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Paper # 2

PWR and WWER Fuel Performance
A Comparison of Major Characteristics

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Introduction

For a most economic performance of nuclear fuel the main technical targets are

- most effective use of the energy stored in the nuclear fuel, and
- highest possible reliability of the fuel performance in the reactor.

A most effective use of the energy stored in the nuclear fuel leads to the technical targets:

  - Optimized neutron economy by minimizing neutron losses in core and fuel structural materials. This leads to optimizing the fuel reload strategies and the use of fuel structure materials with low neutron cross sections.

  - Optimizing the fuel burn-up versus the fuel cycle back-end cost, which up to today leads to as high as technically feasible burn-up. The technical feasibility of this optimized burn-up requires the knowledge of and the control on the technical limitations of this burn-up, in particular cladding corrosion in Western PWRs and mechanical and dimensional stability in WWERs.

Highest possible reliability of the fuel performance in the reactor means

  - Minimizing any kind of fuel failure or malfunction during operation that leads to production losses and cost for fuel repair. This requires a good basic understanding of and control on the causes that lead to fuel failures under operation.

There are some more aspects of importance for a utility running a nuclear power station that are also affected by the nuclear fuel design, like helping to minimize the radioactivity in the whole reactor system by the use of fuel structural material that does not release highly radioactive corrosion product. One example is the use of low Co containing stainless steel components. However, these aspects will not be discussed further in this paper.

The economy of producing energy in a nuclear power plant is also strongly affected by factors that are not directly correlated with the nuclear fuel design, but nevertheless can have strong feed-back effects on it. Of course any power station can produce electricity most economically by running the plant in base load all over the year. However, the utilities have to adjust their production of electricity energy flexibly to the real time demand. And also every utility needs some significant time for inspection and maintenance activities, for which the power plant has to be shut down. Such requirements decrease the overall load factors of the plant and thus decrease the energy output.

One consequence from this needs is a world-wide tendency to increase the cycle length from 12 months to 18 months or longer, thus increasing the effective full power days (EFPD) within one cycle. This leads to increased reliability requirements for the fuel.

Flexible production on demand may vary from adjusting the power to seasons' demands, to day/night cycling or even to power variations during one day.

There are many details of the core and fuel assembly design to be considered to meet all those requirements. And all fuel designers in East and West take care of it. However it is beyond the scope of this paper to discuss all these details. In this paper just the consequences for fuel performance and operation reliability will be discussed with focus on a comparison of the status of PWR and WWER fuel performance with regard to optimized

  - neutron economy,
  - fuel burn-up, and
  - fuel operation reliability.

Optimized Neutron Economy

There are basically two ways to optimize neutron economy for LWR fuel:

1. Applying low leakage reload strategies, and
2. Using structural material with low neutron cross section, like Zr-alloy materials, for the structural components of the fuel assemblies, in particular the spacer grids and the guide thimbles. However, in particular with spacer grid designs a consideration is necessary, balancing the advantages of

Low Leakage Reload Strategies

Low leakage reload strategies (using so called "in-in-out" core patterns) are very successfully in use in PWR cores worldwide, as well as in WWER cores (in and out-side o Russia) since more than a decade. Their introduction started already in the late 1980ies, when 3-years cycle were still commonly in use for both types of reactors. Then 4-years cycle with low leakage strategies have been successfully introduced, and in the meanwhile 5-years cycles with this reload strategy are more and more introduced, both in PR and WWER plants. The advantages of this reload strategies are commonly accepted. They can be summarized as e.g. recently published in a Russian paper [1] for cores in WWER-440 and WWER-1000 plant as follows:

- *Savings in consumption of natural uranium, ranging from 12 to 19 percent;*
- *Decrease of the total number of fuel assemblies in use, ranging from 25 to 30 percent;*
- *Reduction of the neutron flux on the reactor's housing (i.e. pressure vessel), ranging from 20 to 25 percent;*
- *Increase in fuel burn-up of fuel assemblies.*

Structural Material with Low Neutron Cross Section

The other important measure to optimize the neutron economy in LWR cores is the introduction of low neutron absorption material for fuel assembly structure components, in particular spacer grids and guide thimbles.

This process was started in the West already a long time ago, first by developing various types of spacer grids with mainly Zry-4 as structural material and Inconel (mainly Inc 718) as spring material. These designs were called bi-metallic spacers. Some fuel designs (e.g. the fuel assemblies of Combustion engineering) started directly with all-Zry-spacers, where the springs were made of the same material as the spacer structure.

As a matter of fact during the now about three decades of using Zry-4 based bi-metallic space grids quite some disappointing experiences had to be made. Various grid designs caused fuel rod defects by grid to rod fretting. The reason for those defects partly was insufficient thermo-hydraulic design, partly an insufficient mechanical design, and partly inappropriate material treatment of the Inconel spacer springs. It is not unfair to say that the history of the bi-metallic PWR spacer grids was a history of such problems, as shown in table I and figure 1 [2, 3]. In some specific cases the fuel designer returned to full Inconel spacer grids to avoid the risks of failing fuel rods with the high cost of repairing the damaged fuel assemblies and the even much higher cost of missing energy production for the utility.

Failure Cause	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Handling Damage		6	2			1	1		2		
Debris	146	11	67	20	13	6	10	1	10	3	
Grid Fretting	14	18	9	33	36	9	33	52	21	57	
Primary Hydriding		1		4							5
Crudding Corrosion							4		4		
Cladding Creep Collaps							1				
Other Fabrication	1	15	1	5	3		15	5			
Other Hydraulic					1	1				2	1
Inspected/Unknown					36	36	13	9	10	2	1
Uninspected	43	58	35	61	14	3	12	3	8		3
Yearly Totals	**204**	**109**	**114**	**123**	**103**	**56**	**89**	**70**	**55**	**64**	**10**

Table I
Causes of Fuel Failures in US PWRs over the 1989 to 1999 Time Period [2]

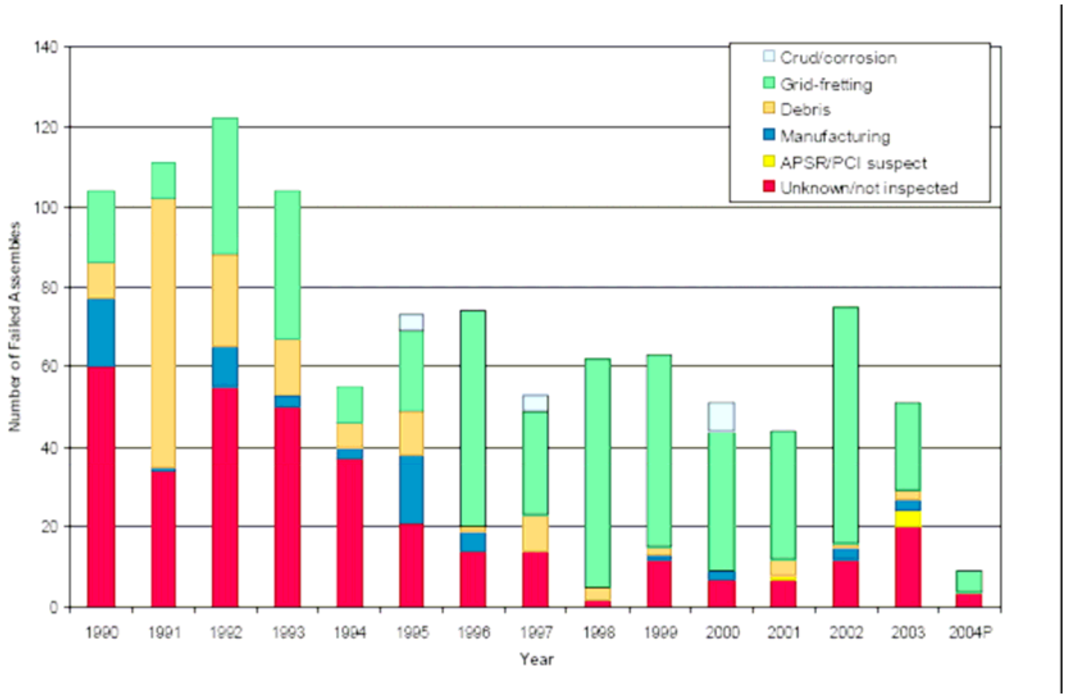

Figure 1 Trend in US PWR fuel failure root causes *(2004 results are incomplete)* [3]

Today there exists at least one spacer grid design which appears to be able to avoid such problems. This is mainly the so called HTP spacer grid which interestingly is a full Zr-alloy grid, i.e. without Inconel springs. This spacer design was described in some detail on the previous 5th WWER fuel conference in Albena, Bulgaria in 2003 [4]. When introduced first this spacer grid was made of improved Zry-4, which nowadays is replaced stepwise by M5 material.

Later than with PWR fuel, but in the meanwhile also more than a decade ago, Zr-alloy based spacer grids started to be introduced in the fuel assemblies for WWER-440 and WWER-1000 plants [1, 5]. Different from the Zry-based PWR spacer grids the WWER spacer grids always were designed as all Zr-alloy (E 110) spacer grids. And the rod-to-grid fretting problems also occurring in WWER FAs were not a result of replacing the stainless steel spacer grids by the Zr-alloy E 110. These problems were already experienced with fuel assemblies equipped with spacer grids made of stainless steel [6]. Therefore the measures to be taken to avoid this problem had to be different.

The replacement of stainless steel material by Zry-4 for the guide thimbles in PWR fuel assembly was another, later step taken in the West. With one exception there were no major problems observed with this design change. The one exception was a severe hydriding of Zry-4 guide tubes up to 80% of the wall in a European PWR that occurred during start up, due to a combination of four causes (figure 2):

- Sensitive inside surface of guide tube, from special sandblasting process,
- Too high Ni content in reactor water,
- Too high pH in reactor water,
- Too early hydrogen injection into reactor water.

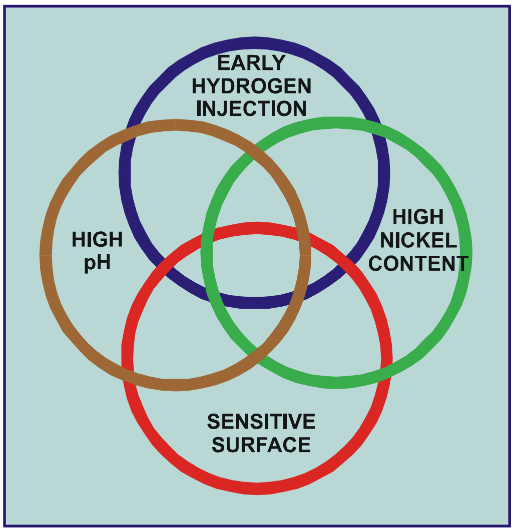

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Figure 2
Four Reasons for Excessive Hydriding in PWR Guide Tubes made of Zry-4

Interestingly the guide thimbles did still work during one full cycle operation, due to the high ductility of hydrides in Zry-4 at operating temperatures. However, afterwards some of them broke during shut-down tests.

Also in WWER fuel assemblies the guide thimbles are replaced or are being replaced by Zr-alloy, up to today using E 110 material. But in more advanced WWER fuel assembly designs (TVS-2 FA) at least the top and the bottom spacer grids are made of E 635 material [7]. Similar or other specific problems with guide tubes in WWER fuel assemblies made of Zr-alloys are not reported in the literature.

High Burn-up

General

The burn-up of PWR as well as of WWER fuel has been increased all the way down since the early days of the first designs. The driving force behind this increase is the also at all times increasing cost of the fuel cycle back-end. On the other hand continuously improving design, materials and fabrication technology had to provide the safe technical feasibility of this increase.

In parallel to this development of course the U-enrichment and the operation time had to be continuously increased.

The most recent development in the area of PWR fuel was presented and discussed on the last ANS Meeting on LWR Fuel Performance, held in Orlando, Fl/USA in 2004. In particular a broad and consistent utility view on today's fuel cycle management strategy and perspectives was given their by EdF [8]. The presently at EDF broadly reached average batch-burn up is reported to be 44 GWd/t_U with an authorization for UO_2 fuel up to 52 GWd/t_U average assembly burn-up. EdF's policy aims at 55 GWd/t_U average batch-burn up during the next decade.

According to this survey given at EdF the current fuel management modes, resulting in an average burn up of 44 GWj/t, are the following:

- on the 900 MW units: 4.2% per third and 18 months cycle on CP0 units; 3.7% per quarter and 13 months cycle on standardised CPY units;
- on the 1300 MW series: 4% per third and 15/18 months cycle;
- on N4 1500 MW units: 3.4% per quarter and 11months cycle.

In the meanwhile for PWR fuel the magic limit of 5% initial U-enrichment has been reached for a first time in a European reactor [9], corresponding to an achievable discharge burn-up of up to 65 GWd/t_U. Of course such high burn-up goes along with an extension of the operating time to at least 5 one-year cycles. The whole situation and the technology behind these figures has been discussed in some detail during the previous WWER Fuel Conference in Albena in 2003 [4].

For WWER fuel the respective figures are similar:

WWER 440 fuel assemblies* with up to 4.4% enrichment have passed 5 one-year cycles with commercial quantities [10, 11]. Average burn-up of discharged FAs is 46 – 49 MWD/kg_U.

WWER 1000 fuel assemblies* have reached a commercial burn-up of 45 MWD/ kg_U with 4 one-year cycles and 52 MWD/ kg_U, with 5 one-year cycles.

For both fuel types, PWR as well as WWER fuel, this increase of burn-up, and consequently increase of initial enrichment and time of operation (numbers of cycles), goes along with a reduction of the number of fuel assemblies per reload. This leads to a higher ratio between the maximum assembly power and the average power of all assemblies in the core, as for example shown for reactors built by Siemens in figure 3.

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* most recent data see papers on this conference

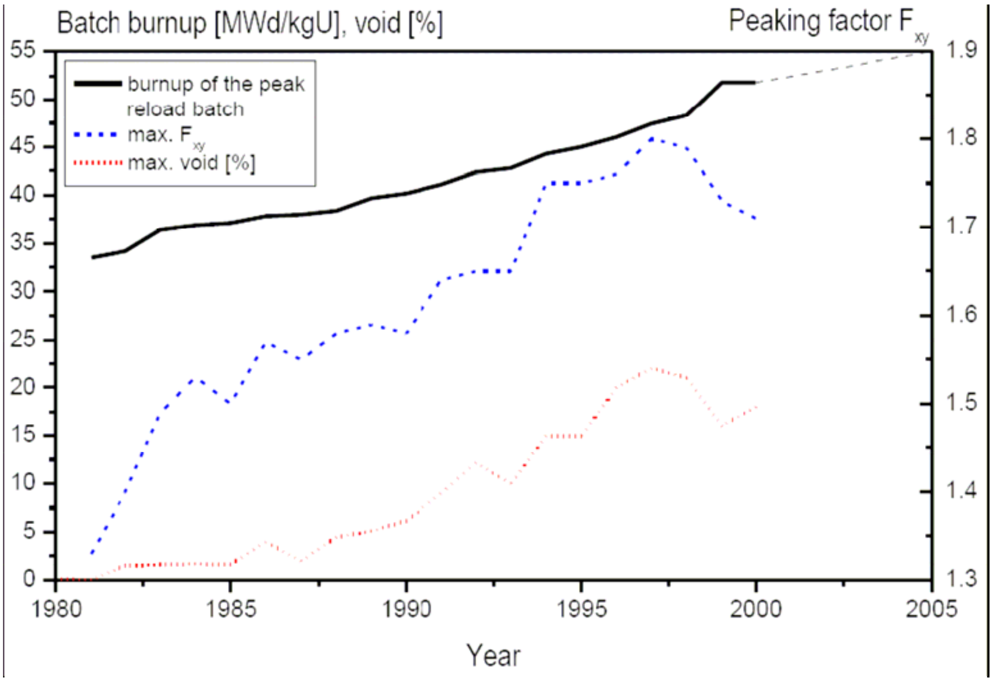

Figure 3 Evolution of Fuel Assembly Discharge Burn-up and Operating Conditions in PWRs Built by Siemens [12]

A higher maximal power results in more boiling areas on the fuel rod surface of the highly loaded fuel assembly. All these increased operational requirements can only be met by improved fuel designs with either (in PWR FAs) new or (in WWER FAs) highly optimized cladding and structural materials. This was only possible (for PWR and WWER fuel) due to an intensive development of the operation properties of

- the fuel rod (for WWER FAs often called ‘fuel element’),
- the fuel assembly components, in particular the spacer grids and the guide tubes, and
- the total fuel assembly,

in combination with an adequate core management, which includes not only the physics and the thermo-hydraulics, but also the mechanics, i.e. the dimensional behavior of the core.

Focus of Development

However, it is important to understand that the focus of the technical development was and is different for PWR and WWER fuel in some important areas:

- For PWR fuel the corrosion of the fuel rod cladding and the hydriding of the FA structure made of Zr-alloys, in particular, the spacer grids, is the essential burn-up and life-time limiting factor. Overviews on these topics were given on the 4th and 5th WWER Fuel Conferences in Albena, Bulgaria in 2001 and 2003 respectively [13, 4].

  Mechanical and dimensional behaviour in general is important, but with clearly lower priority.

- For WWER fuel the mechanical stability and the dimensional behaviour of the fuel assemblies (and the whole core) is of high importance.

  Corrosion of fuel rod claddings and hydriding of the FA structure made of Zr-alloys is of 2nd order importance, with of occasionally observed enhanced localized corrosion.

Corrosion and Hydrogen Uptake

Today the internationally in PWR-FAs used fuel rod cladding materials for high burn-up fuel in PWRs are M5 for French fuel) and Optimized (low Sn) ZIRLO™ (for Westinghouse fuel).

An updating on the behaviour of the French M5 material under regular and accident conditions in PWRs was given recently [14] In figure 4 the latest status of M5 corrosion, in figure 5 the respective hydrogen uptake is given.

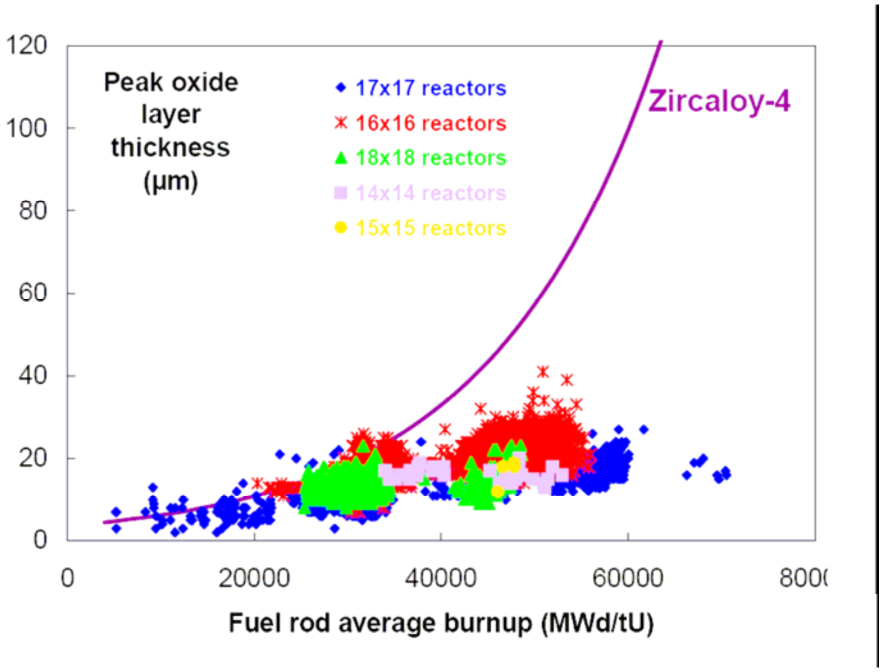

Figure 4 Corrosion Performance of M5™ in PWRs [14]

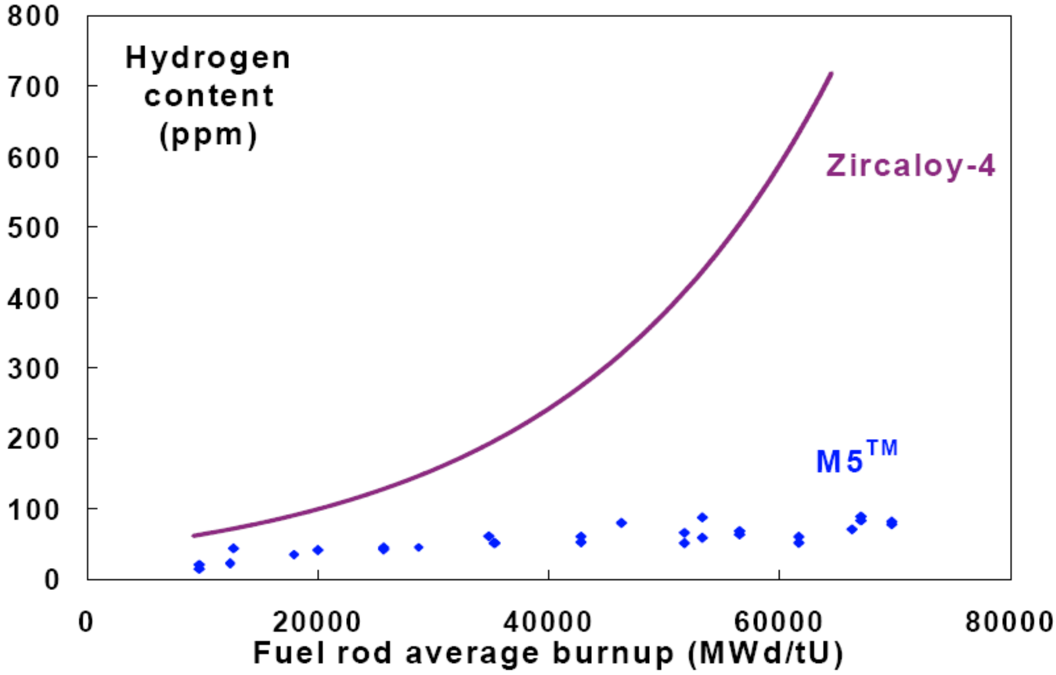

Figure 5 Hydrogen Performance of M5TM in PWRs [14]

M5 is also used increasingly for the FA structure components in French fuel [4].

Recently given [15] corrosion data of “Optimized (Low Sn) ZIRLOTM“show a strong improvement as compared with the corrosion of “Standard ZIRLOTM” (figure 6).

Both materials, M5 and ZIRLOTM now show comparable corrosion behaviour at high burn-up.

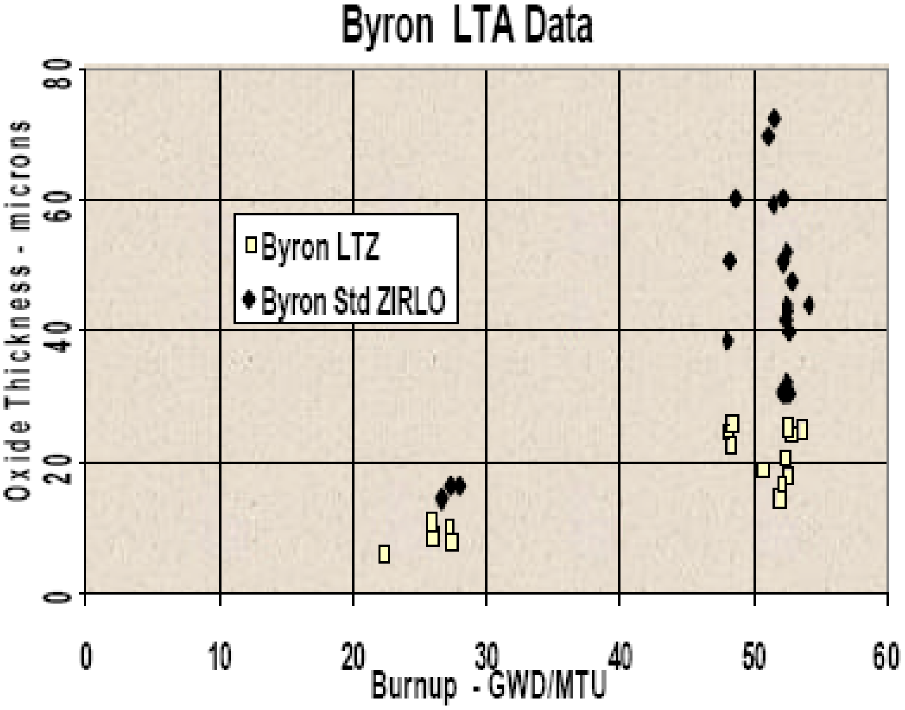

Figure 6 Optimized (Low Sn) ZIRLO^{TM} Corrosion Data [15]

In WWER fuel (WWER 440 and WWER 1000) still the Zr1Nb alloy called E-110 us the commercially used standard cladding material. Corrosion (oxide layer thickness <10 µm) and hydrogen uptake of this material in WWER environment is a “non problem” also at the now commercially achieved high burn (average FA discharge) of up to 55 MWD/kg$_U$ [16].

Dimensional Behavior: Creep and Growth

In PWRs creep of Zr-materials was always under safe control. However the irradiation induced growth of Zry-4 showed a second increase with higher burn-up. This problem is now completely solved with the new materials M5 and “ZIRLO^{TM}“[13].

Creep and growth of E-100 cladding tubes also is under safe control. At average FA burn-up around 50 to 55 MWD/kg$_U$ .The gap between cladding tube and the (swelling) pellets is completely used up.

However, this is also the case in PWR fuel rods at comparably high burn-up, but never turned out to be a performance problem.

Other High Burn-Up Criteria

There are of course other high burn-up criteria to observed besides corrosion/hydrogen uptake and the dimensional behaviour of cladding tubes. In particular the dimensional and micro-structural behaviour of the fuel pellets and the fission gas release form these pellets have to stay under control also at the increased burn-ups.

Post irradiation examinations have shown that this is as well for PWR a for WWER fuel.

Already some years ago detailed investigations of the development of the fission gas release and its dependence on the development of the fuel microstructure up to very high burn-up (~ 100 MWD/kg$_U$ fuel rod average burn-up) have been performed and described [17]. The over-all result is shown in figure 7:

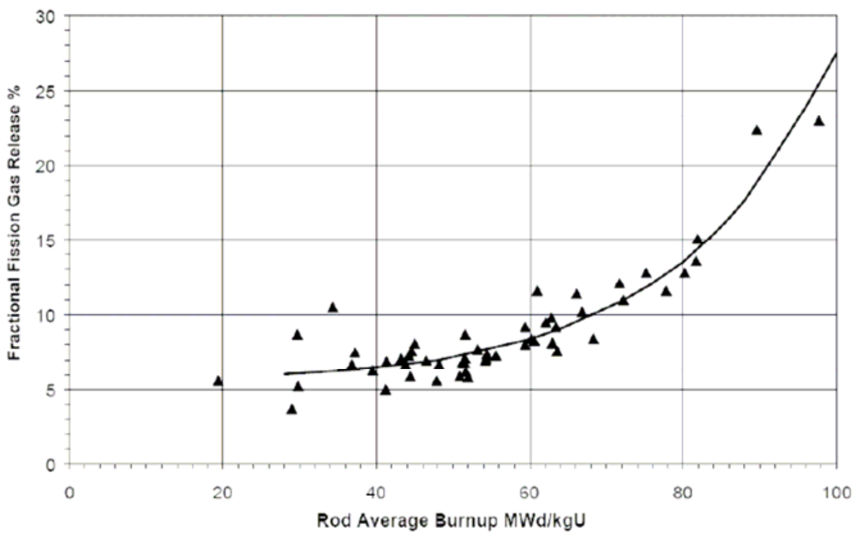

Figure 7 Fission Gas Release in PWR Fuel Rods with Initial Enrichment of 3.5 – 4.2% U235 as a Function of the Fuel Rod Burn-Up [17]

With the results of this investigation not only the amount of fission gas release could be determined up to very high burn-up values, but the various mechanisms involved could be understood. With this knowledge it became possible to adjust the models to calculate the development of the internal fuel rod pressure up to those high burn-up.

The same holds for the measurement and understanding of the fission gas release in WWER fuel rods under high burn-up [16, 18]. And again the computer codes for these fuel types could be adjusted for 4 and 5 one-year cycles.

As already touched above, the fission induced swelling of the fuel, in combination with the creep down of the fuel rod cladding leads to the closure of the gap between pellet and cladding, but without serious problems for design of the fuel rods, as well for PWR as for WWER fuel.

All above discussed criteria for high burn-up also cover the increasing burn-up of MOX fuel as discussed in more detail in [4].

Fuel Performance Reliability

General

The criteria for fuel performance reliability is the full and unquestionable availability of the whole reactor core for the operation intended by the utility. This operation may occur – as in many cases – in the base load mode, i.e. constant power, at 100% or may be also at reduced power. More and more NPPs have to able to run their plant in a flexible way, e.g. day/night- or working days/week end load following.

The most important requirement for this availability is the integrity of the fuel rod and assembly during the intended operation. But there are also other requirements of importance. The experience of the past has shown that such requirements are mainly

- Impact of FA bow on the
  - core geometry (water gaps) and the
  - control rod drop time,

- Other potential impact on the continuous and safe operation of the core, like the already discussed degradation of the guide tubes or strong vibrations or fluctuations of the coolant in the core. Also deviations in the coolant chemistry may effect the core performance, e.g. by effecting the coolant flow.

Fuel Failure Rates and Root Causes

Most commonly the fuel failure rate is used as measure for the fuel performance reliability. A fuel failure is a defect in the fuel rod cladding leading to release of fission products an possibly also fuel (UO_2 or UO_2 PuO_2). However, a fuel defect may be very small just releasing some gaseous fission products or it can be medium or very large, releasing also other fission product and fuel. This method does not account for the size and the severity of a fuel failure, I e. it is not a measure for the consequences of a fuel failure on the availability of the core for undisturbed operation. And of cause it does not tell anything about the fuel failure causes. Also there is no continuous independent international survey on fuel failure rates, sizes and causes available that allows to compare the fuel performance reliability of different fuel types and designs consistently.

There is periodic information available on the fuel failure characteristics of BWR and PWR fuel in the USA, provided by EPRI[1]. And there are fuel failure statistics for BWR and PWR fuel published from time to time by the major nuclear fuel vendors in the West. Most recent information on PWR fuel failure rates from those sources is available in the proceedings of the 2004 ANS International Meeting on LWR Fuel Performance, held in Sept. 2004 in Orlando, Florida/USA [3, 15, 19, 20] .

The EPRI evaluation of 2004 [3] on US PWR fuel failure rates in figure 8 shows that after a continuous decrease from 1980 to 2001 there is some increase observed in 2002 and 2003. From figure 1 it can be concluded that the major contributor to fuel failure rates in PWRs remains the grid-to-rod fretting. But there is also an increase of fuel failures with unknown root causes. EPRI believes that these failures primarily affects optimized fuel designs with a thinner rod diameter.

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[1] EPRI: Electric Power Research Institute, supported by al major US utilities.

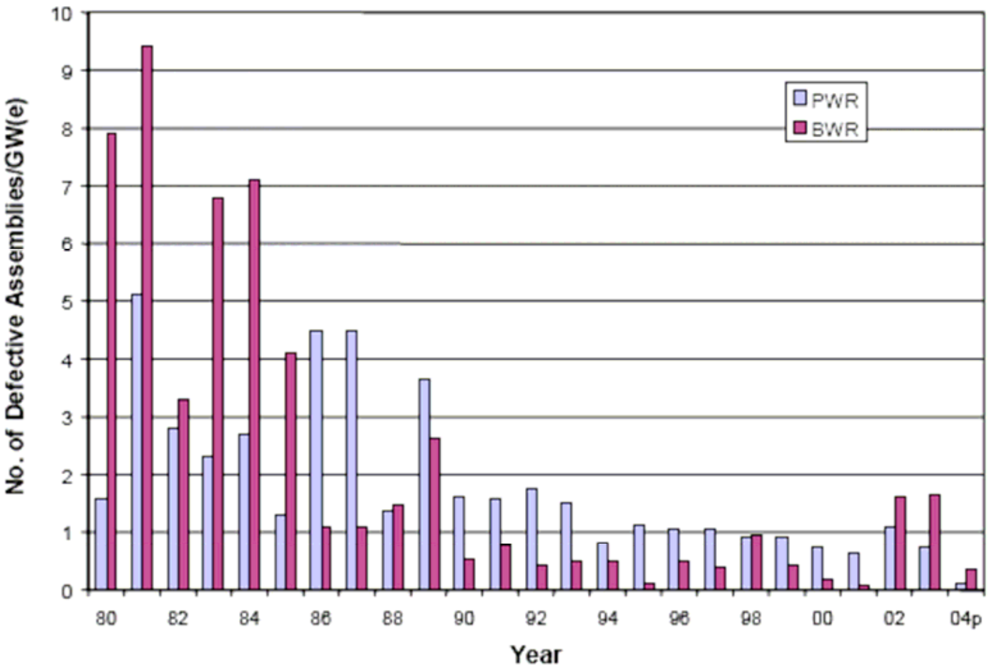

Figure 8 Trend in US fuel failure rates (2004 results are incomplete) [3]

An EdF paper [19] reports on 5 FAs in 5 different units that were leaking recently in 900 MWe NPPs, and that the cladding failures in 1300 MWe NPPs improved greatly in 2003. Five FAs in 4 units wee leaking in the 1300 MWe series. The root cause of these fuel failures was most probably vibration fretting of the fuel rods at the level of the lowest space grids .The level of fuel failure rates in 2003 went back to the one observed at the end of the 1990ies.

One leaking FA was found in the 1450 MWe series.

The same paper reports a very good behaviour of the MOX PWR fuel. Since the beginning of the use of this MOX fuel in reactors (first refuelling in Saint-Laurent unit 1 in 1987), only 5 assemblies were found to be leaking, with less than ten defective fuel rods. The most frequent root cause was the presence of debris.

In a Westinghouse paper given at the same ANS conference [15] an interesting supplementary information is provided on the US industry-wide fuel reliability trend over the last 10 years. It has levelled out in the 1990ies and is recently decreasing (figure 9).

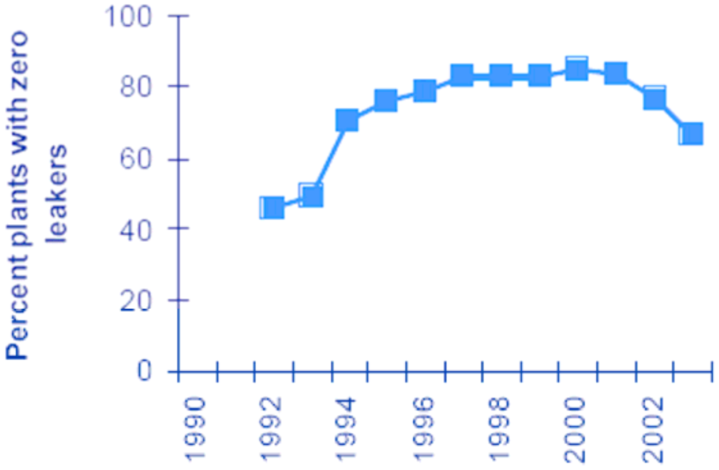

Figure 9 US Industry Fuel Failure Trend [15]

The same Westinghouse paper can show recent trends in the reliability of their fuel PWR performance after several years of fuel leakers, due to flow induced grid-to-rod fretting wear. Figure 10 shows the recent trends on a “leaking rods per million operating rods” basis.

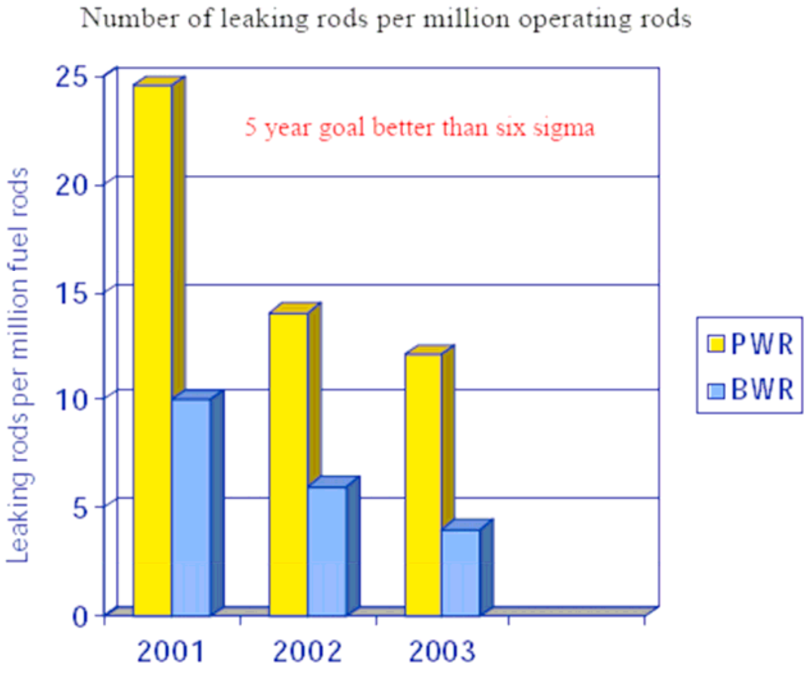

Figure 10 Westinghouse Fuel Performance Trend [15]

A Japanese paper gives an overview on PWR fuel performance in Japan during the last three decades [20]. According to this report the fuel leakage rate was less than 2x10-6 or zero in the last 10 years, as shown in figure 11. There was also no fuel failures due to Axial Offset Anomaly (AOA) observed like in US-PWRs. Also no incomplete rod injection was found.

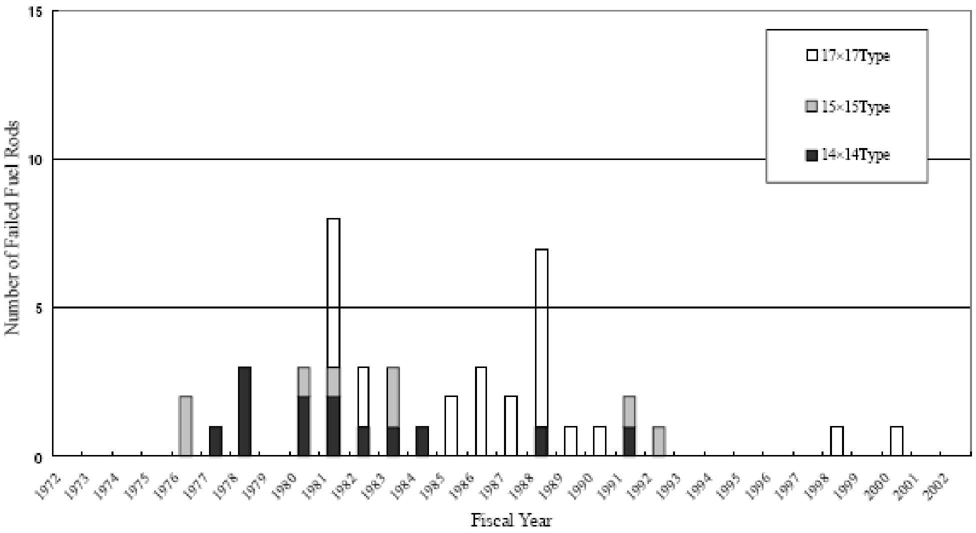

Figure 11 Number of Failed Fuel Rods at PWRs in Japan [20]

Interesting information on the statistics of WWER-1000 fuel failures is given in a paper during the 5th International WWER Fuel Conference in 2003 in Albena/Bulgaria [21]. In figure 12 an overview is given on failure root causes identified during 1992 – 2002. Besides a large number of unidentified causes the most frequent cause is damage by debris. This was confirmed by hot cell investigations. Different from Western PWR fuel experience, fuel-rod-to-spacer-fretting doe not play a significant role. On the other hand there is a very high number of defected fuel where no failure cause is known.

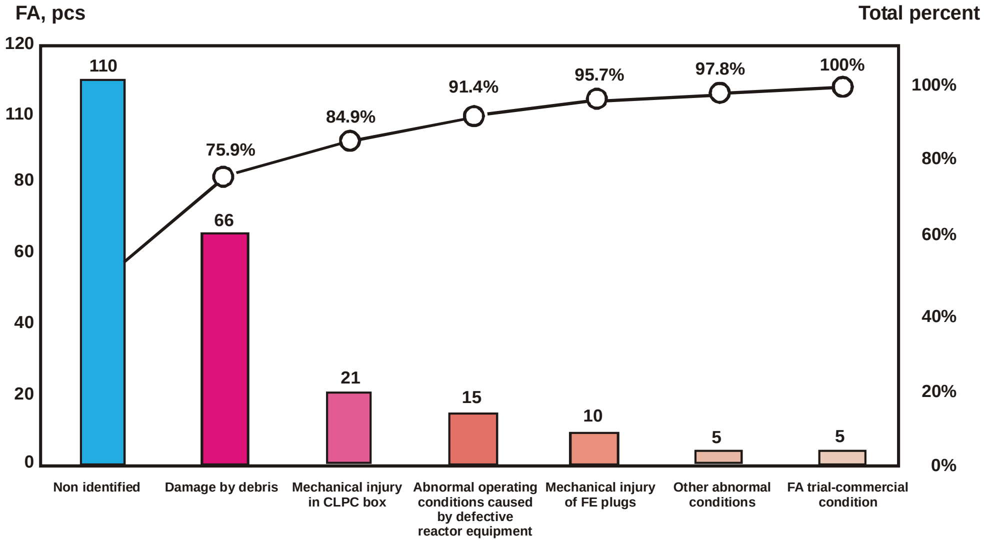

Figure 12 WWER-1000 FAs Distribution as by Depressurization Causes within the Period of 1990-2002 [21]

In the same paper an overview is given on the number of WWER-1000 units with zero fuel damage in the period 1992-2002 (figure 13). These data are based on “Cladding-Leak-Proofness-Control” (LCPC) over the whole operational period. At present 21 units are in operation in 9 NPPs in Russia, Ukraine and Bulgaria. The figure shows a trend of continuously improving fuel operation reliability within the investigated time period.

As on January 2003, 157 advanced FAs have finished operation, two of them have completed 4 fuel cycles with a burn-up of 55.44 MWD/kg$_U$.

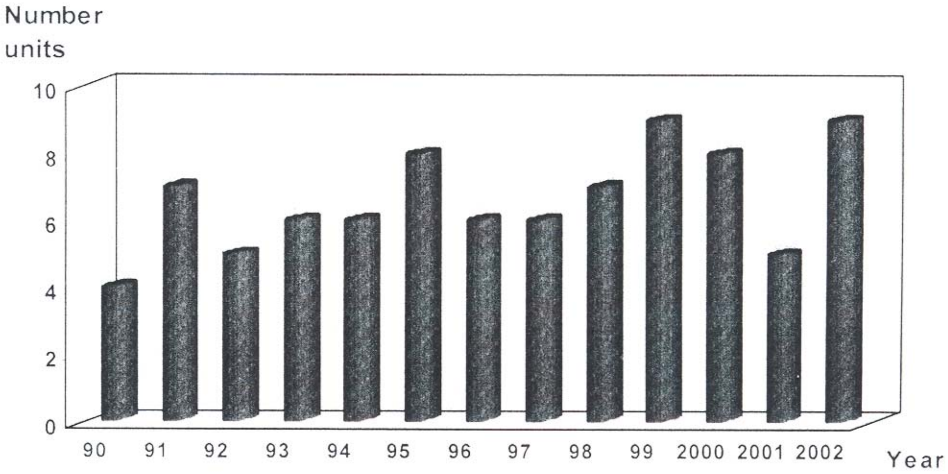

Figure 13
Number of WWER-1000 Units with Zero Damage Rates over the Period of 1990-2002 [21]

Fuel Performance Reliability Summary

As a consequence from these data it can be summarized for the performance reliability of both, PWR and WWER fuel:

- Grid-to-rod fretting caused by FA and fuel rod vibration phenomena is a generic concern, where questions of the FA and FA component design on the one hand, and questions of the core thermo-hydraulics on the other hand play a role. There are many studies available and still under way in the West and in Russia, struggling with this problem [e.g. 22, 23, 24, 25, 26, 27, 28, 29]
- Fuel assembly bow temporarily played a role mainly for some special fuel PWR assembly designs, mainly with regard to control rod dropping times [30]. It appears to be a more general problem for WWER fuel assemblies and also whole WWER cores [7, 31].
- Debris caused fretting defects at fuel rod claddings have almost disappeared with PWR fuel, obviously as a result of the generally introduced debris filters. Presently this fuel failure type still plays a significant role with WWER fuel. However, it can be expected that this kind of defect will also disappear there in the near future.

One other root causes of importance appears to play a role only for PWR fuel in the US. This is localized crud induced accelerated corrosion on fuel rod claddings, mainly as a result of the so called “Axial Offset Anomaly” (AOA). This phenomenon was discussed already discussed in the previous WWER Fuel Conference in Albena in 2003 [4].

Finally the data available on fuel rod failure statistics of PWR and WWER fuel demonstrate, that the often discussed “Zero Defect” performance is no longer a futuristic vision but today a reality in many PWRs and WWERs.

Conclusions

- PWR and WWER fuel technology have the same basic performance targets:
  - Most effective use of the energy stored in the fuel,
  - Highest possible reliability.
- PWR and WWER fuel technology use basically the same strategies to reach these targets:
  - Optimized reload strategies,
  - Maximal use of structural material with low neutron cross sections,
  - Decrease the fuel failure frequency towards a “zero failure” performance by understanding and eliminating the root causes of those defects.
- The key driving force of the technology of both, PWR and WWER fuel is high burn-up. Presently a range of 45 – 50 MWD/kg_U have been reached commercially for PWR and WWER fuel.
- The main technical limitations to reach high burn-up are typically different for PWR and WWER fuel:
  - for PWR fuel it is the corrosion and hydrogen uptake of the Zr-based materials,
  - for WWER fuel it is the mechanical and dimensional stability of the FA (and the whole core). Corrosion and hydrogen uptake of Zr-materials is a “non-problem” for WWER fuel.
- Other performance criteria that are important for high burn-up are the creep and growth behaviour of the Zr materials and the fission gas release in the fuel rod. There exists a good and broad data base to model and design both fuel types.
- FA and fuel rod vibration appears to be a generic problem for both fuel types but with more evidence for PWR fuel performance reliability. Grid-to-rod fretting is still a major issue in the fuel failure statistics of PWR fuel.
- Fuel rod cladding defects by debris fretting is no longer a key problem for PWR fuel, while it still appears to be a significant root cause for WWER fuel failures.
- “Zero defect” fuel performance is achievable with a high probability, as statistics for US PWR and WWER-1000 fuel has shown.

Literature

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