MOX use in PWRs EDF operation experience

Jean-Luc Provost
Nuclear Operation Division
EDF - Generation

Main items

1 – EDF back-end fuel cycle strategy

2 – Reactor adaptation for MOX fuel

3 – Fuel design and core management

4 – MOX fuel operation experience

5 – MOX fuel reliability

6 – EDF perspectives on MOX fuel

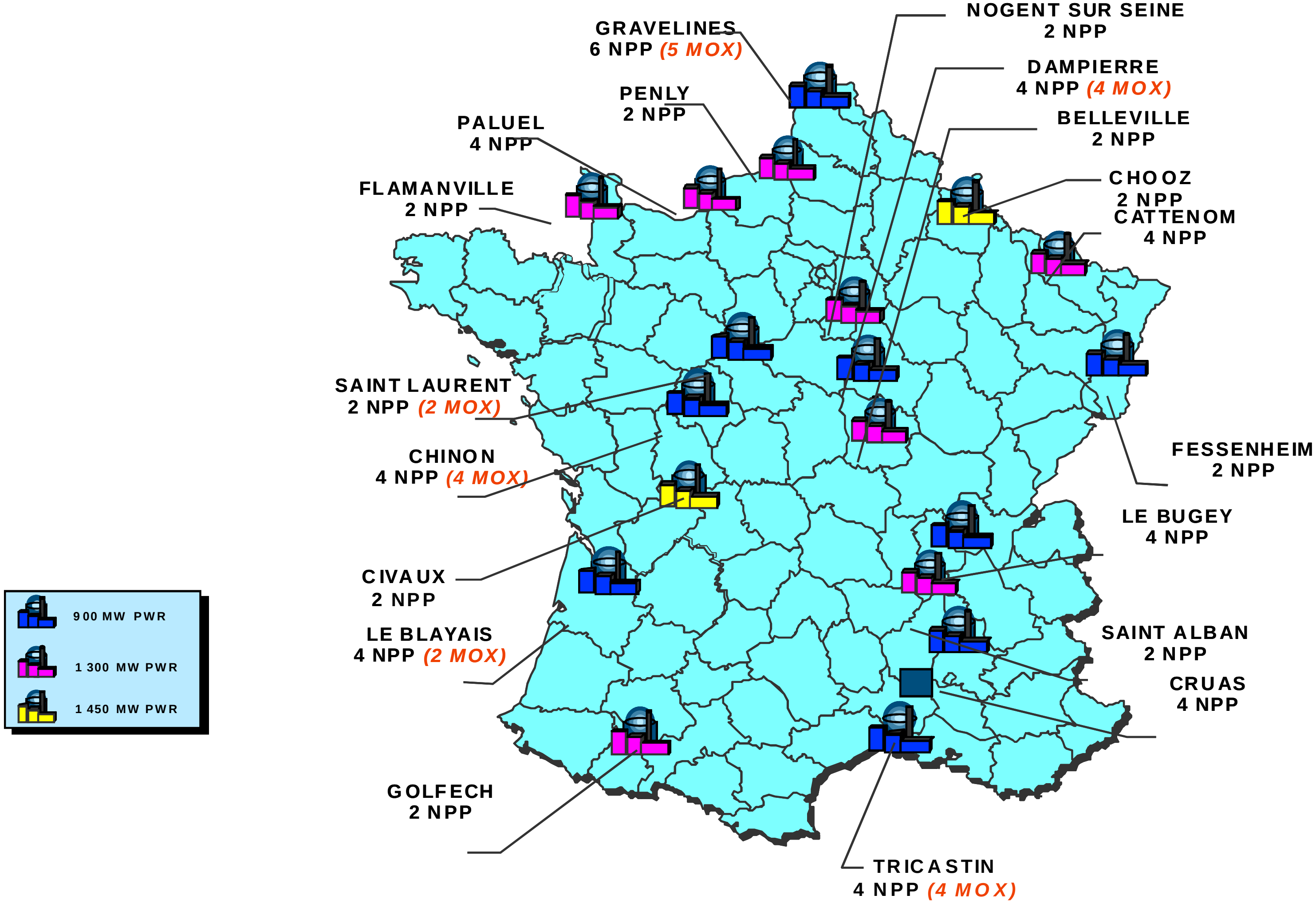
7 – Conclusions

1 – EDF back-end fuel cycle strategy

- **At the end of 2010**
  - 58 units in operation (total installed capacity 63 GWe)
    (900 Mwe: 34 units, 1300 Mwe: 20 units, and 1500 Mwe: 4 units)
  - 71000 FAs loaded in reactor (3500 MOX)
  - 1230 cycles completed (300 cycles with MOX)
- **In 2010, EDF's generation : 476 TWh**

Nuclear	408 TWh	(86 %)
Hydraulic	46 TWh	(10 %)
Fossil	22 TWh	(4 %)

EDF nuclear power plants



EDF back-end fuel cycle strategy

The **closed fuel cycle strategy**, along with reprocessing and MOX recycling, enables today, with existing facilities :

- **Stabilization of spent fuel quantity** : with respect to underwater storage capacity
  - thanks to reprocessing and progress in fuel performance (average burn up increase)
- **Vitrification of high level nuclear waste** (fission products and actinides)
  - a safe confinement under a reduced volume, internationally recognized,
- **Recycling of plutonium**
  - based on Pu flux equilibrium strategy : 120 tHM MOX/yr or 10 tHM Pu/yr recycled
  - MOX use produces 40 TWh/yr (or 9% of nuclear production)
- **Preservation of long term energy resources**
  - by concentration of Pu in MOX spent fuel under a reduced volume, full safeguard
  - leaves open the possibility to reuse Pu in future fast reactors (GEN IV)

EDF Nuclear fuel cycle strategy

based on the flux balance strategy

Uranium and conversion
≈ 8000 t/year

Enrichment
≈ 5,5 MUTS/year

UO2 Fuel fabrication ≈ 1000 t/year
2000 assemblies/yr (45 GWd/t average, max 52 GWd/t

→ *time period*
20 years

430 TWh /an

58 EDF NPPs
22 units loaded with MOX
4 units with ERU

Spent Fuel:
1200 tons /year
(UOX et MOX)

Spent Fuel Transportation to La Hague, interim storage in cooling pools
1200 tons/year

Recycling: MOX fuel
120 t/year
on 22 units 900 MW
--> 40 TWh/yr

MELOX Fuel Fabrication plant

10 t/yr
Separated plutonium (1%)

Reprocessing
1050 t/year

La Hague

Reprocessed uranium: ~ 1000 t/yr
(U235 content 0,8%)
540t re-enriched and recycled
on 4 units 900W (100% core)
or 80 t/yr ERU--> 30 TWh/yr

Vitrified High level Waste
Interim passive storage
Disposal optimisation

120 m³/yr vitrified HLW

120 m³/yr compacted ILW

2 – Reactor adaptation for MOX fuel

- **Reactivity control devices adapted**
  - Due to higher energy neutron spectrum (higher Pu content)
  - Main adaptations : 8 RCCAs added, boron concentration increase
- **Fuel building adaptation**
  - Reinforcement of the crane (hardware and software)
  - Direct storage under water in the fuel pit (dry storage forbidden)
  - Visual examination by video camera of each MOX FA under water
  - Reinforced safeguards on the plant (cameras in fuel building, …)
- **Fresh MOX fuel transport by MX8 cask (**design similar to spent fuel cask)
  - To reduce the risk of excessive exposure of the operators during handling
  - To improve transport safety and nuclear materials safeguards
  - Unloading currently under water, dry solution planed
- **Operators training (fuel handling, core monitoring)**

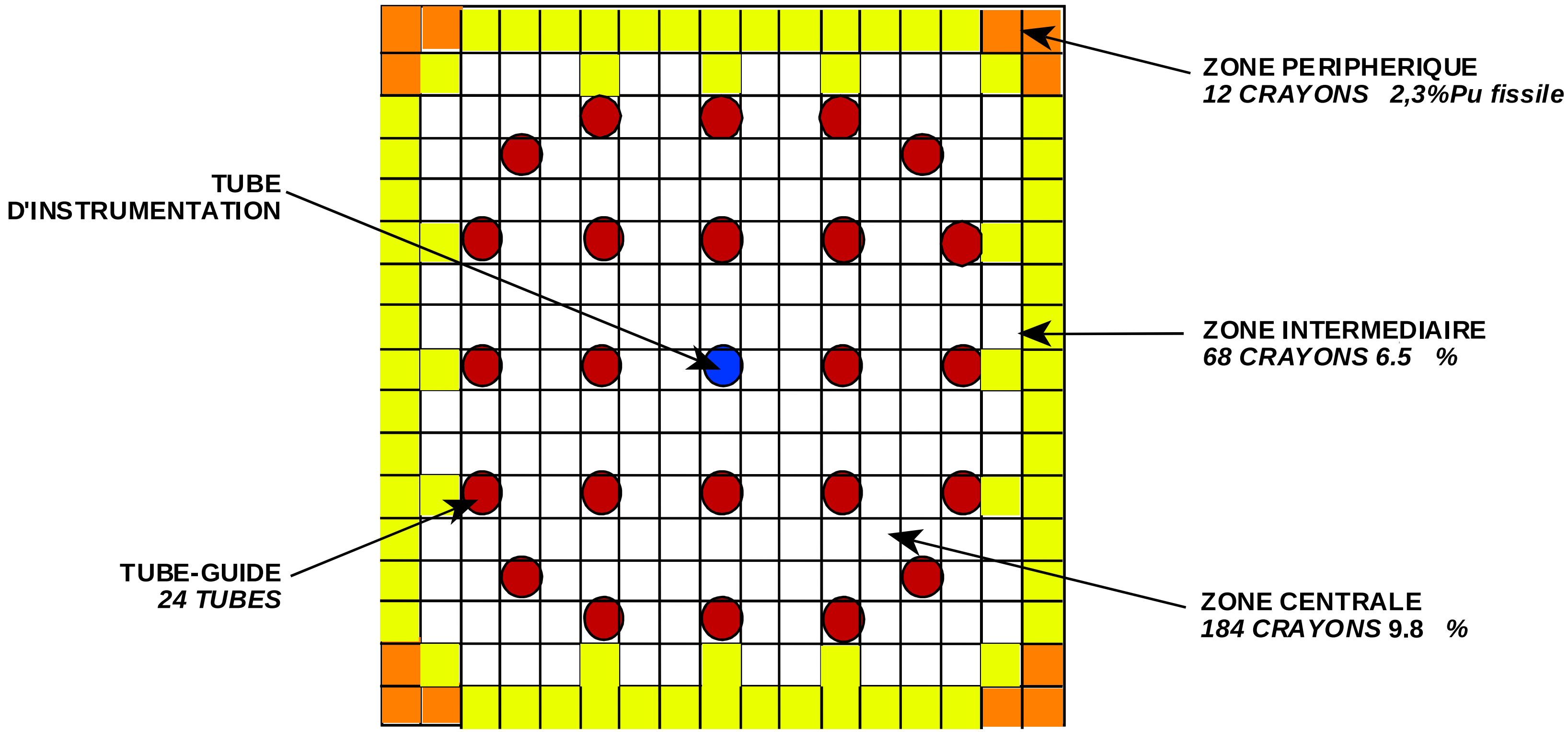
3 – Fuel design and core management

- **MOX Fuel design**
- **MOX Fuel Assembly zoning**
- **MOX Parity core management**
- **Typical loading pattern**
- **Discharge burn-up**

MOX fuel design

- **Fuel type currently used : AREVA AFA-3G geometry**
  - M5 cladding and Zircaloy 4 structure
- **Use of depleted uranium (0,25% U235)**
  - To maximize the Pu concentration in FAs
- **Plutonium isotopic vector**
  - Minimum fissile isotopes Pu139 + Pu141 : 63%
  - MOX energy equivalence to UOX 3.7% ➔ 8.65% Pu content
- **zoning : 3 Pu contents used**
  - To control the power distribution at MOX-UOX interface (high differences of fission cross-sections)

MOX AFA 3G zoning
(average content : 8.65% max)

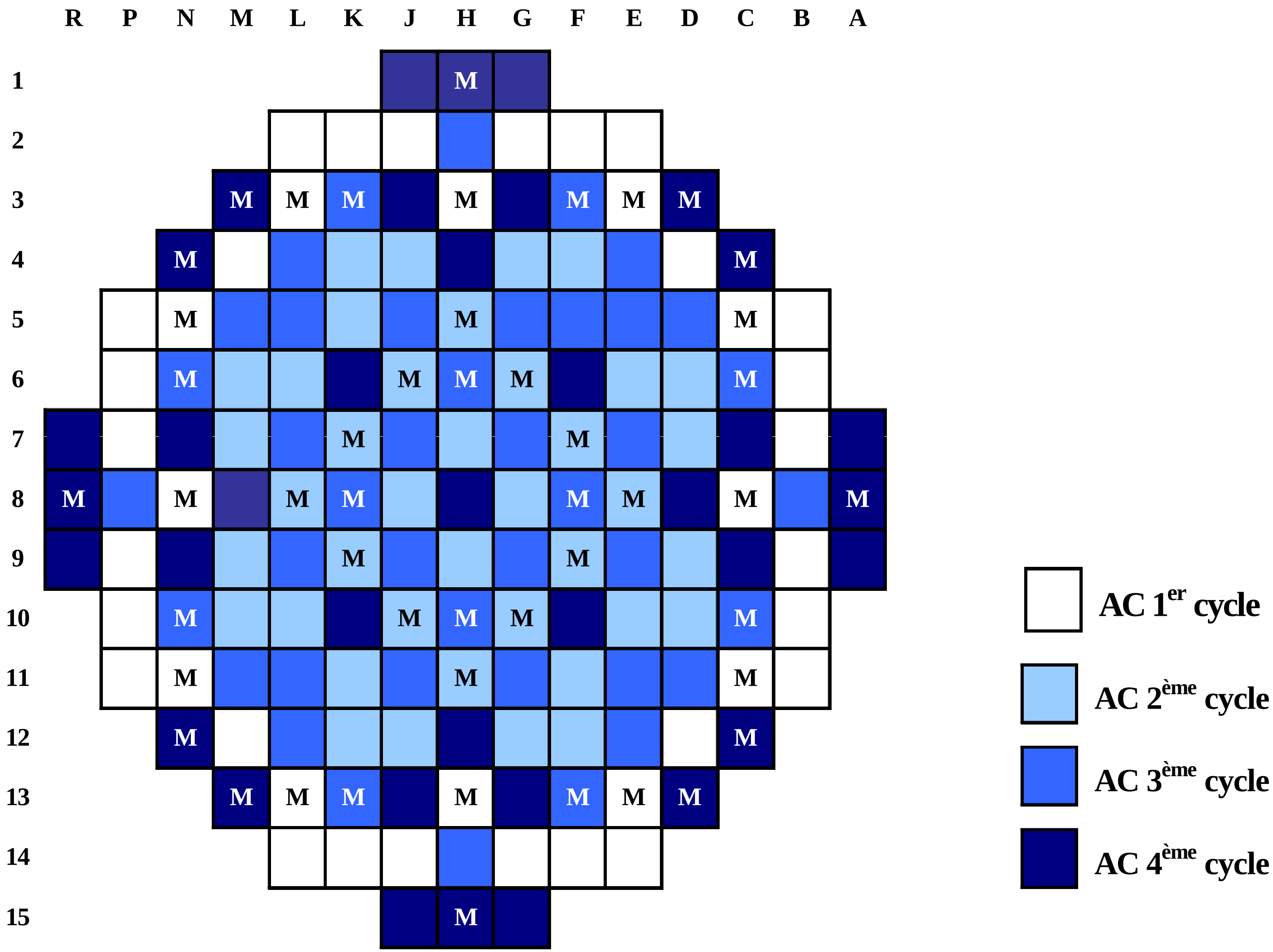


Core management with MOX

- **Recycling rate limited to 30% max (48 FAs/core)**
  - To maintain reactivity control devices efficiency (boron and RCCAs)

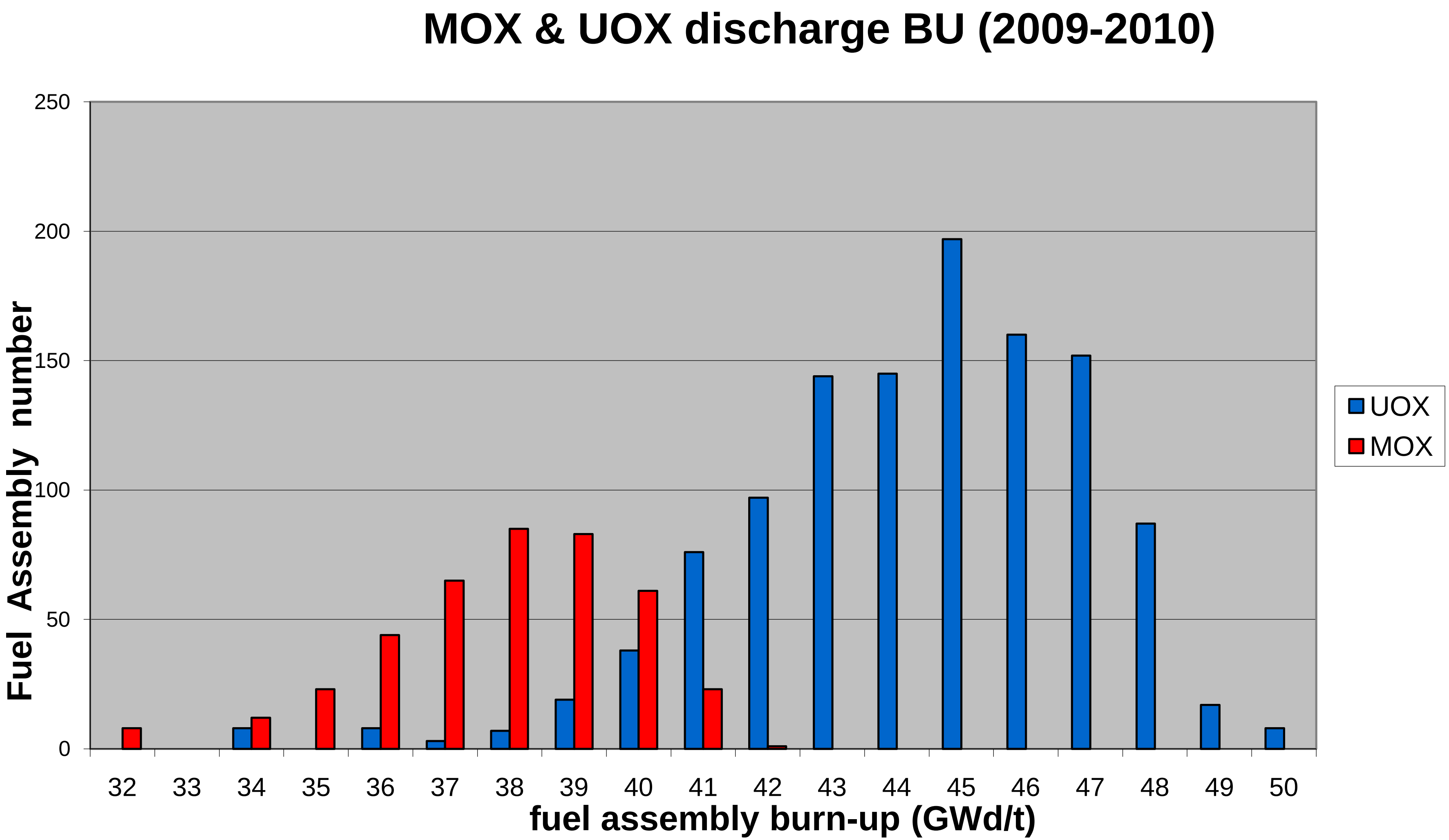
- **MOX Parity management** (licensed in December 2006, implemented on 1 unit in 2007, 7 units in 2008, 17 units in 2009 and 20 units in 2010)
  - 4-batch core management for MOX and UOX
  - Each reload : 12 MOX (3.7% equivalent) + 28 UOX (3.7%)
  - Pu content = 8.65% (fissile Pu: 63% total Pu)
  - UOX average BU : 48 GWd/t (4 cycles) - max 50 GWd/t
  - MOX average BU : 48 GWd/t (4 cycles) - max 50 GWd/t
    - ➔ Parity of energy generated by UOX and MOX (after 4 annual cycles)

MOX Parity : typical loading pattern



UOX and MOX fuel discharged BU

EDF experience (2009-2010)



4 – feedback experience of MOX use

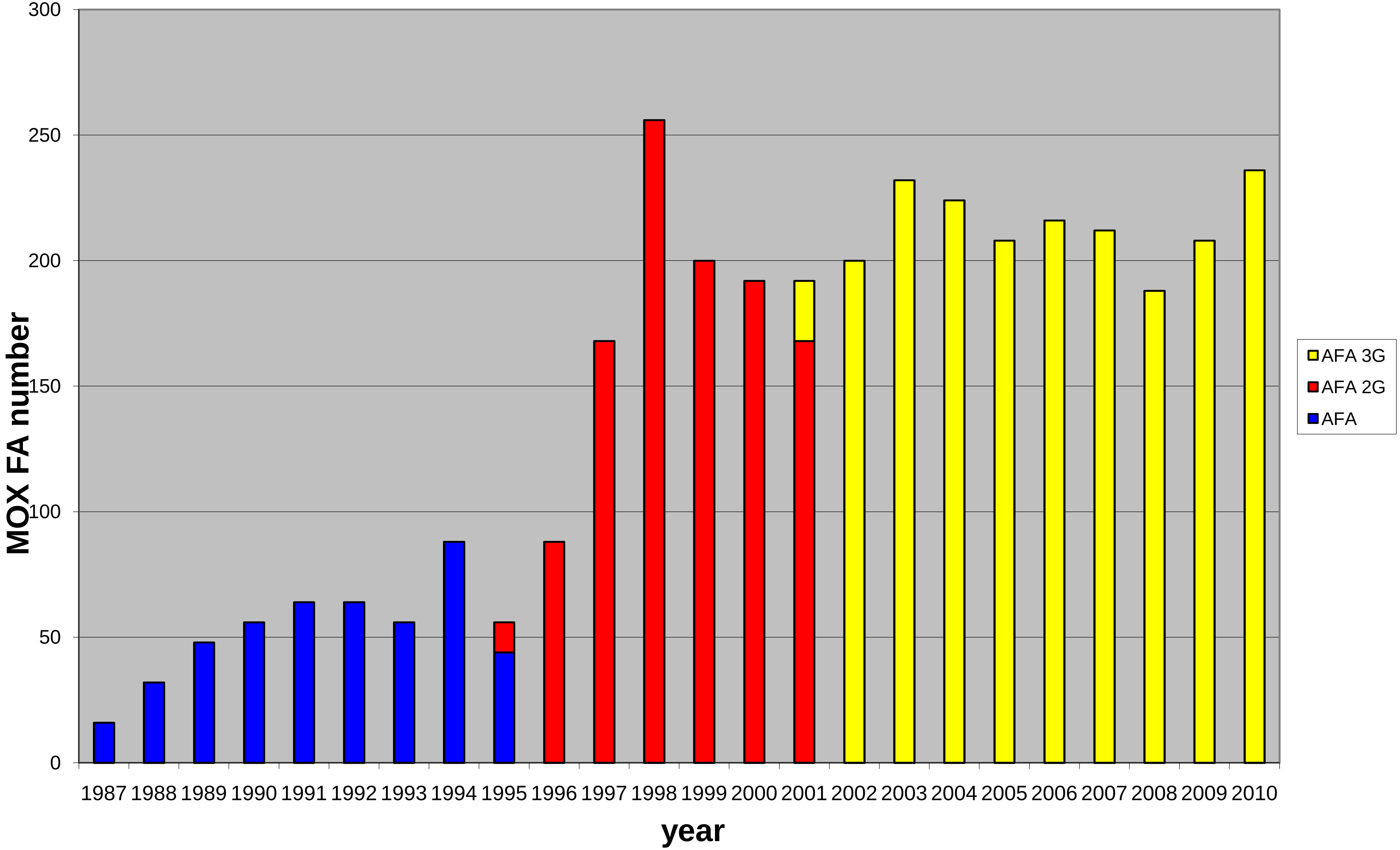
- **MOX use on EDF PWR units**
- **Core Physics measurements**
- **Load follow operation**
- **Environment impact**

MOX use on PWR 900 MW units

- **22 PWR 900 MW units licensed to plutonium recycling**
  - 1987 : Saint Laurent B1 (first unit opened to MOX)
  - 2008 : Gravelines 6 (21st unit opened to MOX)
  - 3500 FAs loaded which corresponds to 1600t MOX or 102t Pu recycled
  - 22nd unit Gravelines 5 will be open to MOX in 2012
- **Public inquiry launched in November 2011 for 2 new units with MOX**
  - New Decree for Blayais 3 and 4 in 2012 : licensing in progress
- **EPR Flamanville 3**
  - an option with 30% MOX has been taken into account in the NSSS basis design

MOX FA loaded in PWR 900MW

3500 MOX loaded # 102 tHM Pu recycled (end 2010)



Core Physics measurements

- **Core Physic start-up tests**
  - Good coherence between measurements and calculation
    - Boron concentration
    - temperature coefficient
    - RCCA rod worth

- **Core Physic measurements during periodic tests**
  - Good agreement between measurements and calculation
    - Flux maps (incore instrumentation)
    - Power picking factors

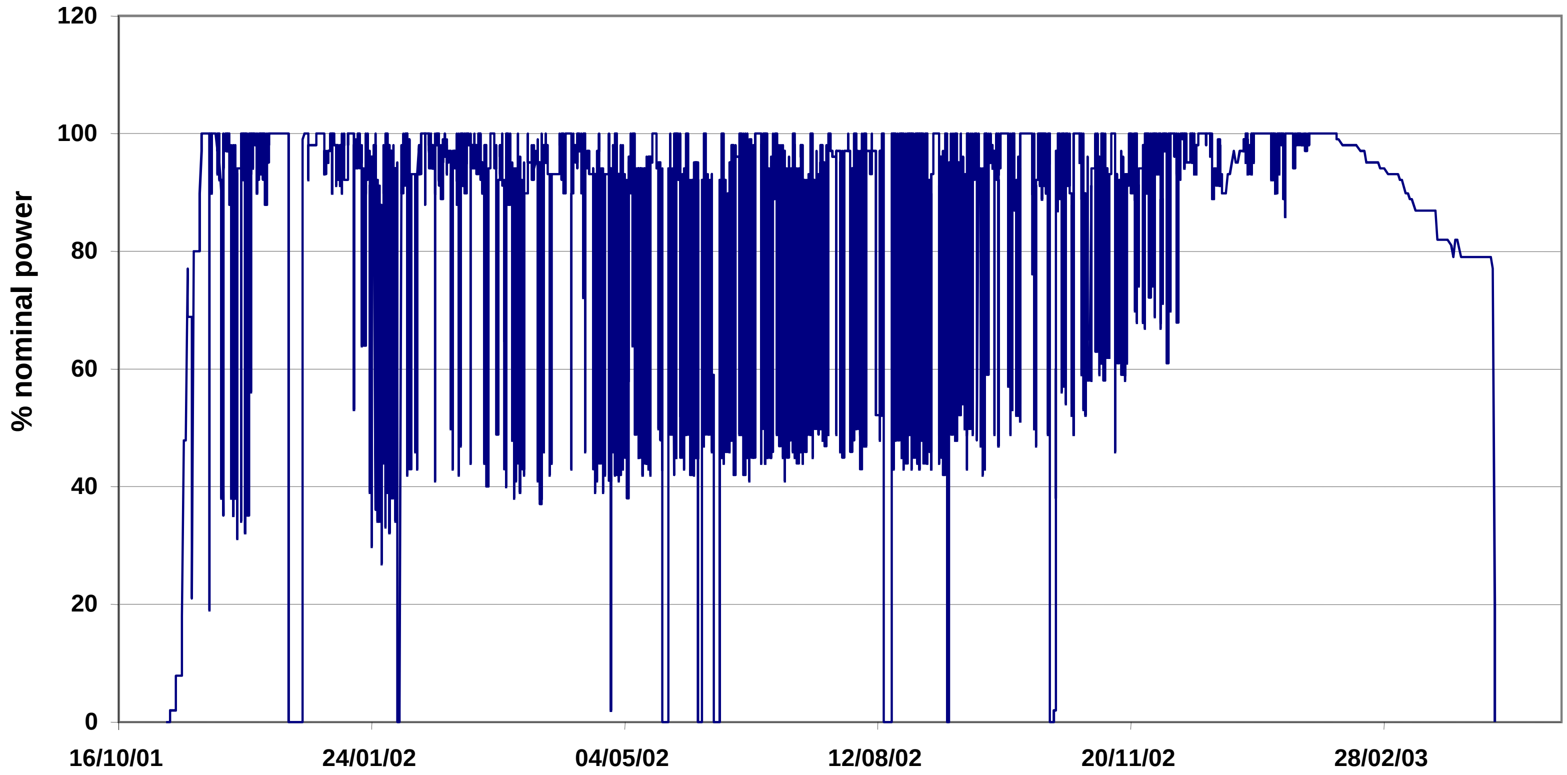
- **Conclusion : safety assessment calculations validated**
    - Same uncertainties can be taken into account for UOX and MOX in the EDF safety reload demonstration (key parameters check-list)

Operation experience : load follow

- **All EDF NPPs operated in load follow**
  - Frequency control (+/- 2%)
  - Remote control (+/- 5%)
  - Daily load follow (typically 6 hours at 50 % NP during the night)
  - Extended low power operation (ELPO) during the week-end, and in summer
- **Load follow experience with MOX**
  - Liquid waste volume decrease : 30% (due to Xenon effect)
  - Ramp tests on MOX rods at Studvik
    - ⇨ better PCI behavior for MOX than for UOX
    - ⇨ No specific Technical Specifications for MOX
- **CONCLUSION :** no specific problem regarding plant operation with MOX

Operation experience

example of a typical power history during a cycle

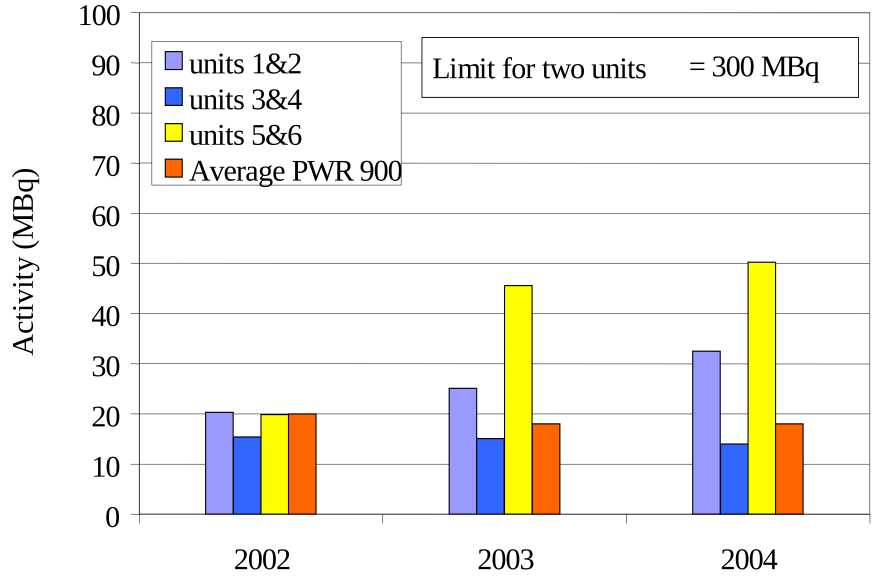


no specific problem identified regarding plant operation with MOX

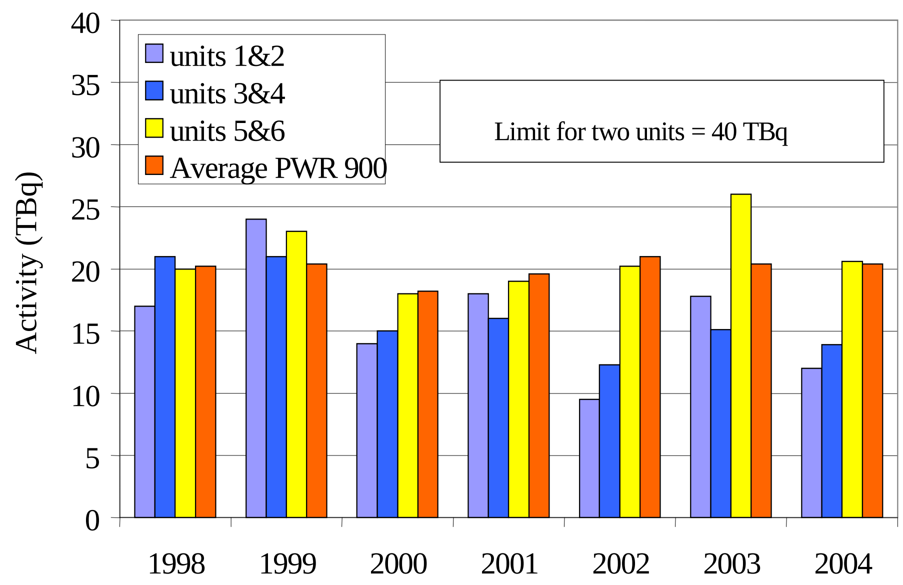
Environment : MOX impact on waste release

- **Waste release**
  - Gaseous and liquid waste release are similar for MOX and UOX plants
    - Iodine and Tritium releases equivalent
  - waste release mainly due to fuel rod leakage history

Liquid waste release

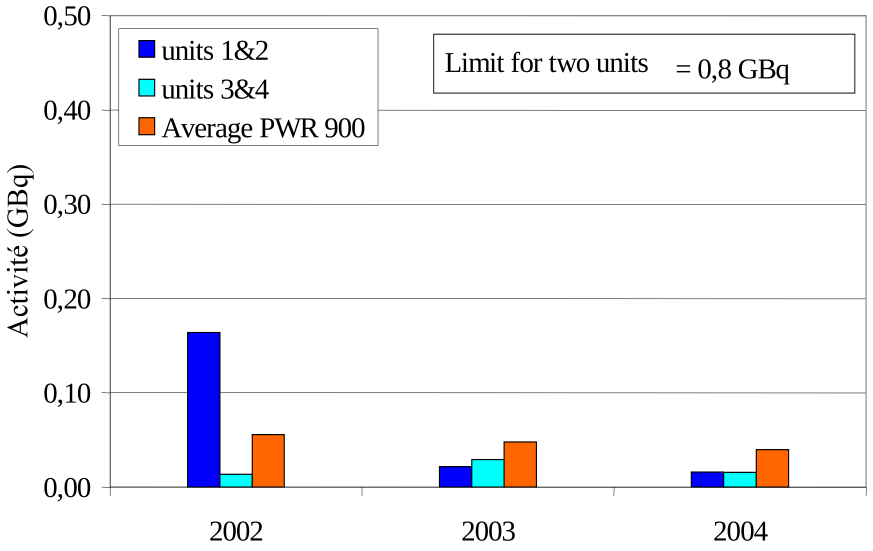


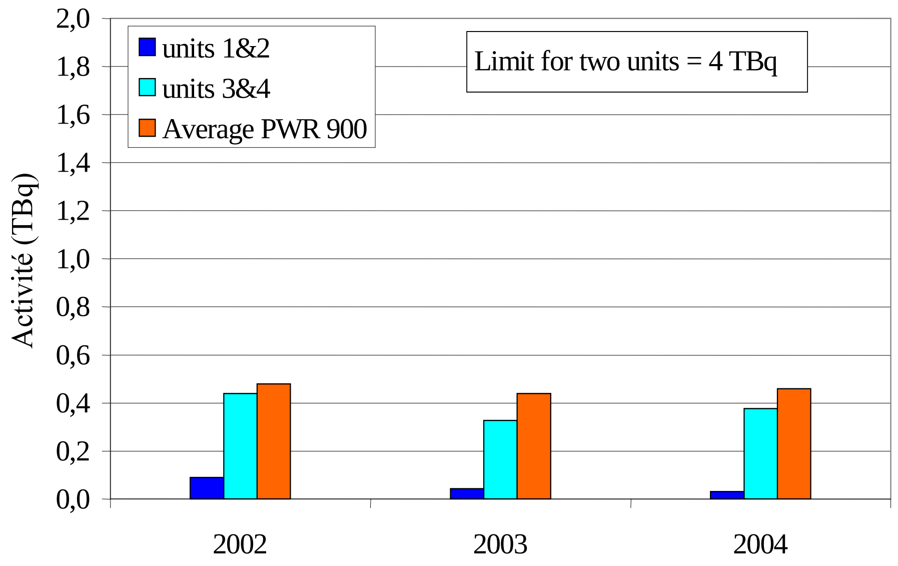
Iodine release
Units 1-4 used MOX fuel
Units 5-6 used only UOX fuel



Tritium release
Units 1-4 used MOX fuel -
Units 5-6 used only UOX fuel

Gaseous release





Iodine release
Units 1-2 used MOX fuel
Units 3-4 used only UOX fuel

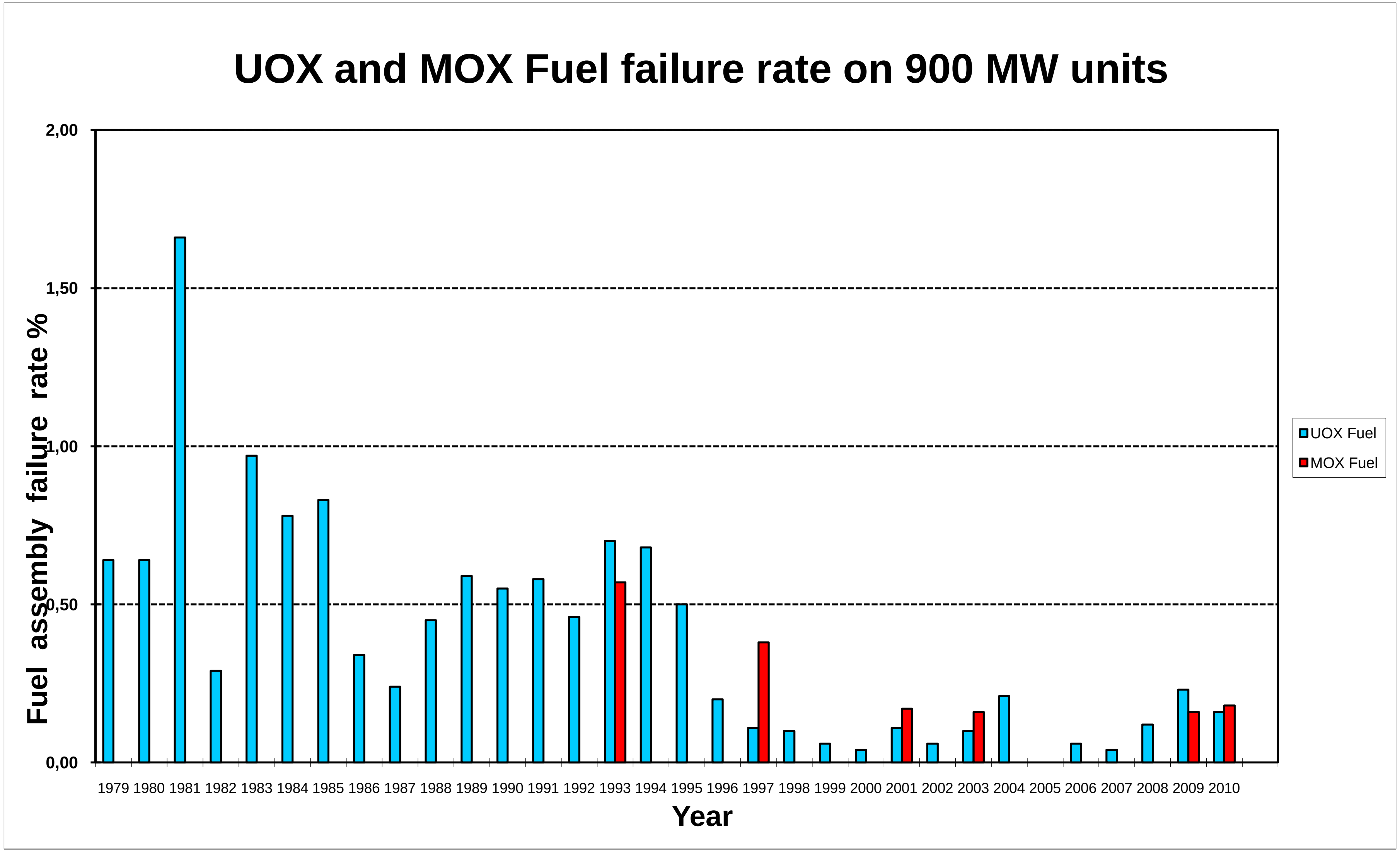
Tritium release
Units 1-2 used MOX fuel
Units 3-4 used only UOX fuel

5 - MOX fuel reliability history (to end 2010)

- **6 FA leakages from the origin :** detected in operation by radio-chemistry analysis (discrimination based on Xe135/Kr85m)
  - Dampierre 1 in 1993 (due to debris, reloaded)
  - Tricastin 2 in 1997 (due to debris, repaired and reloaded)
  - Tricastin 4 in 2001 (due to debris)
  - Dampierre 1 in 2002 (at EOL, no examination)
  - Dampierre 4 in 2009 (due to debris)
  - Dampierre 4 in 2010 (due to debris)

- **CONCLUSION at end 2010 :**
  - ⇨ 24 years of operation
  - ⇨ more than 300 reactor-years of experience
  - ⇨ good reliability of MOX, equivalent to UOX

MOX fuel reliability history (to end 2010)



MOX impact on reactor operation Summary

- **No change regarding plant availability of the PWR 900MWe fleet**
  - Same annual cycles
  - Light increase of outage duration due to decay heat (Tpool<50℃)

- **No significant impact regarding operational maneuverability**
  - Better axial flux stability during power transients (reduced xenon efficiency)

- **Environment** (liquid and gaseous waste release)
  - reduced volume of effluents (30%) during power transients,
  - similar gaseous and liquid waste release for MOX and UOX plants

- **No impact on Radioprotection**
  - Doses during outage mainly due to maintenance
  - low sensitivity to fuel (BU or Pu content)

6 - EDF perspectives on MOX fuel

- **Plutonium isotopic vector has changed during these last 20 years**
  - Thanks to evolution of core management and of fuel performance
  - Spent fuel burn-up has significantly increased (from 33 to 45 GWd/t)

- **Isotopic vector taken into account currently in MOX Parity core management**
  - Minimum fissile isotopes (Pu139 + Pu141) content : 63%
  - Origin : UOX spent fuel BU = 43 GWd/t, stored 9 years before reprocessing
  - Separated Pu stored 3 years before MOX manufacturing

- **Available UOX spent fuel to be reprocessed during the next decade:**
  - Increased BU > 46 GWd/t, stored more than 10 years (Pu139 decrease)
  - Longer time of separated Pu storage before manufacturing (Am141 increase)
  - Main consequence : isotopic vector degradation to 61% fissile isotope

- **To maintain UOX 3.7% equivalence, total Pu content needs to be increase from 8.65% to 9.5%**
  - Each accidental transient of SAR has to be re-assessed and to be reviewed by the French Regulator

7 - Main Conclusions

- The large EDF experience of 24 years with MOX is globally satisfactory (plant safety and availability, fuel reliability, environment and radioprotection),

- From 2007, implementation of MOX Parity fuel management achieves the balance of MOX and UOX fuel performance and contributes to stabilize the amount of separated plutonium