure through enhanced oxidation. This problem is being addressed by careful core design and control of the water chemistry.

17. The recommendations for water chemistry have evolved over the years for all water reactor types. An example is indicated in Figure 3 for PWRs, where the major events started with the introduction of lithium for pH control in the 1980s, and more recently zinc addition for steam generator corrosion control followed by elevated pH and fuel assembly cleaning to help control crud. The influence of all these changes has to be continually monitored for any effect on fuel performance beyond that intended, a process that takes many years and which accounts for the long lead times before any alterations are widely accepted.

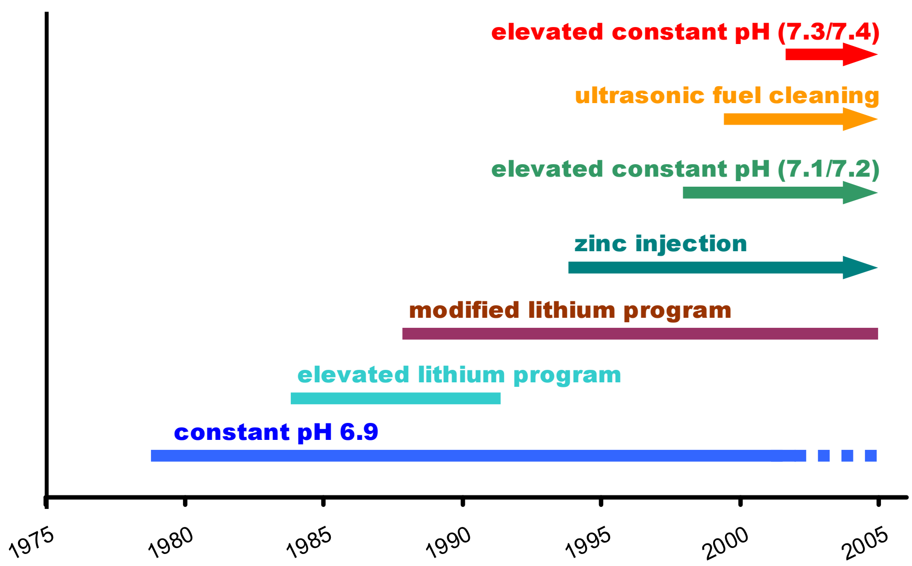

Figure 3. Evolution of recommended PWR water chemistry

E.3. Assembly Strengthening

18. Another problem with long residence time in a reactor is that the radiation field can cause elongation of the fuel rods and of the assembly skeleton that holds the rods in place. This elongation is constrained within the reactor, and the assembly has the possibility of bending under the stresses that arise. This 'assembly bow' has been observed in both PWR and WWER reactors. The distortion of the assembly can cause local power changes and problems with control rods sticking within the assembly structure. The response has been to stiffen the assembly, and Figure 4 shows the angle stiffening on the advanced TVSA fuel assembly for a WWER 1000 reactor.

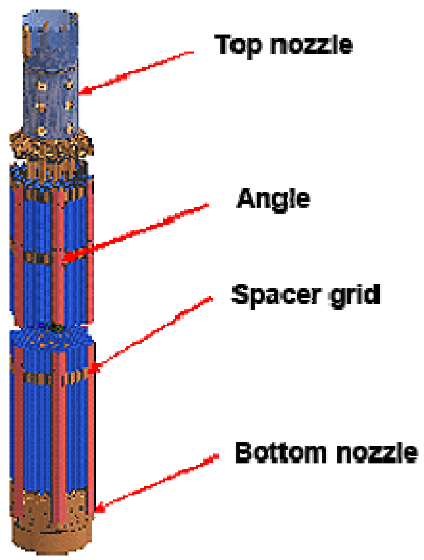

Figure 4. Angle stiffening on the advanced TVSA fuel assembly for a WWER 1000 reactor

E.4. Fission Gas Release

19. The main problem for fuel designers wishing to increase burnup today is that of fission gas release. Fission gas is generated within the fuel during operation, and the amount is roughly proportional to the burnup. The higher quantity of fission gas is of concern if it is released from the fuel pellet, causing high pressure inside the fuel rod and concerns about clad expansion. There is evidence of increasing release rates of fission gas at high burnups, and many ideas are under investigation to understand and control the phenomenon. Options include adding dopants to the fuel pellet to control microstructure with the aim of reducing the release rate from the fuel during operation and also to increase the resilience of the fuel to power ramps. Currently, WWER fuel pellets have annular geometry, with the central hole providing lower centre temperatures and a free volume to allow any released fission gas to expand and thereby reduce internal pressure. However, WWER fuel designers are considering moving to a solid pellet to allow for a higher fuel load in an assembly and improved utilisation, while conversely, PWR fuel designers, who already use a solid pellet, are investigating the use of annular pellets.

20. New physical phenomena are also becoming evident as fuel pellets achieve higher burnups. A high burnup structure (HBS) with high porosity is seen to develop on the rim of the pellet, affecting fuel temperature distribution as the pellet burnup exceeds 45GWd/tU. This structure is first seen when fission gas release rates are increasing, but experimental investigations do not confirm that this structure is solely responsible. The actual effect of the HBS on the performance of fuel at higher

burnup and also of other potential mechanisms that could cause changes in fission gas release rates are the subject of much research and debate.

E.5. Fuel Failure in Normal Operation

21. The improvement in fuel failure rates has been a very important trend over the past twenty years. Failure occurs when the cladding is breached, allowing coolant to enter the fuel rod and fission products to escape. A nuclear power plant is designed with appropriate clean up systems so that a few fuel failures do not challenge operation, nor do they generally diminish plant performance. However failed fuel does release radioactivity to the primary coolant circuit, and this can cause additional operator exposure and is an unwanted source term for accident analysis. Power plants have defined limits on the amount of radioactivity that they can tolerate in the circuit, and if sufficient fuel failure occurs it is possible that the plant may have to constrain operation or even shut down to remove the failed fuel. Further, there is general acceptance that reloading failed fuel into a new operational cycle is not acceptable, so expensive search and repair is undertaken when failed fuel is discharged. Systematic efforts have been made to identify and eliminate causes of fuel failure during normal operation and much has been achieved. Figure 5 shows fuel failure rate trends in US plants (Yang et al. 2005).

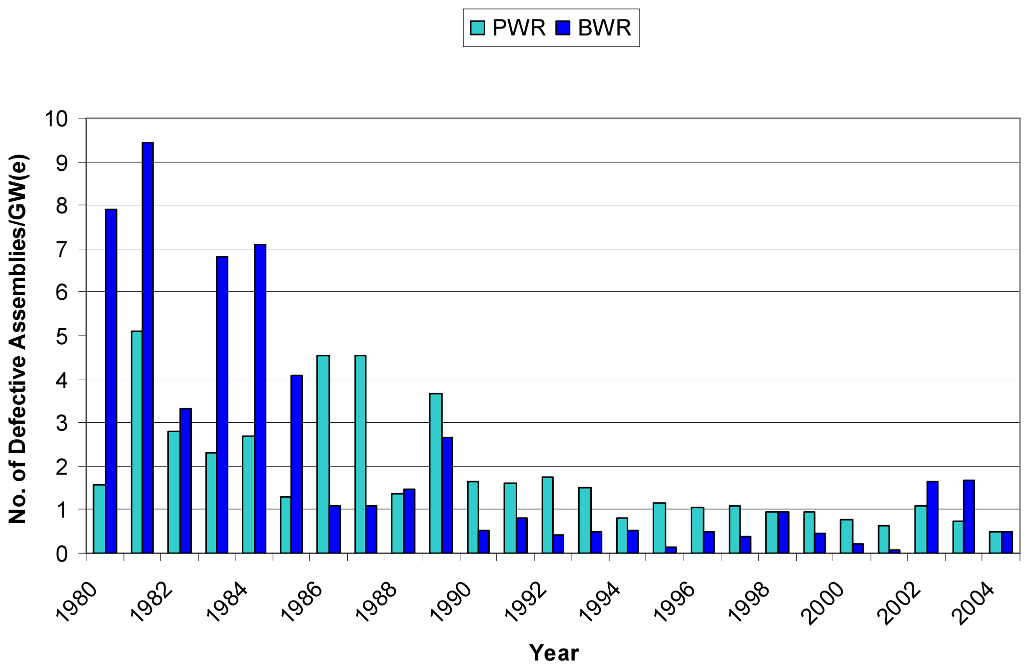

Figure 5. Fuel failure rates in US plants.

22. Failure mechanisms that have been identified and remedied include the following. First are manufacturing defects, which are remedied through improved quality assurance methods. Second is grid-rod fretting, which is caused by the grid springs rubbing against fuel rods and wearing through the cladding, and which has been reduced through detailed design changes to assembly grids. Third is debris induced failure, which has been addressed through better plant procedures to avoid debris ingress to the coolant circuit, and also through the introduction of debris filters for the assemblies and protective end caps on fuel rods.

23. Trend diagrams, such as Figure 5, are used to spot early signs of a new problem, and attention has been paid to oxide failures in BWRs which have been occurring over the past few years. Fuel

vendors are pursuing a goal of 'zero defects', and some recently introduced fuel types are very close to this ideal.

E.6. Burnable Poisons and Core Design

24. To achieve high burnup through the use of higher enrichments, it is necessary to control the additional reactivity of fresh fuel assemblies. To this end, fuel designers include burnable poisons into fuel assemblies. These are materials that absorb neutrons and ensure that the nuclear reaction can be controlled safely. Early designs used discrete components containing boron or other neutron absorbers alongside the fuel rods, but more recently the poison has been added directly to fuel pellets to allow more flexibility and economy in their use. Examples include boron coating of fuel pellets and gadolinia doping. These poisons are designed to deplete (burnout) during irradiation, and the poison loading and depletion rate are optimised to improve fuel utilisation.

25. Further improvements in fuel utilisation have also been achieved by careful core design. In batch loading reactors, the location of fresh fuel assemblies and their relationship with partially burnt assemblies in a core will affect the power distribution and neutron economy. Current low leakage core designs are intended to ensure that neutron loss is minimised and that all assemblies reach a burnup on final discharge that is as close to the theoretical maximum as possible.

E.7. Improved Manufacturing

26. The manufacturers of nuclear fuel are also improving and upgrading their capabilities, and improvements in fuel utilisation arise here too. Stricter tolerances on manufacture can be turned to advantage through reduced uncertainties that need to be analysed in a safety submission. Improved fuel utilisation is being achieved within advanced gas cooled reactor fuel by small reductions in pellet bore size and cladding wall thickness, within the original specification, but allowing consistently higher uranium loadings and a smaller amount of neutron absorbing material in the core.

E.8. Improved Calculational Routes

27. It is required to demonstrate that the operation of nuclear fuel is safe, and to do this vendors and utilities employ codes and models to simulate the fuel operation in the reactor. The codes are used to model fuel performance, reactor physics and thermal hydraulics, as well as many other safety related issues. The codes are also subject to continuous improvement and as computing power has increased over the years it has been possible to remove pessimistic assumptions about fuel behaviour and model important phenomena more accurately. For example it has been the practice to calculate fuel pin behaviour using worst case, bounding assumptions on the fuel duty (a concept which combines burnup, fuel rating and other stresses on fuel). No actual rod has ever experienced such worst-case duty, and the resulting calculations have been very conservative. It is now possible with reactor physics codes to accurately follow the actual fuel duty seen by every fuel rod in a core (typically 50 000) and then use fuel performance codes for each rod to find the most onerous operating conditions, and apply suitably conservative assumptions to this rod. These calculations can demonstrate additional margins for safe fuel performance, giving operators and regulators confidence as burnups are increased.

28. Fuel modelling codes have been developed alongside the physical improvements made to the fuel. The purpose of these codes is to simulate the behaviour of fuel in reactor, and allow predictions of the status of the fuel for use in deign and safety studies. The codes use models of the processes occurring within the fuel as burnup proceeds, considering temperatures, fission gas release and cladding behaviour. The codes are validated against experimental data, and international exercises,

such as the IAEA Coordinated Research Project, FUMEX-2, allow access to high burnup experimental data for modelling teams throughout the world. Changes to fuel materials or design pose a challenge to fuel performance codes as new materials may have different burnup dependencies, for example the creep rate of the cladding material or its potential for hardening. Experimental verification of such high burnup properties is difficult and expensive and very time consuming. Current fuel performance codes are generally validated to a rod burn up of around 65GWd/tU, corresponding to around 60GWd/tU assembly average.

E.9. Reprocess and Reuse

29. The early intention of countries undertaking reprocessing of spent nuclear fuel was to try to extract the remaining fissile isotopes (mainly plutonium, but also ^{235}U) and in particular to close the fuel cycle through the use of fast breeder reactors. This development is still well in the future, but there has been utilisation of reprocessed fuel, and nuclear fuel has been manufactured containing plutonium (MOX fuel) and the reprocessed uranium (repU). MOX fuel use is increasing slowly, particularly in France, (Figure 6) as there is a need to manage plutonium stocks arising from existing reprocessing contracts, but some countries are ending their use of MOX fuel as existing arrangements expire, and are reverting to a simple storage of spent fuel.

30. Another approach to the management of spent fuel, and to increasing the energy obtained from such material, is the DUPIC programme to develop fuel for PHWR reactors directly from the spent fuel of LWR plants. The quantity of enriched uranium remaining in spent LWR is potentially appropriate for use in a PHWR. The problems of manufacturing the new fuel are daunting, but trials have taken place and this remains a promising development.

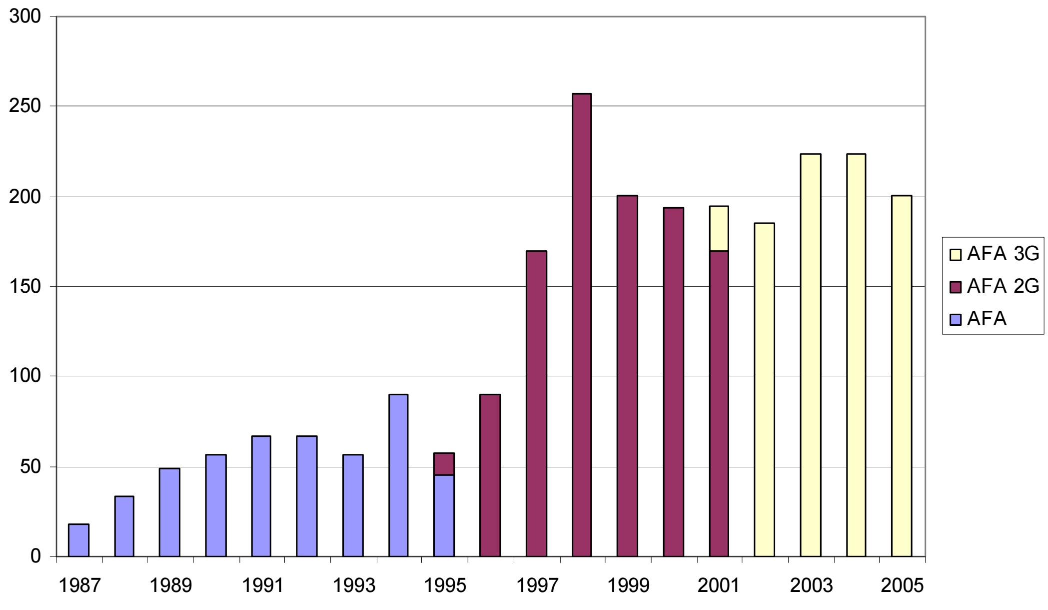

Figure 6. Number and type of MOX fuel assemblies loaded in French 900MW PWRs

F. Future Development

31. Driving the improvement in fuel performance has been a balance between cost and benefit. Over the past thirty years fuel has become more reliable and the original burnup levels have doubled, with LWR fuel now approaching 60GWd/tU, thus halving the number of fuel assemblies needed.

32. Improvements are still possible, previous limitations on fuel endurance, such as cladding oxidation have been overcome by a move to advanced cladding alloys, assemblies have been strengthened to survive longer dwell times without significant distortion and fission gas release has been addressed with advanced fuel pellet technology. It is believed that the current technology could support LWR burnup to even 100GWd/tU. However, there remain additional costs in reaching these levels, one of which is the need for higher enrichment to go to the higher burnups. All current criticality assessments have been made on the basis of a maximum enrichment level of 5%U-235 and levels in excess of 8%U-235 are needed to reach the 100GWd/tU target. There is a large investment in fuel manufacturing, transport and on-site handling which has been designed and built for the current enrichment maximum of 5%U-235 and there is currently only one new manufacturing facility that is being designed for a 6%U-235 limit. Experimental work remains to be done on the criticality of such enrichments, and it is likely that further increases in burnup will follow the same slow incremental upward trend that has characterised the past. A second drag on the rapid implementation of new fuel types is the long lead times for irradiation testing to a new burnup level.

33. One area where new developments are beginning is in the use of slightly enriched uranium fuel for PHWRs. One such reactor, in Argentina, is already using uranium enriched to around 0.9%U-235 and burnups have increased. CANDU operators are looking at higher enrichment levels and considering burnups up to 25GWd/tU. Once again, the process will be a slow, careful introduction of advanced fuel, combined with improving the calculational tools to ensure predictability of performance and demonstrating experimentally good in-core behaviour.

34. The nuclear fuel market today is fully commercialised and is a highly competitive one, in which there is currently over-capacity. The vendors are seeking to win orders outside their traditional markets and extending their product ranges to suit different reactor types, a development that is especially noticeable for PWR and WWER vendors. Utilities are using the market and changing vendors when it suits their particular needs. This competition is also forcing the vendors to improve their fuel designs and is another strong force leading to higher reliability and durability. The vendors are attuned to the needs of their customers and to the local conditions in which their customers work. Utilities are now able to pick and choose which fuel enhancement they wish to purchase, which enrichment and burnup target they need, and which cycle length best suits their local electricity market. This is leading to a wide range of customised fuels, and the optimum utilisation of a power plant will be tuned to its local market conditions.

G. Conclusions

35. Nuclear fuel has developed significantly over the past thirty years. Reliability has increased, and fuel pin failure levels are approaching 10^{-6} over the lifetime of the pin. Burnup levels have doubled and issues associated with assembly strength and clad oxidation, among many others, have been addressed. Thermal hydraulics and heat transfer have been improved. Current nuclear fuel technology

is capable of fuelling the advanced reactors that are starting to be built, and it is likely that the incremental improvements in fuel burnup, giving optimum utilisation, will be the main change over the next decade.

36. The liberalisation of electricity markets in the recent years has seen an increase in competitive pressures in both the overall electricity market and also the nuclear fuel market. This has led – and continues to lead – to a continuous improvement process, with fuel subject to competitive pressure. Vendors will continue to supply the most cost effective solution to a particular utility, whether they wish to use MOX or another advanced fuel type, or whether they prefer a conservative approach utilising only well proven fuel designs.

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