

ANALYSIS OF FUEL RELIABILITY / FUEL FAILURE CAUSES AND MITIGATION

Workshop on “Modelling and Quality Control for
Advanced and Innovative Fuel Technologies”

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Types of fuel operation damages

- Fuel failures – damage to fuel rod (FR) cladding, either with fuel washout into coolant or only with gas untightness. In both cases fission products enter the cooling circuit from leaking FRs. They are discussed in this report.
- There are other damages to fuel assembly and its components, e.g. spacer grids (SGs), guide tubes (GTs), etc. These damages may limit fuel safety margins (e.g. Incomplete Control Rod Insertion because of fuel bundle including GTs bow and strong interaction of dropping control rod with inner surface of GT), but are not resulted in activity release. They are out of the scope of this report.

Evaluation of LWR fuel failure rates (1)

- Number of leaky fuel assemblies (FAs) / fuel rods (FRs) is defined by sipping in combination with fuel inspection and post-irradiation examination (PIE)
- Methodology to calculate fuel failure rate was provided in the IAEA Technical Report Series 388 (1998) “Review of Fuel Failures in Water Cooled Reactors”
- **$R \approx r \times D/N$** , where:
 - R** is an annual rod failure rate (leaky rods/rods in core);
 - N** is the number of rods in core for all operating reactors during that year;
 - D** is a number of leaking FAs in a year and
 - r** is the average number of leaking FRs per leaking FA, agreed as 1.1 for BWRs and WWER-440s and 1.3 for PWRs and WWER-1000s

Evaluation of LWR fuel failure rates (2)

- Another methodology to calculate fuel failure rate was also provided in the IAEA TRS 388 and appears as the number of failed FAs per year and 1 GWe installed capacity. Data for calculation and comparison with methodology (slide 4) are given in Table 1 (slide 5). With these figures a given number of failed FAs per GWe and year can be transformed by the following approximation:

- $\mathbf{R} \approx \mathbf{b} \times \mathbf{r} \times \mathbf{A}$, where:

\mathbf{R} is an annual rod failure rate (leaky rods/rods in core);

\mathbf{b} is the average electric power per rod (GWe/rods in a core), see Table1;

\mathbf{A} is the annual number of leaking FAs per GWe

Evaluation of LWR fuel failure rates (3)

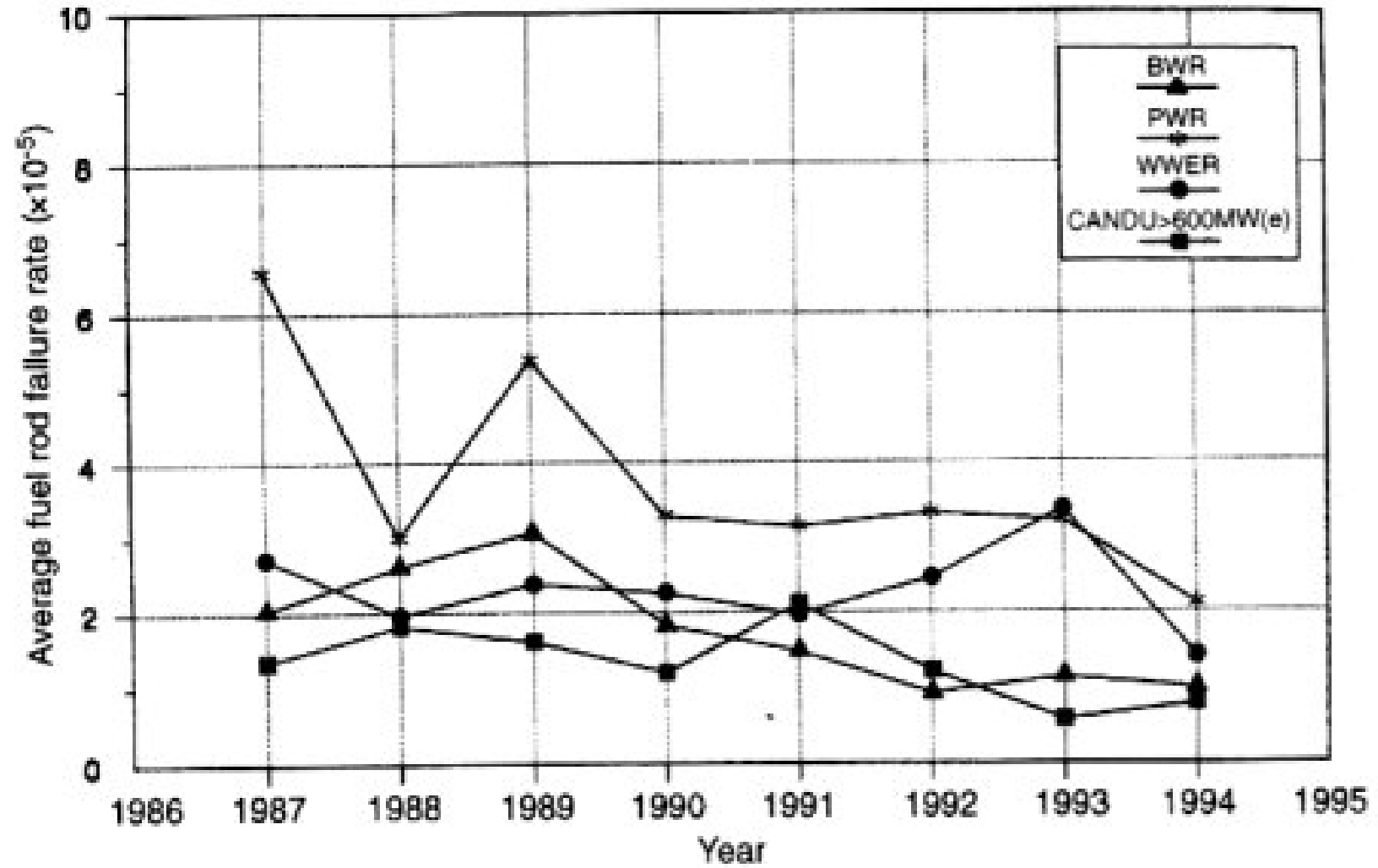
Table 1. World averages of inserted fuel per GWe installed capacity as of 31 Dec. 2004

Characteristics/Reactor Type	BWR	PWR	WWER
Number of units in operation	93	214	53
Installed capacity, GWe	82.6	204.7	35.9
Number of FAs in operation	58.2	36.0	15.1
Average GWe per 1000 FAs	1.4	5.7	2.4
Number of FRs in operation (10^6)	3.8	8.6	2.5
Average GWe per 10^5 FRs	2.2	2.4	1.4

Evaluation of LWR fuel failure rates (4)

- Both methodologies do not take into account differences in load factor and burnup, but provide, at least, good indication and direction when analyzing changes in failure rates because of changes in fuel design, materials, operation conditions and implementation of remedies. Depending on detalization of input data, difference between results calculated using both methodologies might reach 5-10 %.
- At present more and more specialists/organizations give preference to express fuel failure rates in ppm. 1 ppm means 1 failed rod per 10^6 rods in core per year. 1ppm is a value that has already been reached at the group of some Japanese plants. But for the whole nuclear community it is a value to that it is striving for.
- Consideration of average fuel failure rates may be of limited relevance for individual plants, but can be a valuable means of comparing the industry-wide fuel reliability. TRS 388 introduced regional (e.g. Europe, Japan, USA) and world average fuel failure rates in 1987-1994 (see Fig. 1 below):
 - 1) There is tendency for rate's decreasing
 - 2) Rates are basically in the range of 10-40 ppm
 - 3) Usually sharp divergences are due to new phenomena

Evaluation of LWR fuel failure rates (5)-Fig. 1



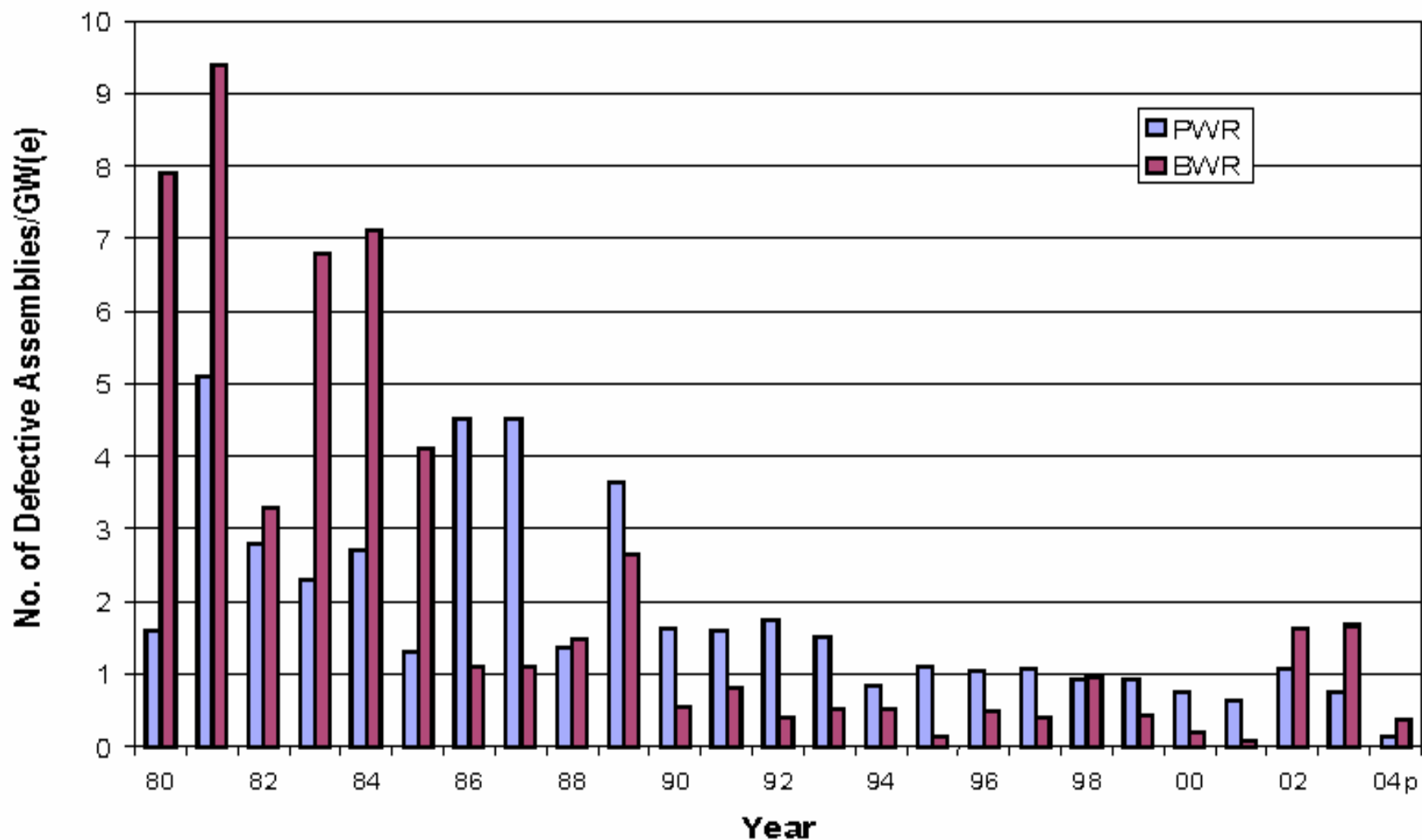
Evaluation of LWR fuel failure rates (6)

Table 2. Estimated world average FR failure rates in 1991-1994 (TRS 388).

Next slides present fuel failure statistics for several countries with significant nuclear electricity share (USA-slide 10, France-11, Germany-12, Spain-13 and also for all operating WWERs-14) for the wider time span including 2004

Average annual FR failure rates / Reactor type	BWR	PWR	WWER
Failed rods per 10^5 rods	1.1	2.9	2.3
Failed rods per GWe	0.5	1.2	1.6
Exposed fuel in kg UO ₂ per GWe	1.5	2.0	2.4

Fig. 2. Trend in US Fuel Failure Rate (EPRI report to the 2005 Conference on LWR Fuel Performance)



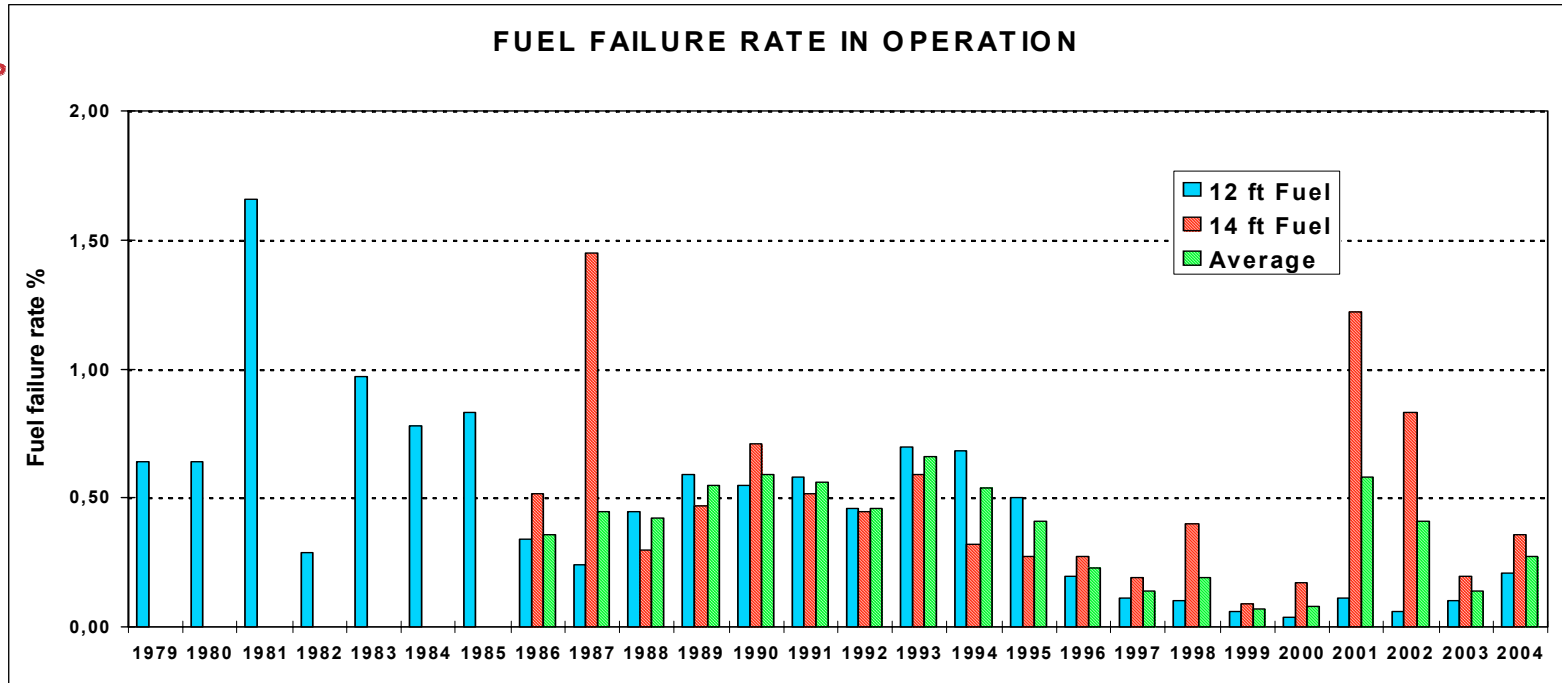


FIG. 3. Total failure rate: 0.27 % (1.02×10^{-5}), French report to the 2005



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FIG. 4 Evolution of the discharge burnup of FRAMATOME ANP GmbH PWR+BWR fuel assemblies and the Annual fuel rod failure rate (H.-P. Fuchs, report to the IAEA TWGFT Meeting, April 2005)

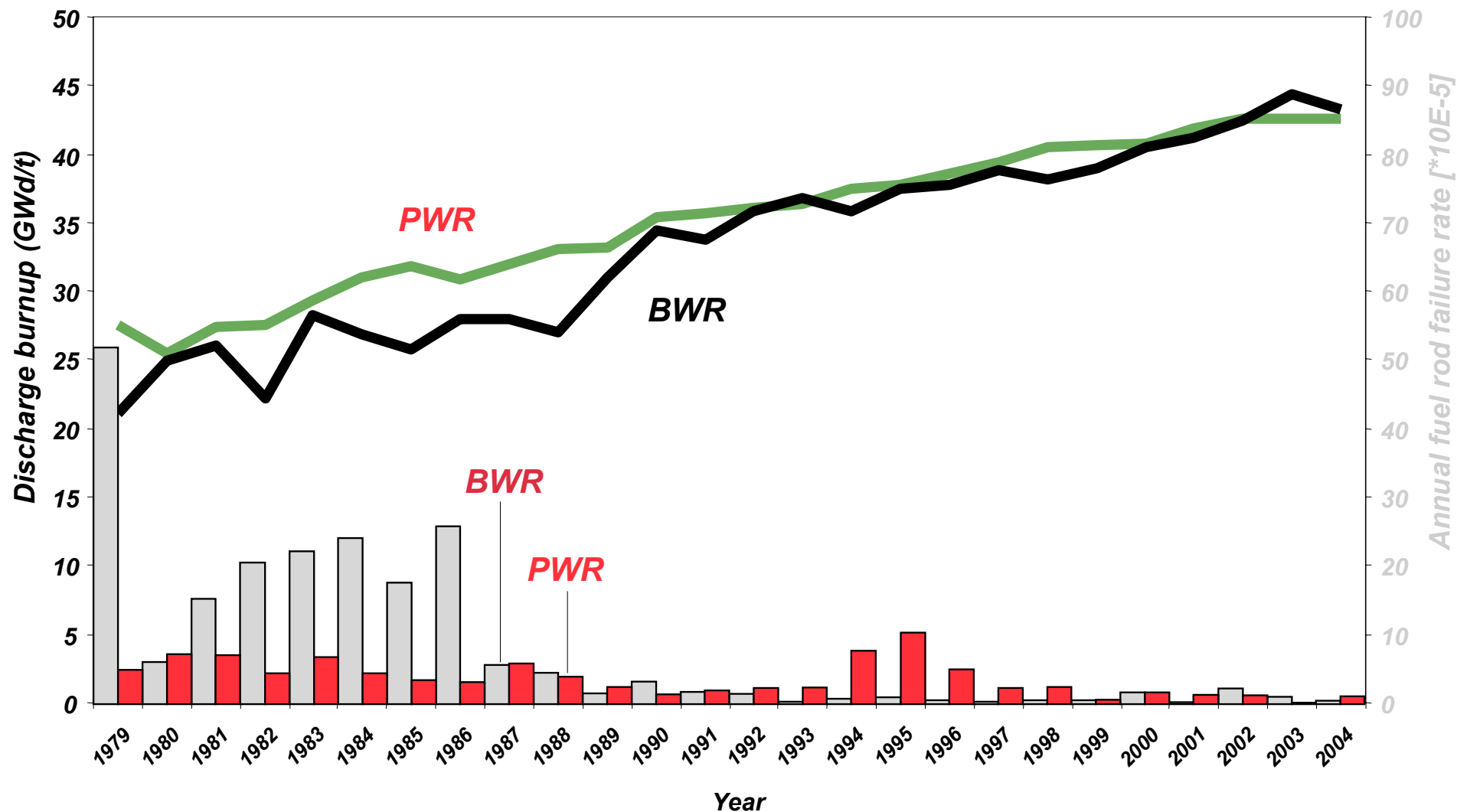
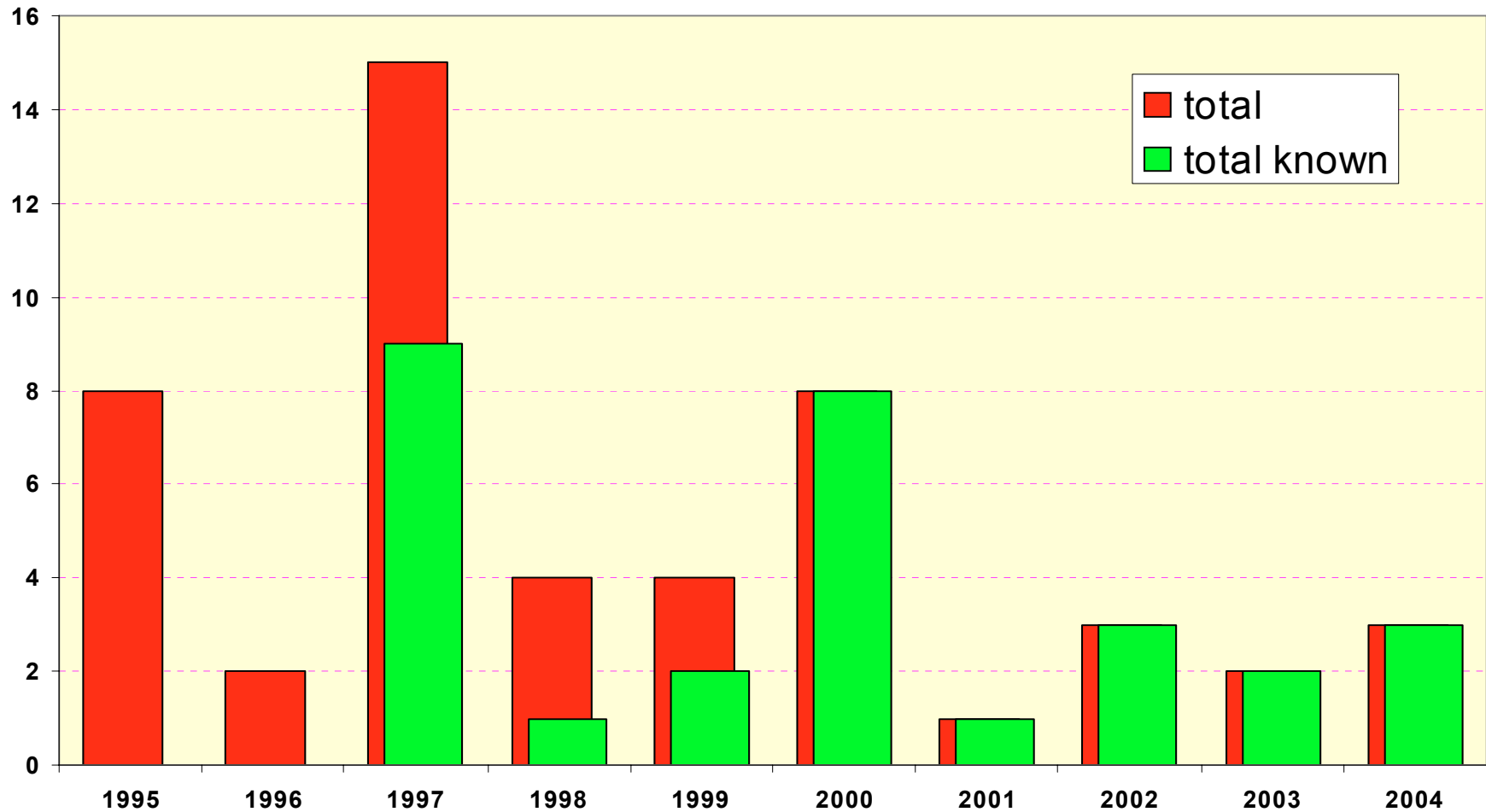
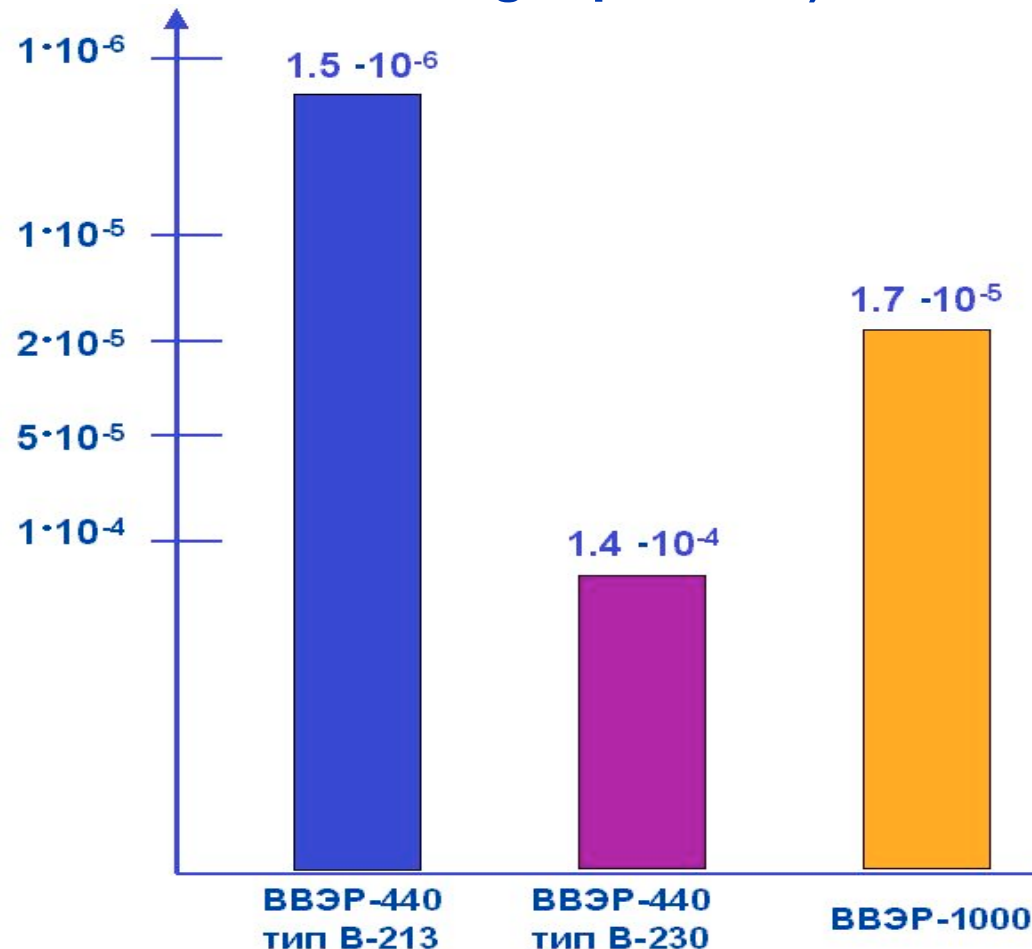


FIG. 5 Fuel rod failures in Spain



*data from fuel manufactured by ENUSA, only- presented by
J.M. Alonso Pacheco at the IAEA TWGFPT Meeting, April
2005*

FIG. 6 Fuel rod failure rates for all WWER reactors operating in Russia and other countries during last several years (V. Novikov, report to the IAEA TWGFPT Meeting, April 2005)



Evaluation of LWR fuel failure rates (6)

Table 3. Estimated world average FR failure rates in 1995-2004

Evaluation of fuel failure rates was done by lecturer using data from TRS 388, graphs above plus data from Sweden presented at the IAEA 2005 TWGFPT meeting; *- rate for WWER-440 of V-213 and V-230 designs and WWER-1000; ** - for WWERs without WWER-440 of V-230 design ; Japanese data (rates are lower usually in Japan) were not taken into account. In brackets there are data on world average fuel failures rates in 1991-94, see Table 2 above.

Average annual FR failure rates / Reactor type	BWR	PWR	WWER
Failed rods per 10 ⁵ rods	1.3 (1.1)	1.8 (2.9)	2.5*/1.0** (not applicab.)

Consequences of fuel failures for utilities

- Fuel failures usually do not impact directly reactor safety. However, they may increase dose rates, especially in case of fuel washout.
- Fuel failures are very costly. It was mentioned in the EPRI report at the 2005 Conference on LWR Fuel Performance that “even a single BWR failed rod can cost to utility more than \$ 1 mln. in outage time, fuel and power replacement costs. Failures affecting a larger portion of a reload, e.g. crud/corrosion failures, can easily run in the tens-of-millions of dollars”. This is why it is so important to keep fuel failure rate As Low As Reasonably Achievable (ALARA principle).

Utilities policies to maintain good fuel reliability at high burnup operation (1)

- Under economics pressure, utilities operate nuclear fuel under more and more demanding conditions, e.g. higher burnups (see Fig. 4) and thermal rates. To comply with these increasing fuel duties, utility require fuel vendor to provide FAs with better resistance to damaging factors, with better design and better fuel and structural materials. Utilities themselves modernize water chemistry regimes to diminish corrosion and crud deposition on FR claddings and other FA components. All changes/modernizations should be done in the integrated and balanced manner what is very difficult to reach. Table 4 and Figs. 7-8 describe evolution of fuel duties worldwide (BWRs, PWRs and WWERs) and water chemistry parameters in U.S. PWRs and BWRs.

Table 4. Evolution of fuel duty parameters in water cooled power reactors (BWRs, PWRs and WWERs)

Parameter/years	1970's	2004-05	~2010	~2020* <small>*R. Yang, LWR Fuel Perf. Conf. 2005</small>
Fuel discharge average burnup, GWd/tU	28-30	45	48-50	~100
Fuel enrichment, % U-235	3.0	4.5	4.9	~10
Fuel cycle length, months	11	12-18	12-24	12-24
Fuel residence time, years	3	5	6	~10
Relative radiation damage (dpa) to fuel and structural materials	1	1.5	1.7	~3

Water chemistry modifications and decontamination procedures

- Changes of water chemistry parameters illustrated at Figs 7-8 for U.S. PWRs and BWRs were and are typical in general for all park of PWRs/WWERs and BWRs worldwide. These changes were directed on diminishing corrosion/crud deposition on FRs in a core and on diminishing risk of stress-corrosion cracking of coolant circuit materials (adjustment of Electro-Chemical Potential (ECP)).
- During outages, utilities conduct from time to time primary circuit decontamination to reduce dose rates for personnel during maintenance. If procedure and chemicals for decontamination were mistakenly selected, crud deposition may result in FR overheating and massive failures.

Fig. 7. Evolution of water chemistry in U.S. PWRs as response to BU increase (EPRI report at the 2005 Conf. on LWR Fuel Performance)

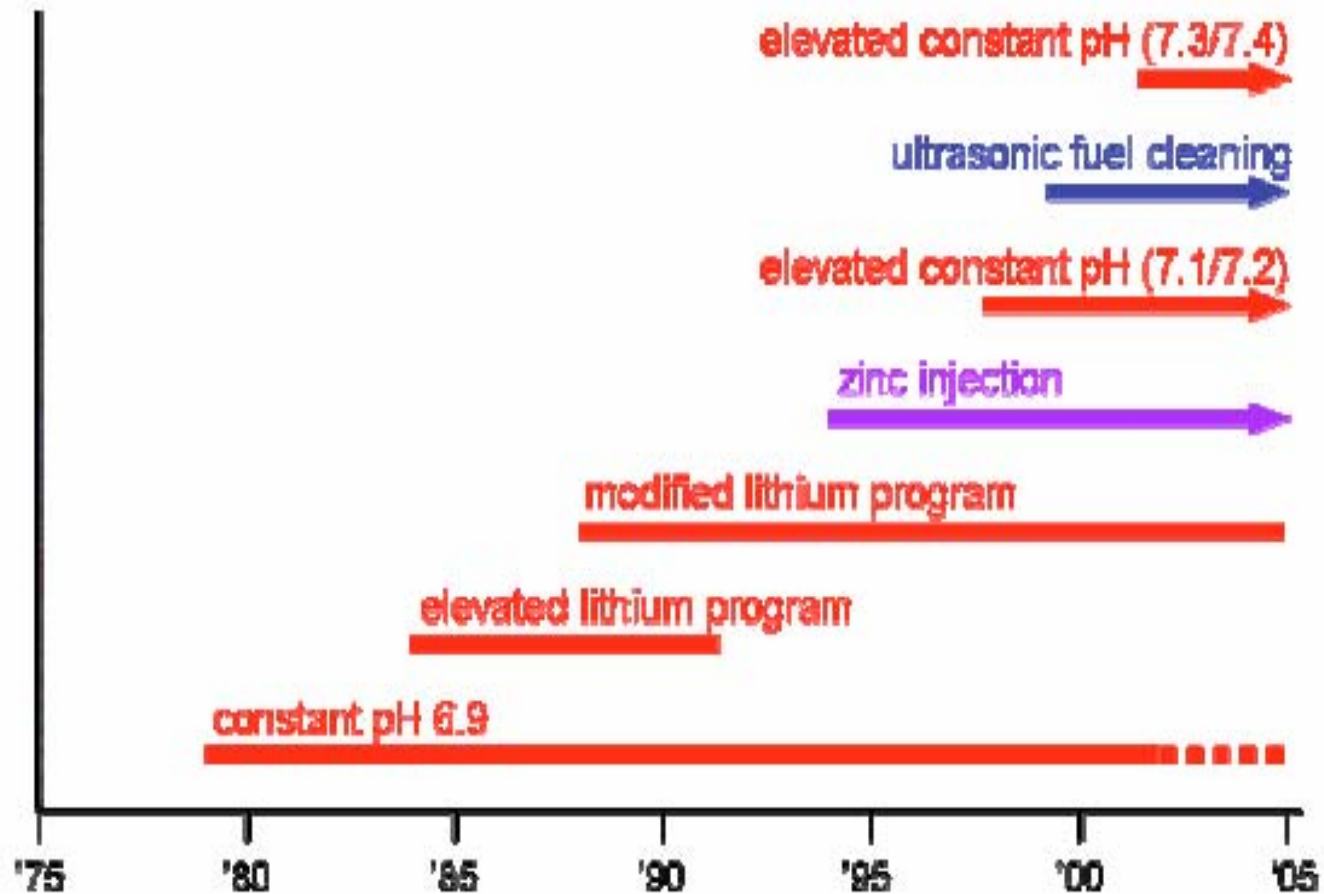


Fig. 8. Evolution of water chemistry in U.S. BWRs as response to BU increase (EPRI report at the 2005 Conf. on LWR Fuel Performance)

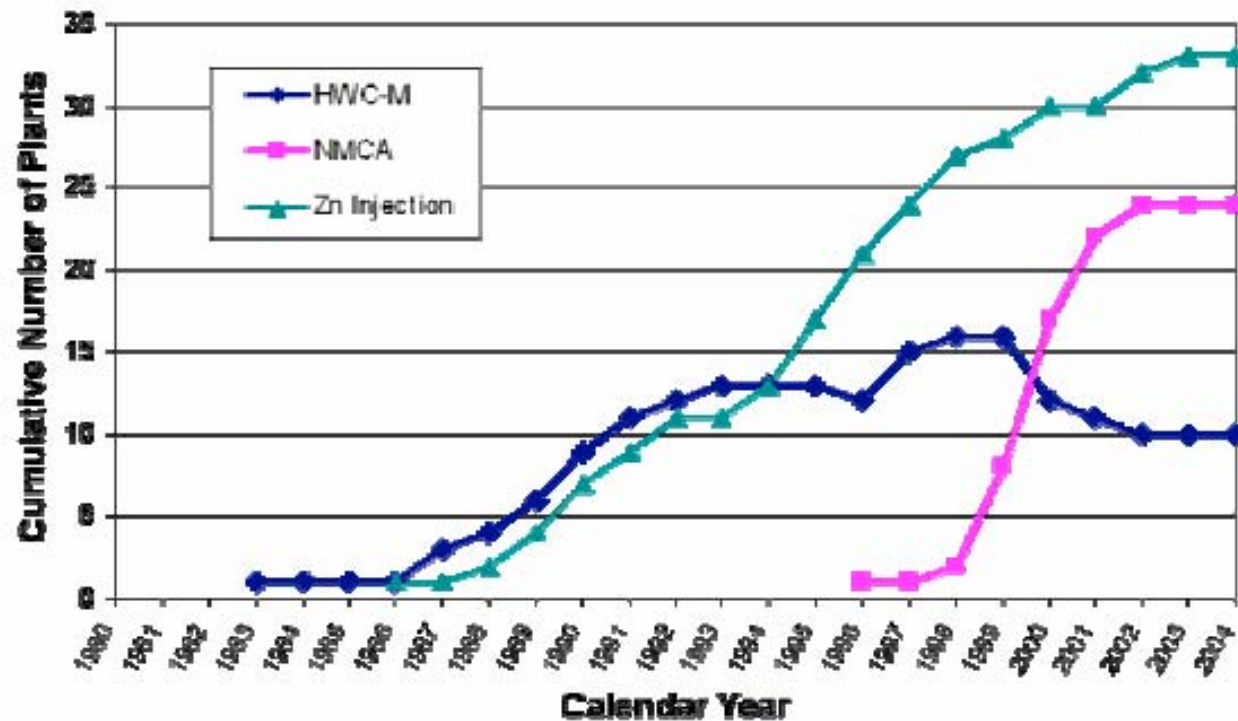


FIG. 9. Distribution of fuel failure causes in BWRs and PWRs in 1987-94

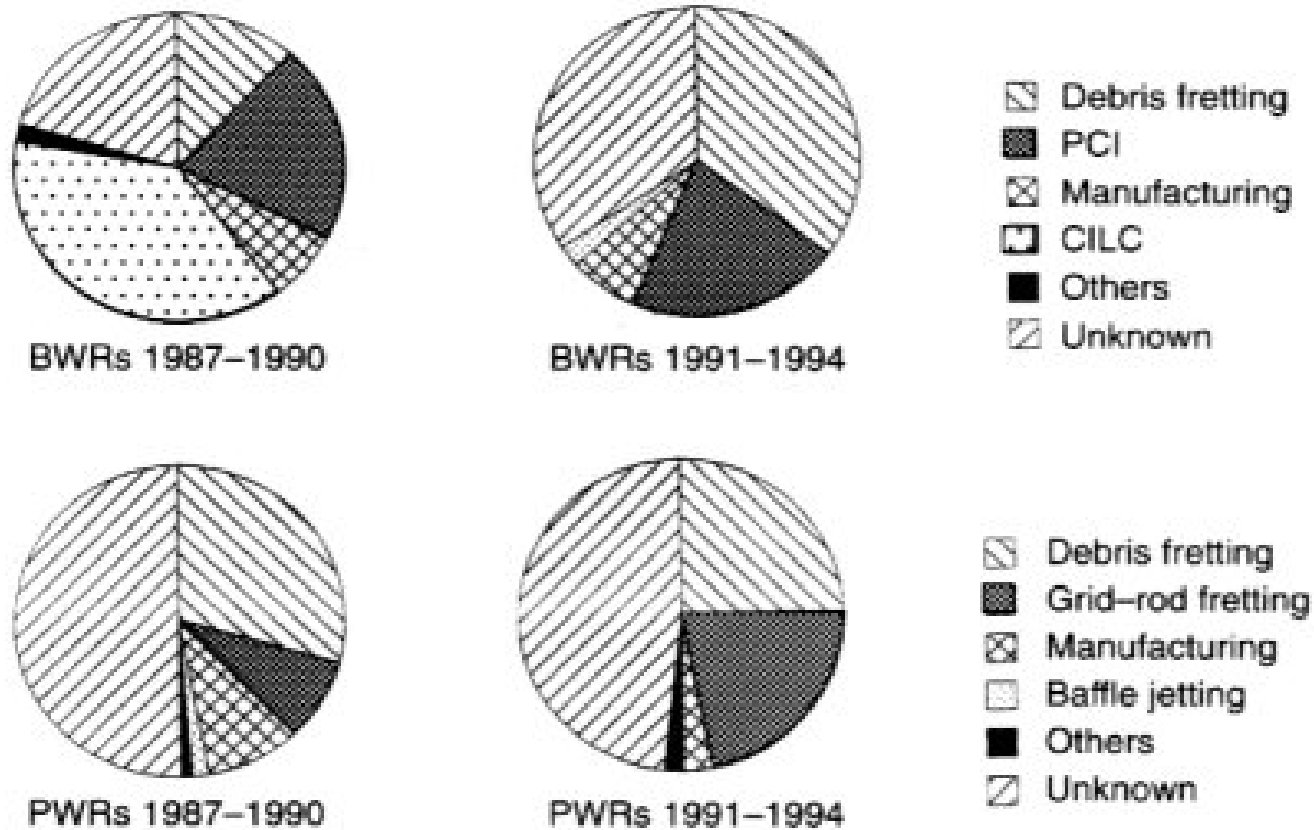


FIG. 10. Baffle Jetting in PWRs

This type of failure may happen in PWRs with the down-flow baffle barrel design. Fig. 10 shows two ways in which the joint between two core baffle plates can open and allow a high pressure jet of water to impinge on some of FRs. Such gaps are caused by stress in the baffle plate assembly. Transverse coolant flow results in turbulence and vibration of the FR periphery row. The appearance of the defect generally showed a long axial fretting worn and resulted in large axial split.

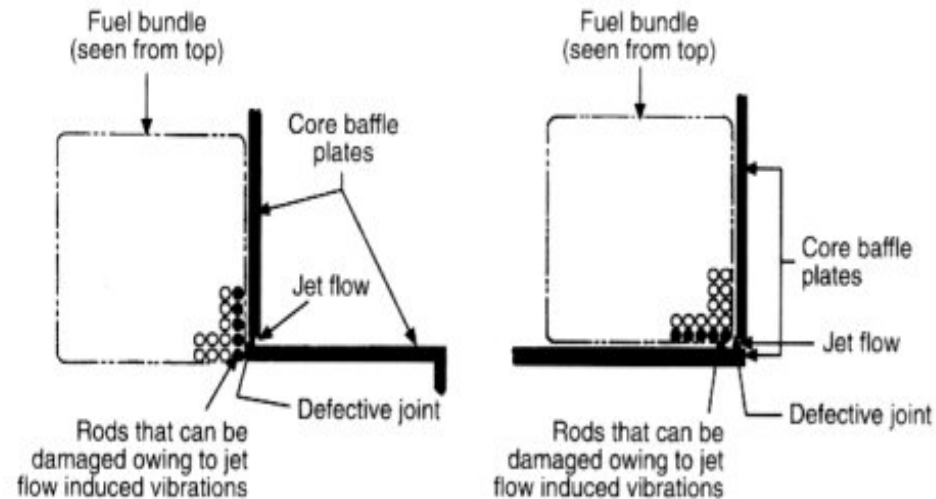


FIG. 11 Fuel Failure Causes in the US BWRs

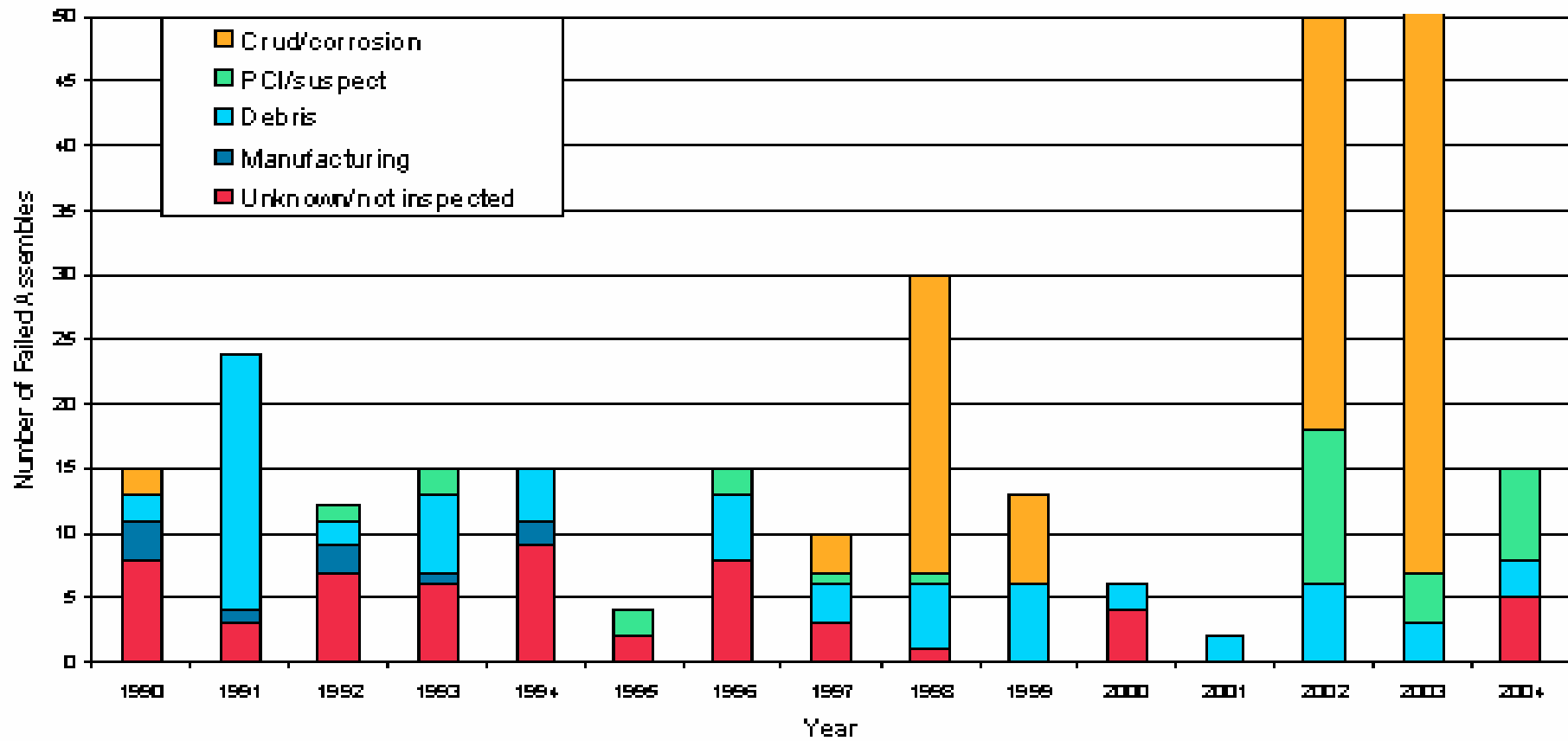


FIG. 12 Example of tenacious crud and surface spallation (River Bend BWR, USA) – EPRI report to the 2005 Conference on LWR Fuel Performance)

Before Brushing

After Brushing



FIG. 13 Fuel Failure Causes in U.S. PWRs

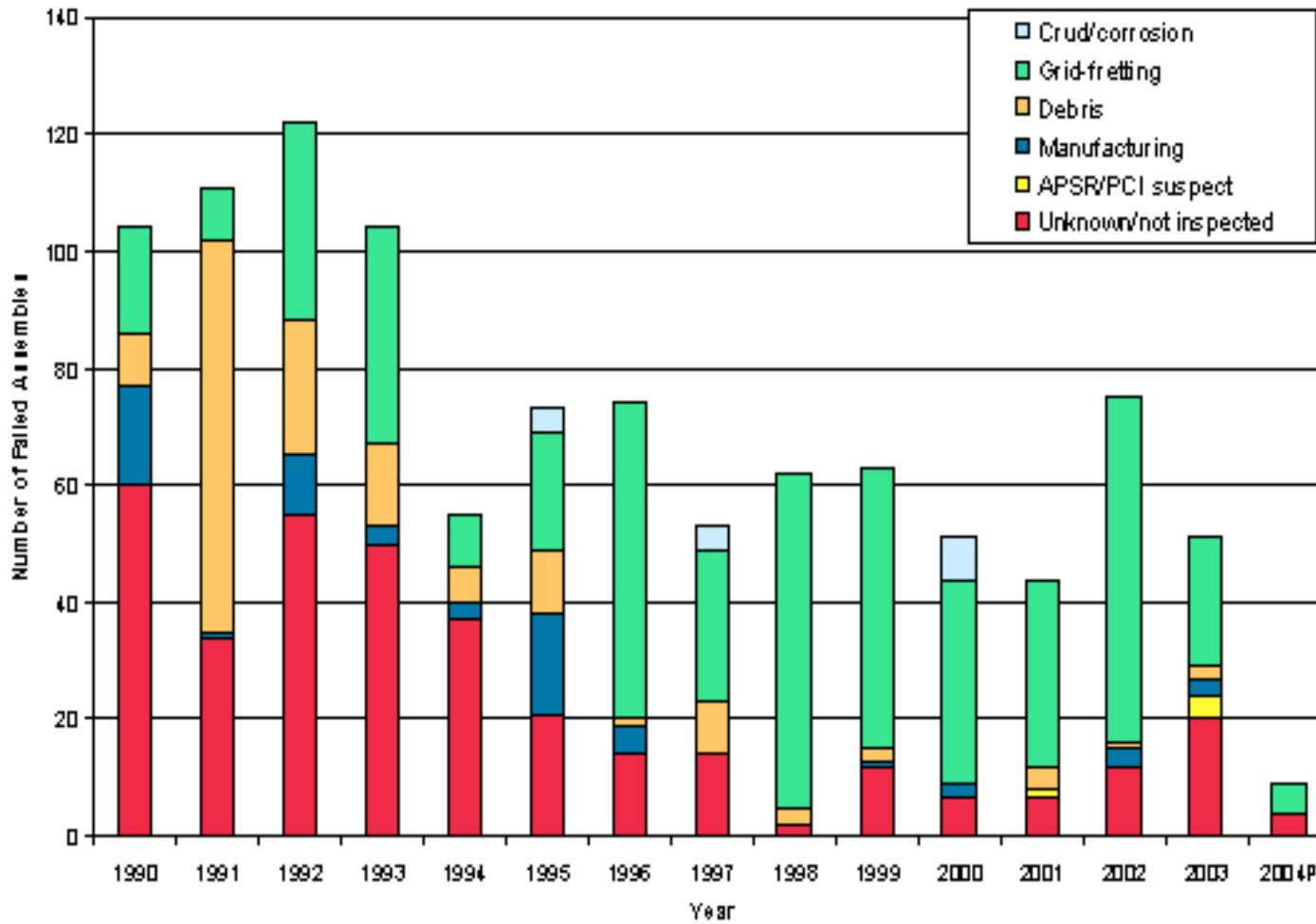
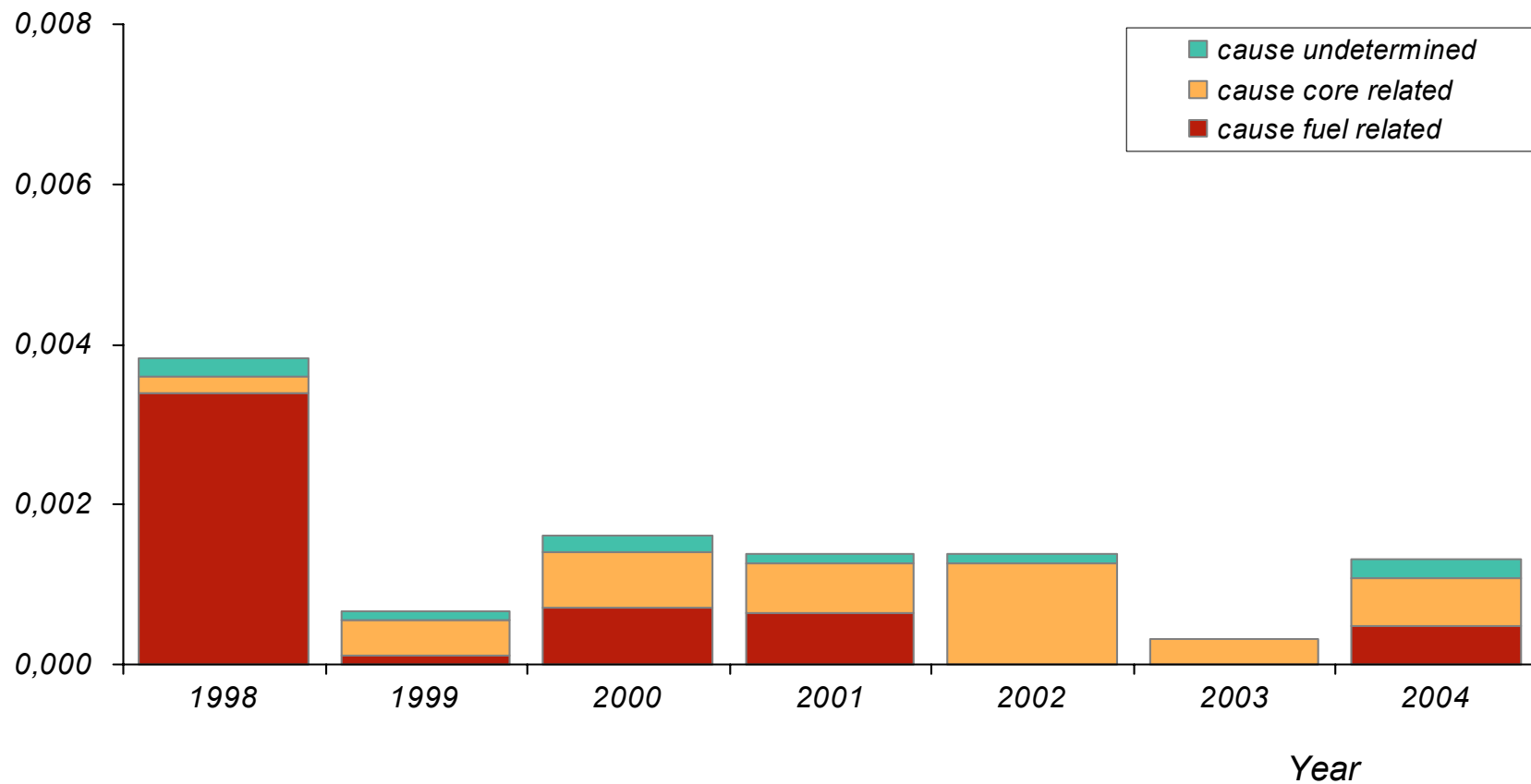


FIG. 14 Framatome ANP GmbH PWR Fuel Operational Reliability 1998-2004, status 12/2004

(H.-P. Fuchs, report to the IAEA TWGFT Meeting, April 2005)

Annual Fuel Rod Failure Rate [%]



**Table 5. Framatome ANP GmbH
Main Causes of PWR Fuel Failures 1996-2004
(H.-P. Fuchs, report to the IAEA TWGFT Meeting, April 2005)**

Cause of failure	1996-2004	2004
Fuel rod fretting in the bottom spacer (IGSCC)	40 %	-
Debris fretting	19 %	22 %
Other grid-to-rod fretting	24 %	45 %
Fabrication (Contamination with hydrogen containing material)	10 %	-
Unknown after examination	1 %	-
No examination performed	6 %	33 %

FIG. 15 Framatome ANP GmbH BWR Fuel Operational Reliability 1998-2004, status 12/2004

(H.-P. Fuchs, report to the IAEA TWGFT Meeting, April 2005)

Annual Fuel Rod Failure Rate [%]

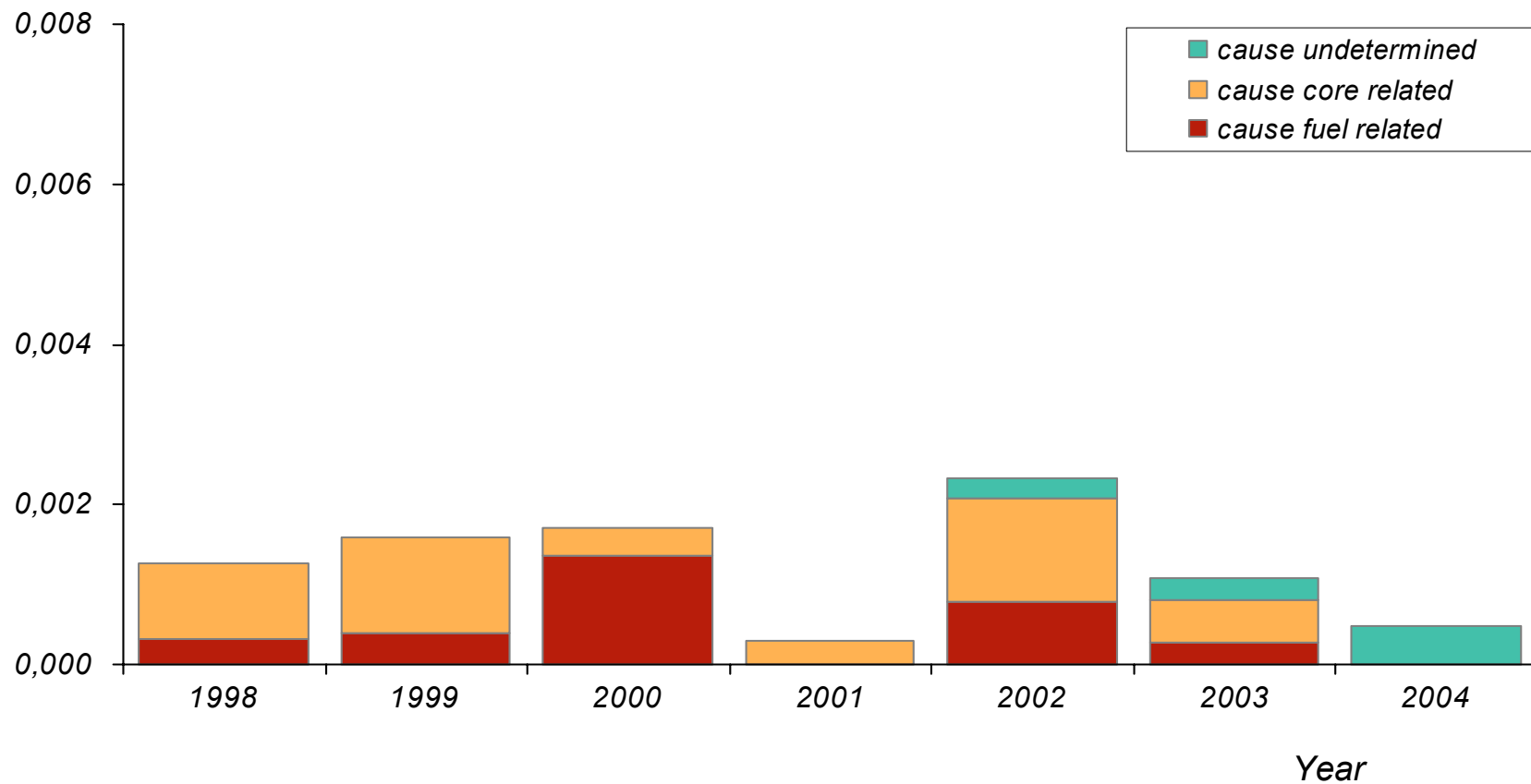


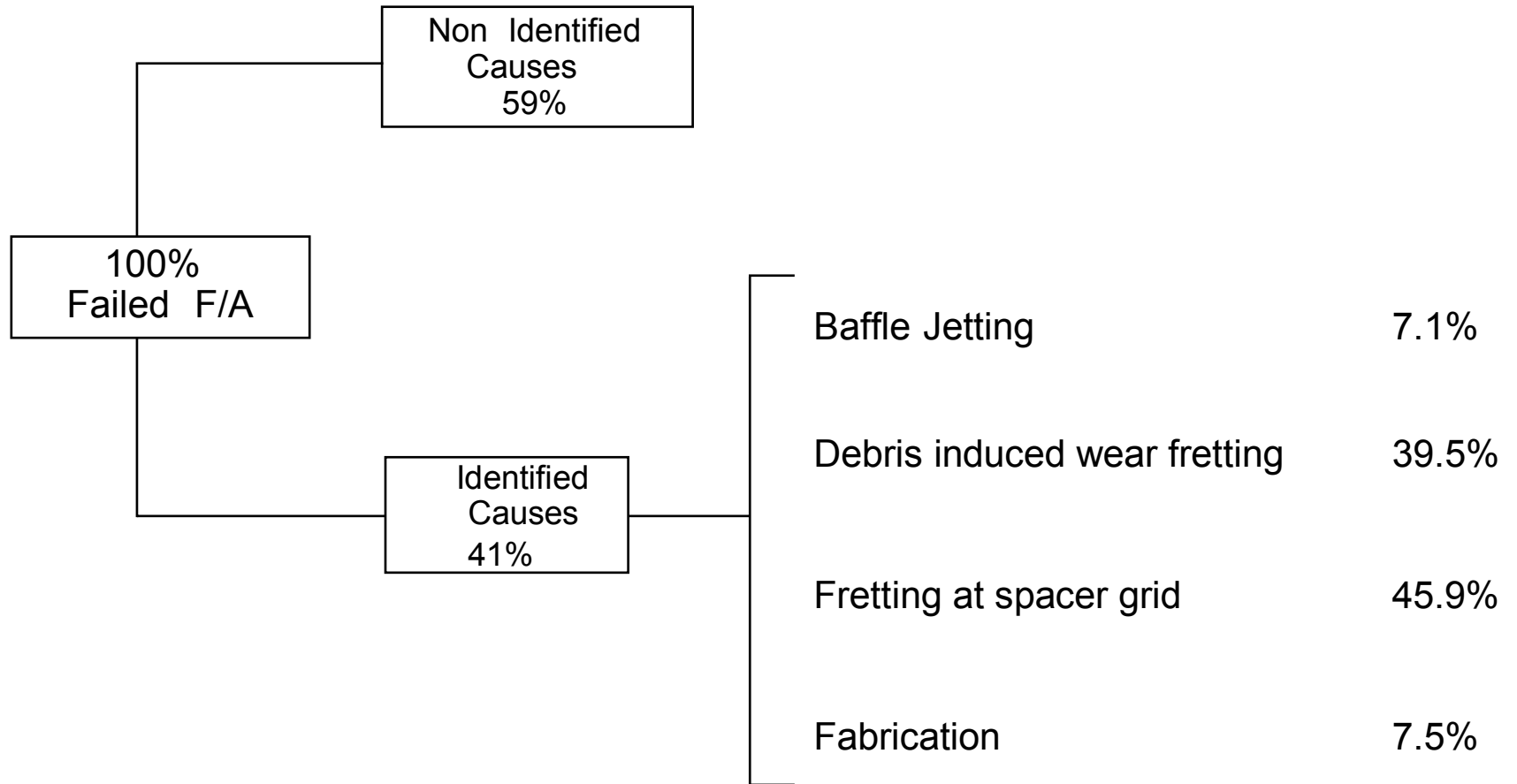
Table 6. Framatome ANP GmbH
Main Causes of BWR Fuel Failures in 1996-2004
 (H.-P. Fuchs, report to the IAEA TWGFT Meeting, April 2005)

Cause of failure	1996-2004	2004
Debris fretting	55 %	-
PCI (non-liner clad)	8 %	-
Fabrication assumed	21 %	-
Unknown after examination	11 %	50 %
No examination performed	5 %	50 %

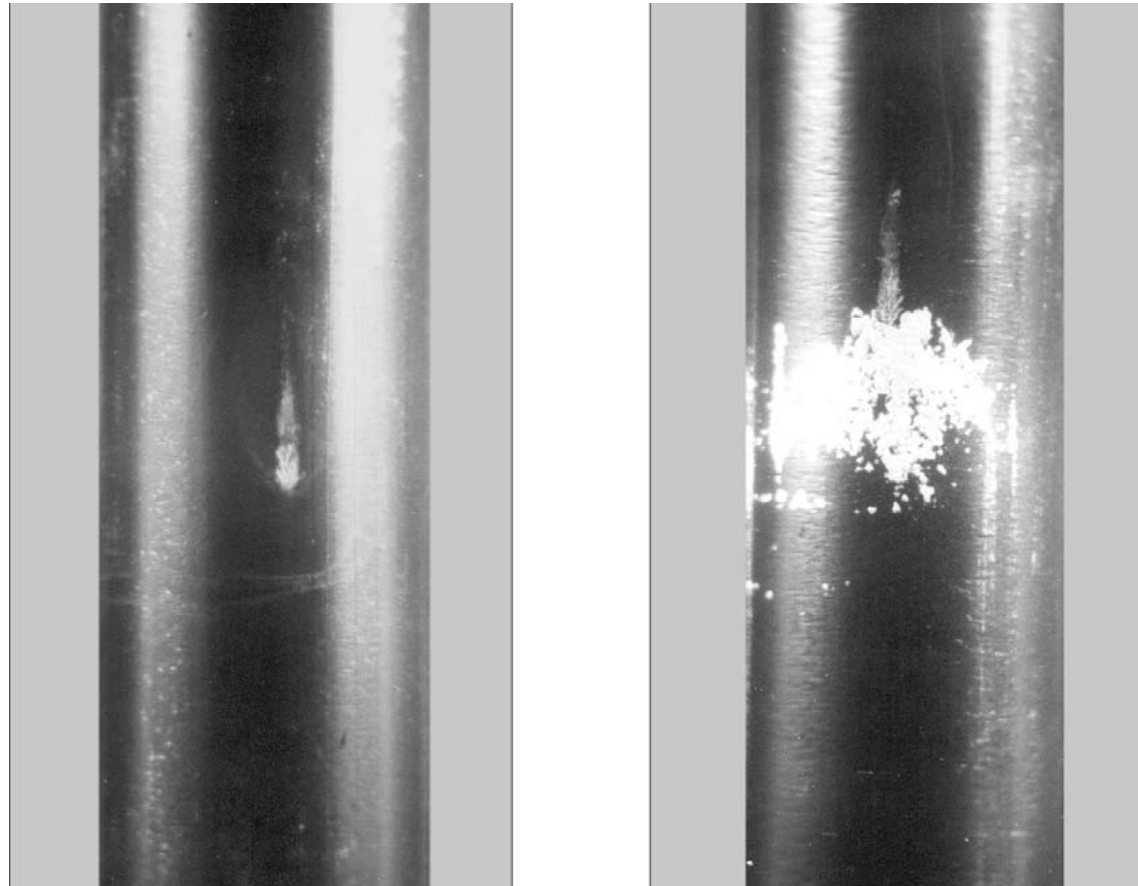
FIG. 16. Total Defective Fuel Assemblies status (up to end of 2004) and origins of the failures (French report to the IAEA 2005 TWGFPT meeting)



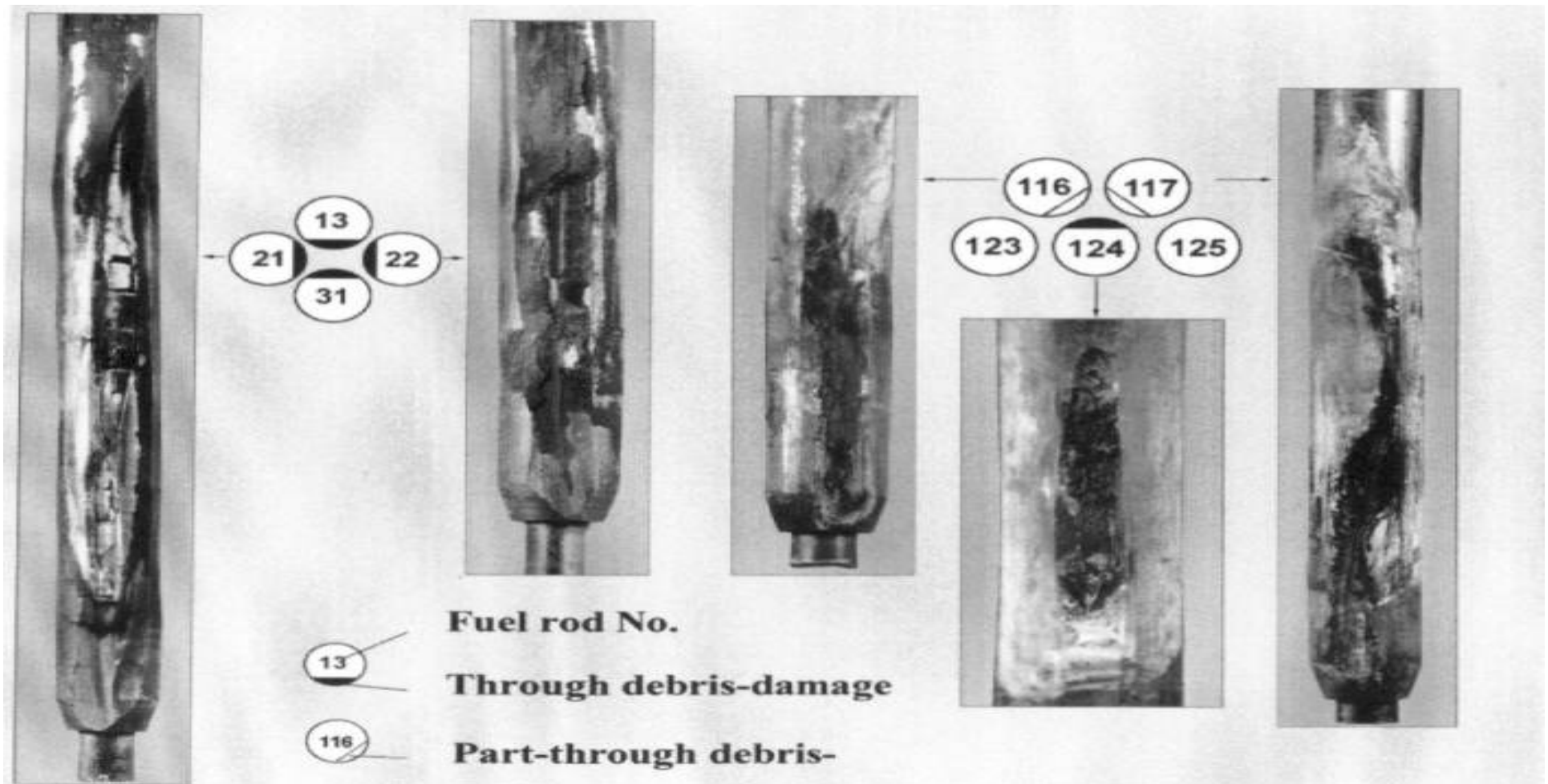
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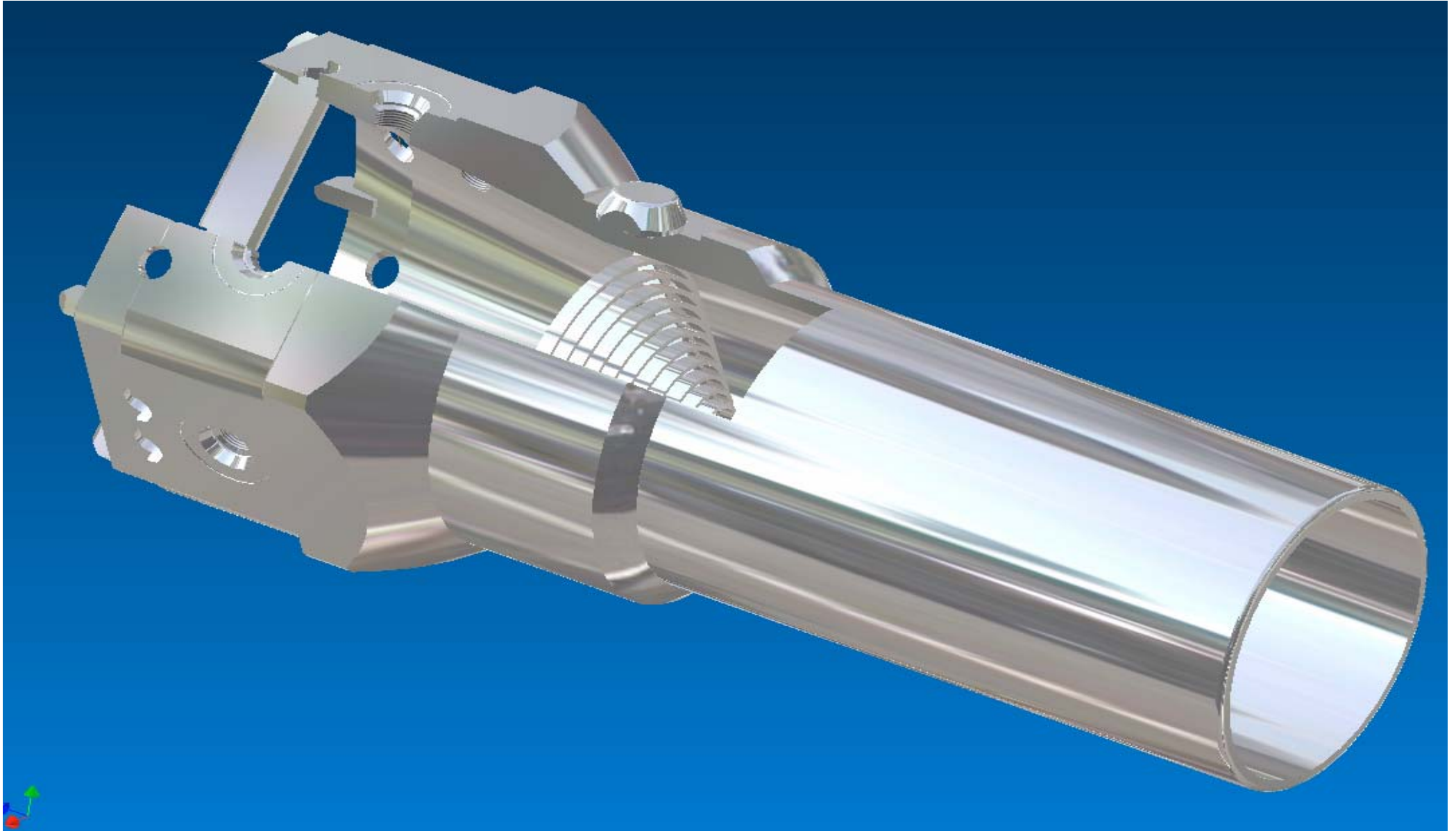
Fretting wear marks under SG, WWER-440, A. Smirnov, IAEA-TECDOC-1345



Debris related fretting damage to WWER-440 fuel rods, V. Chirkov, IAEA-TECDOC-1345



DEVELOPMENT OF THE FILTER CONCEPT FOR WWER-440 FAs



W-ABB TripleWave Debris Filter Unit, A. Soderlund, IAEA-TECDOC-1345

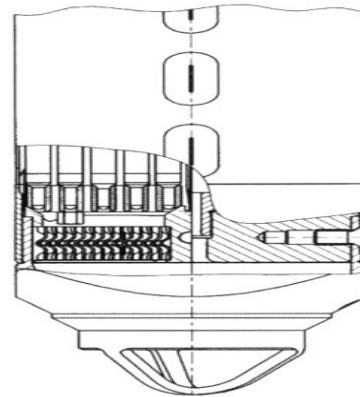


FIG. 1. Fuel Assembly Inlet Part with TripleWave Debris Filter.

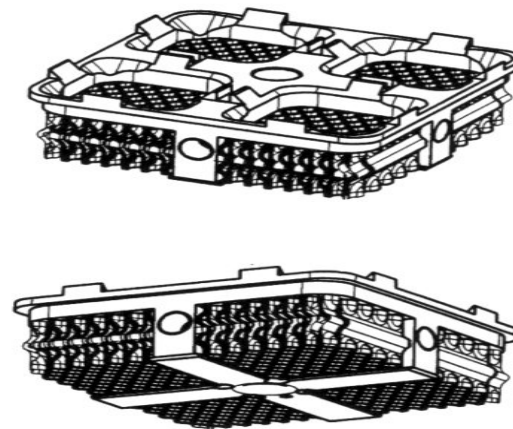
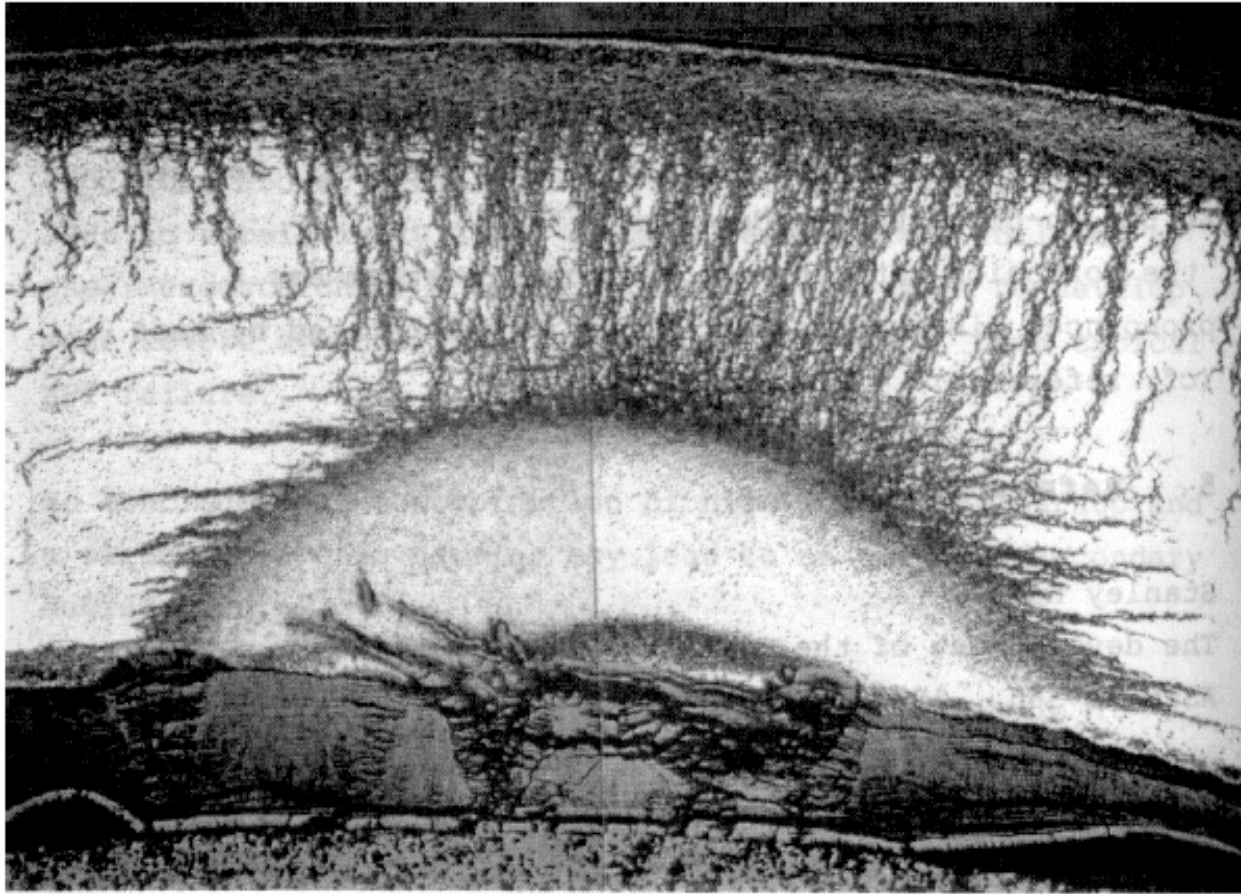


FIG. 2. Bottom Support with TripleWave Debris Filter.

Example of Missing Pellet Surface, G. Bart, IAEA-TECDOC-1345



Example of Massive Hydride (Sun Burst), v. Likhanskii, IAEA-TECDOC-1345



Some cases of “mass” fuel failures in LWRs

8 FAs in Angra-1 PWR in 1997, Brazil: FR-SG fretting wear, vibration, inadequate spring mechanical properties

19 FRs in 10 FAs, North Anna-1 (USA) in 1998: FR-SG fretting wear, vibration in core periphery

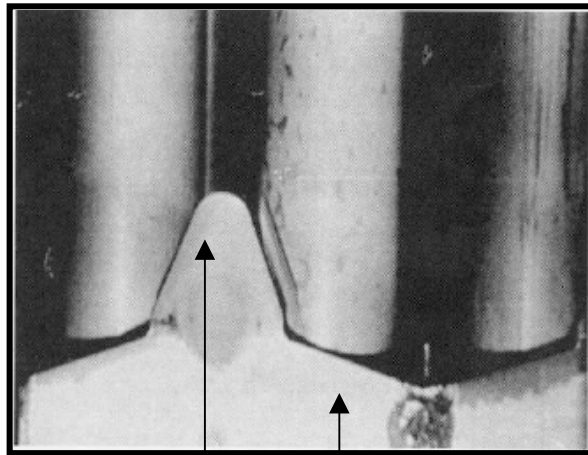
44 FAs in German LWRs in 1995: FR-SG fretting wear, vibration, isolated cases

Several FAs with bimetallic springs in German reactors in 1995: Stress-Corrosion Cracking of Inconel springs пружин

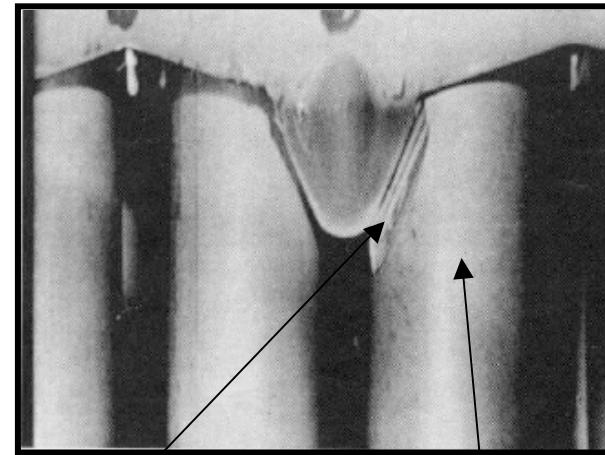
3 FAs in Khmel'nitski NPP, Ukraine in 1995: 50 ppm oxygen in primary circuit

7 FAs in Loviisa-2 NPP: corrosion crud deposition after decontamination in 1995

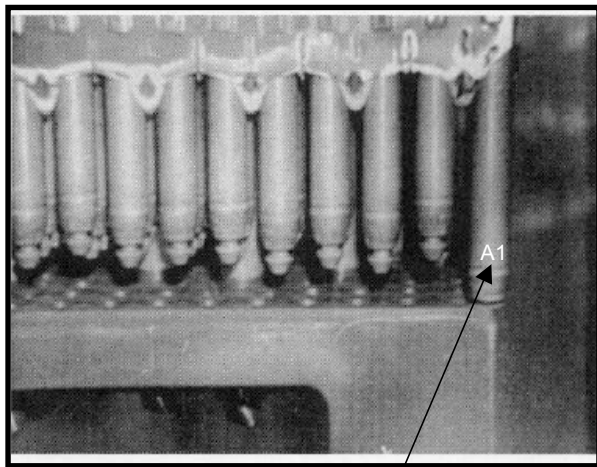
Fuel fretting damage at Angra-1, Cycle 4



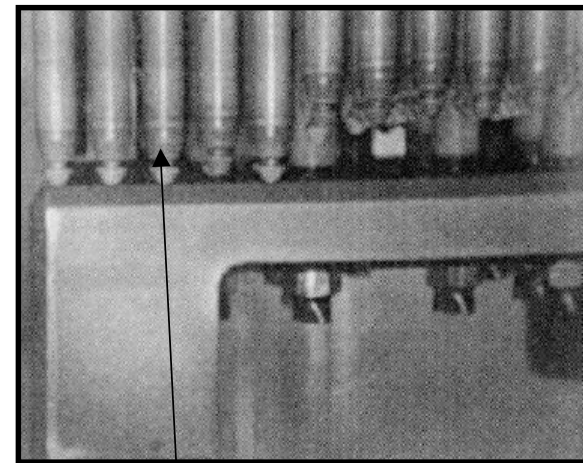
Deflector Vane
Grid side-strip



Fretting Marks
Fuel Rod



Lower end plug of fuel rod A1 fretted away



Slipped Fuel Rods

Case of “mass” fuel failure in PWR Cattenom-3 (EdF, France) in 2001(1)

- Grid-to-rod fretting due to fuel rod vibration remains as a significant cause of fuel failure and is responsible for one quarter of PWR fuel failures. Such failures were observed last year. **28 AFA 2G fuel assemblies developed 92 leaking fuel rods** during cycle 8 of Cattenom 3 (a French nuclear plant). After the outage in early 2001, fuel examinations were performed and it was determined that the primary failures were caused by spacer grid fretting wear under the lower grid and then-secondary failure with big transversal cracks and significant activity release. Studies and hydraulic testing are still under way to fully understand the root cause.

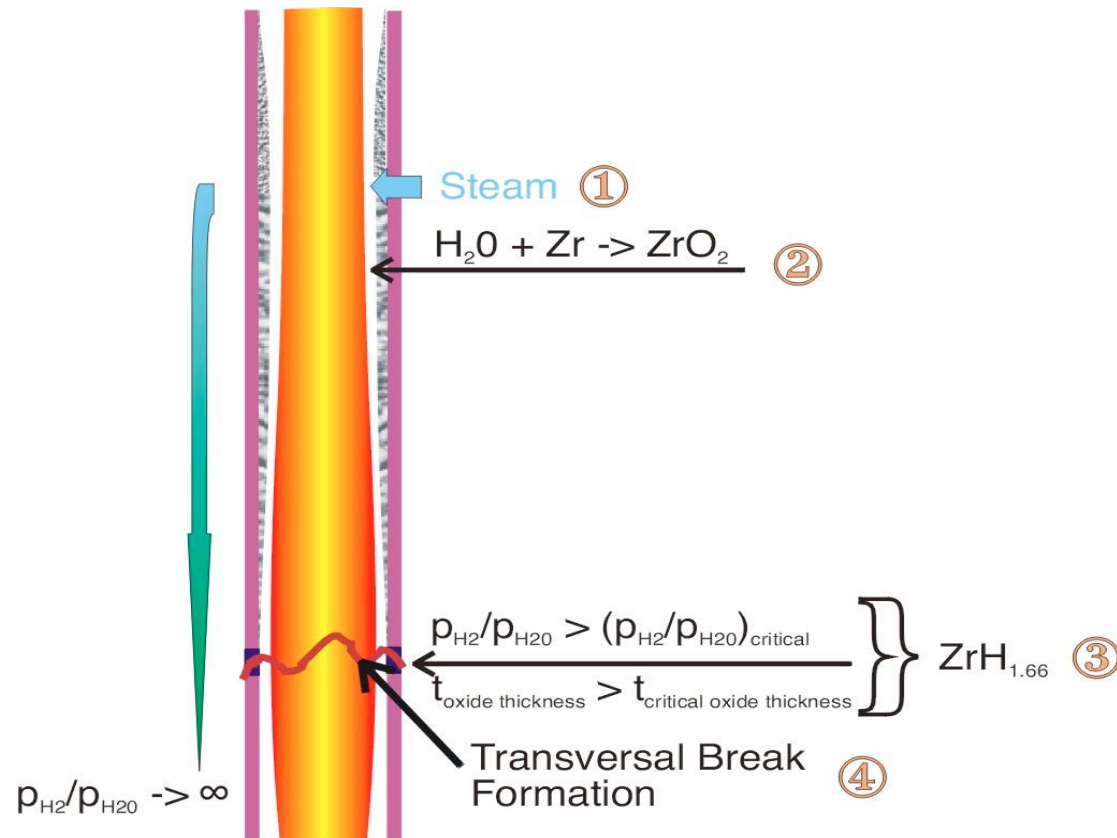
Case of “mass” fuel failure in PWR Cattenom-3 (EdF, France) in 2001 (2)

- This **grid-to-rod fretting** is partially due to Cattenom 3 high **cross flow causing rod vibration** and partially to the long residence time of some of the fuel assemblies in the most demanding positions. Cattenom 3 is a 4- loop 14 foot core plant utilizing long (18 month) irradiation cycles with a load follow and frequency control operation. To guard against the vibration that led to fretting in Cattenom, Framatome-ANP design and manufacturing departments have devised a new assembly design with a **second spacer grid at the bottom of the assembly** to give it more stability. Loading these FAs will start in Fall 2002.

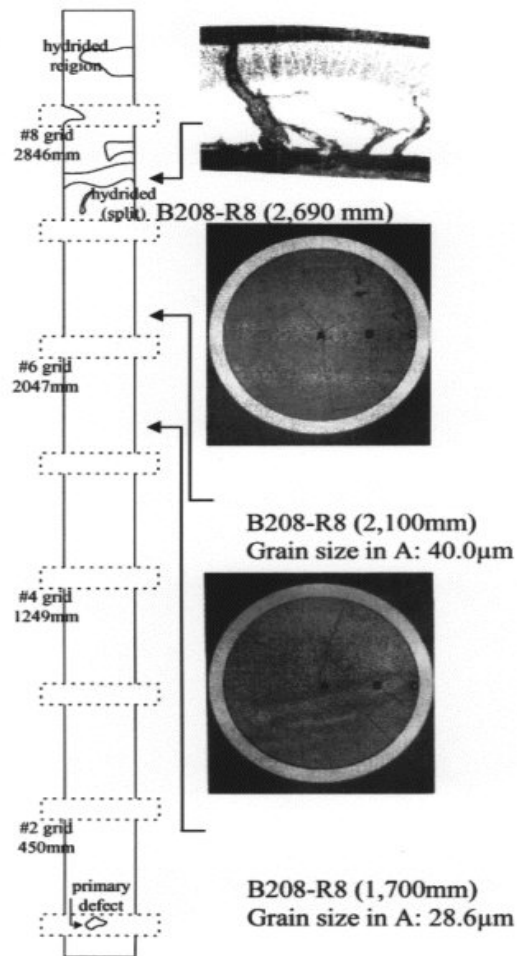
Possible FR failure mechanism in PWR Cattenom-3 (EdF) in 2001 (1)

- This might be secondary hydriding of PWR cladding with formation of transversal cracks of “sun burst”/blister type. The difference from long axial splits (observed sometimes in BWRs) is that their formation is not caused by power ramps and may happen at medium/low burnups and constant power. Sometimes reduction of power promotes water ingress in the primary defect (usually caused by debris fretting) and rather quick reaching the critical hydrogen concentration in the middle part of the FR and formation of transversal crack when going to nominal power.
- The cause of primary defect formation might be FR-SG fretting due to vibration in the area of the lower grid.

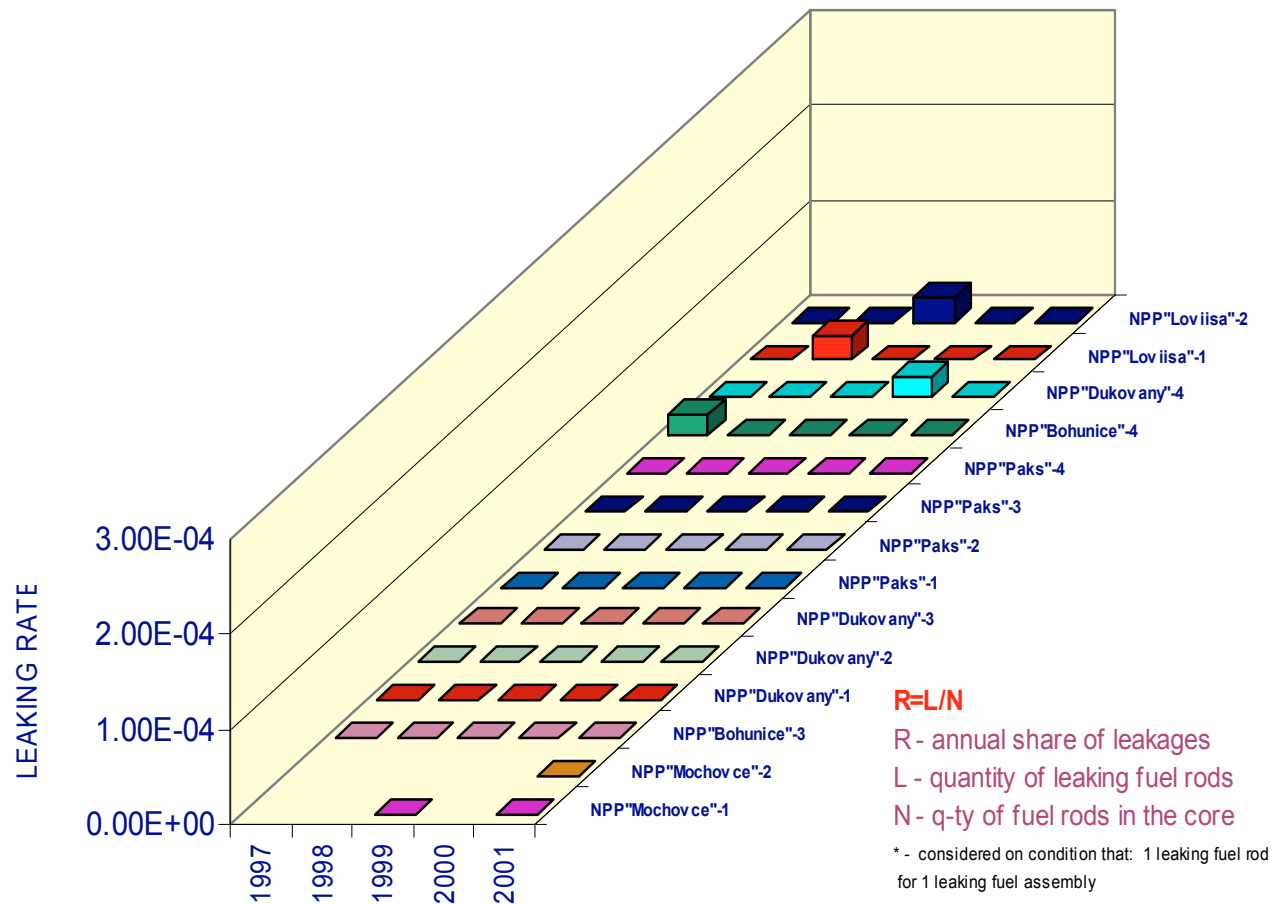
FIG. 17 Possible FR failure mechanism in PWR Cattenom-3 (EdF) in 2001 (2)



Scheme of Secondary Hydriding Damage in PWR Fuel Rod Based on PIE, Y.-S. Kim, IAEA-TECDOC-1345

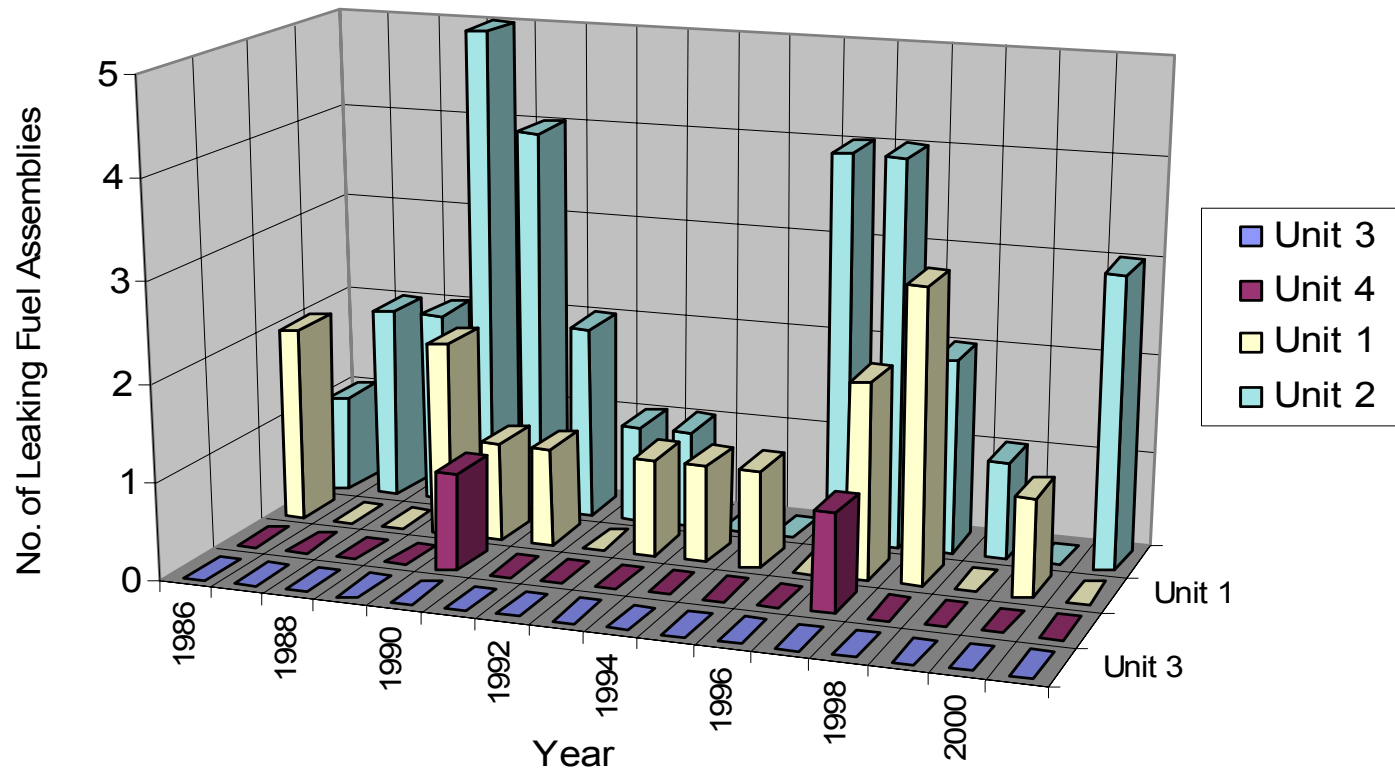


Difference between fuel failure rates in WWER-440s of V-230 (old design) and V-213 (newer design) – (1)
FIG. 18. Rates (1.5 ppm in average) for WWER-440s of V-230 design in 1997-2001 (v. Chirkov, Report to the IAEA TM, Bratislava, 2002, IAEA-TECDOC-1345)



Difference between fuel failure rates in WWER-440s of V-230 (old design) and V-213 (newer design) – (2)

FIG. 19. Rates for Bohunice NPP with Units 1-2 of V-230 design (80 ppm) and Units 3-4 of V-213 design (3 ppm) in 1986-2001 (M. Kacmar, Report to the IAEA TM, 2002, IAEA-TECDOC-1345)



Difference between fuel failure rates in WWER-440s of V-230 (old design) and V-213 (newer design) – (3)

(M. Kacmar, Report to the IAEA TM, 2002, IAEA-TECDOC-1345)

- **Increasing of the assembly and rod average power in consequence dummy assemblies implementation in V-230 Units.**
- • **Different shape of V-230 basket bottom compare with V-213 Units.**
- • **Different fuel assembly flow rates at V-230 Units compared with V- 213 Units. Increased coolant flow at fuel assemblies of V-230 Units.**
- • **Rigid connection of the basket with its bottom at Unit V-230**
- **Position next to 6th group of control assemblies increases probability of fuel damage.**

Ringhals (PWR) approach to mitigation of fuel failures, T. Andersson, Report to the IAEA TM, 2002, IAEA-TECDOC-1345)

Table 2: Defense in depth matrix: For each main core component, two defenses are introduced. The full defense includes 18 areas

Level of defense	General design criteria	Failure mechanisms	First defense	Second defense
1	Core design ^{a)}	Corrosion	Chemistry restrictions	Fuel inspection program ^{c)}
2	Assembly design ^{b)}	Debris fretting	Debris prevention	Debris filters
3	Grid design	Fuel rod fretting	Flow loop testing ^{d)}	Design margins
4	Fuel rod design	PCI	Power ramp restrictions	Liner/Conditioning
5	Fuel pellet design	Impurities/cracks	Quality control	Manufacturing procedures
6	Pellet matrix composition	Secondary degradation	Activity monitoring	Operating strategies
	Fission products			

- a) Includes burnup limitations and thermal margins
- b) Material composition, debris filters efficiencies, hold-down forces
- c) Includes leak testing and repair
- d) Includes operating experience

Major fuel-related phenomena limiting LWR fuel reliability and safety margins at present operation conditions (1)

- LWR fuel corrosion and crud deposition:
 - Need to reduce cladding corrosion rate and
 - Optimization of water chemistry to reduce cladding deposition rate and transport of corrosion products
- Pellet-Cladding Interaction:
 - Fission gas release (FGR), need to reduce FGR
 - Rim layer formation and growth; its impact is unclear
 - Fuel creep and plasticity-need to increase
 - Need to lower degradation rate of cladding mechanical properties (plasticity and creep)
 - Need to increase cladding crack initiation period and lower crack propagation rate

Major fuel-related phenomena limiting LWR fuel reliability and safety margins at present operation conditions (2)

- PWR / WWER fuel assembly mechanical stability at normal operation conditions
 - Need to improve fuel assembly (FA) rigidity to decrease FA bow/twist amplitude and maintain Rod Control Cluster Assembly (RCCA) drop time in allowed limits
- PWR / WWER fuel assembly mechanical stability at accident operation conditions
 - Need to improve modeling of FA and core lateral displacement/stability at seismic loads
 - Need for experiments evaluating lateral displacements of highly burnt FAs/core at seismic loads

What phenomena may limit reliability and safety margins of Advanced LWRs at BUs near 100 GWd/t U

- **Too high pressure of fission products on cladding-high PCI**
- **Too high radiation embrittlement of cladding, also because of aggressive fission products-high PCI**
- **Fuel column may lose plasticity-high PCI**
- **Too high cladding corrosion rate**
- **Too thick deposits on cladding, cooling violation**
- **Increase of concentration of burnable absorbers in fuel may result in raising fuel temperature**
- **Shrinkage of fuel safety margins regarding accident conditions (LOCA and RIA)**
- **Insufficient FA stiffness is possible**

IAEA activities in the area of fuel failure analysis

- **Significant role of the Technical Working Group on Water Reactor Fuel Performance and Technology (TWGFPT)**
- **Technical Meeting on Fuel Failure in Normal Operation of Water Reactors: Experience, Mechanisms and Management in 1992 (Dimitrovgrad, Russian Federation)**
- **TRS 388 entitled “Review on Fuel Failures in Water Cooled Reactors” in 1998**
- **Report “Survey on Fuel Failures in Water Cooled Power Reactors in 1995-98 (CANDUs, BWRs, PWRs and WWERs)” in 2000**
- **Technical Meeting on Fuel Failure in Water Reactors: Causes and Mitigation in June 2002 (Bratislava, Slovakia)**

IAEA activities in 2005-2006 directed on better understanding of mechanism of radiation damage of LWR fuel and structural materials at high burnups

- ***Cladding water-side corrosion, crud deposition*** - start of FUWAC CRP (Water chemistry-corrosion at high burnup and in ageing plants)
- ***Cladding embrittlement – Delayed Hydrogen Cracking*** CRP
- ***FGR and PCI (only part depending on fuel column)*** – Preparation of monograph on UO_2 in 2006-2007
- ***Radiation embrittlement of cladding*** – publication of monograph on Zr alloys in 2006
- ***FGR and PCI*** – finalization of FUMEX-II (fuel performance modeling) CRP and start of FUMEX-III (fuel performance modeling at high burnup) CRP in 2006-2007. Preparation of monograph on UO_2 in 2006-2007
- ***Mechanical stability of FAs*** - publication of TECDOC-1454 in 2005