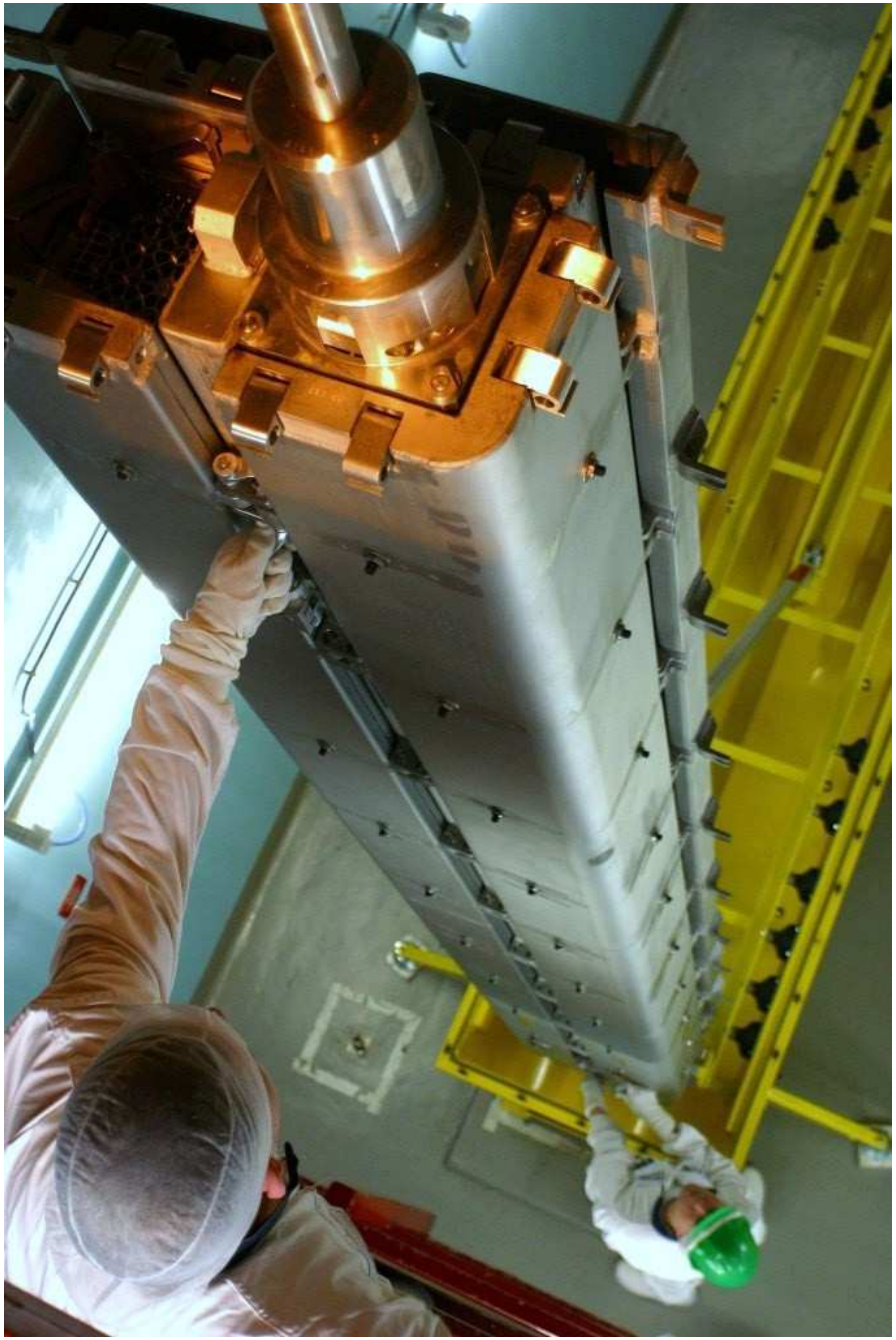
MOX Fuel in PWR
EDF Experience

Sino-French Seminar on the Back End of the Nuclear Fuel Cycle

November 5th, 2015

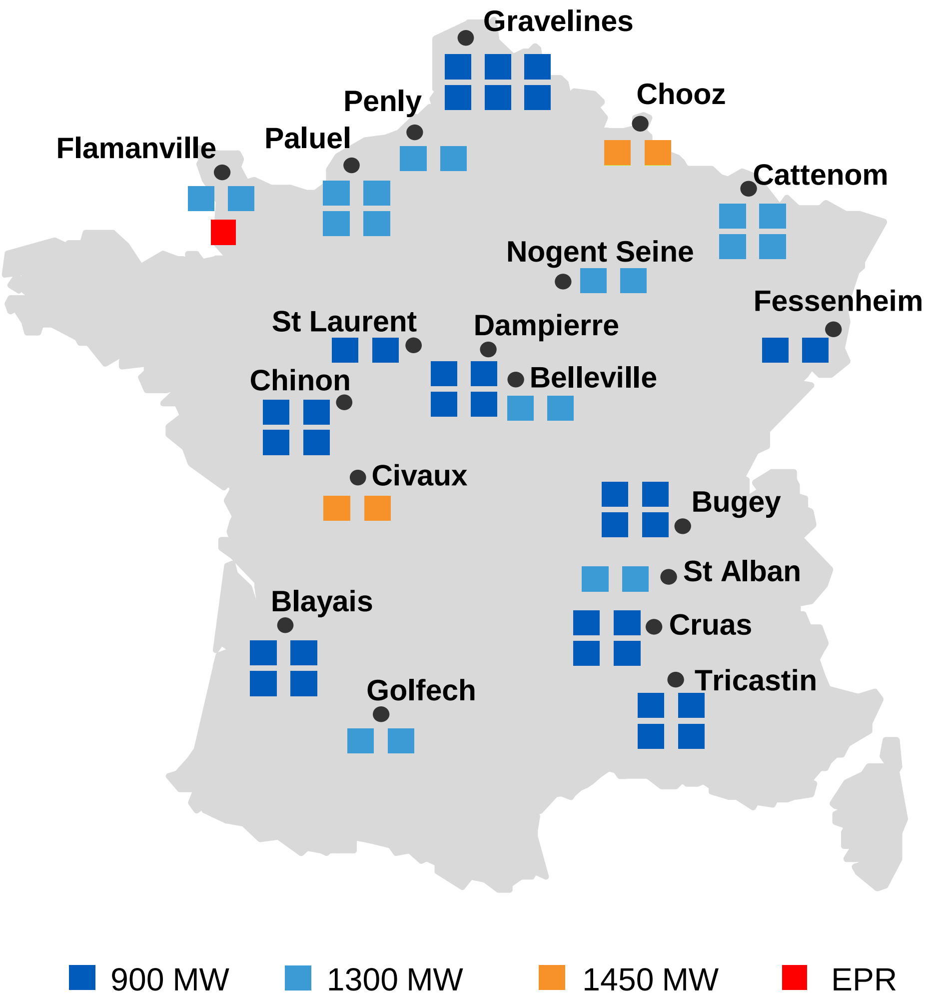


SOMMAIRE

GENERAL PRESENTATION OF FRENCH NUCLEAR FUEL CYCLE

THE FRENCH NUCLEAR POWER PLANT FLEET

- **The French NPP fleet**
  - 58 PWR units in operation
    (total installed capacity 63 130 MWe)
    - 900 MWe : 34 units
    - 1300 MWe : 20 units
    - 1500 MWe : 4 units
  - 1 PWR in construction : EPR 1600 Mwe
- **Until the end of 2014**
  - 80 000 Fuel Assemblies (FAs) loaded in reactor (4 500 MOX and 1 350 ERU)
- **In 2014, EDF's generation :**
  - Nuclear 415.9 TWh (90.4%)
  - Hydraulic 37.5 TWh (8.1%)
  - Fossil 6.9 TWh (1.5%)



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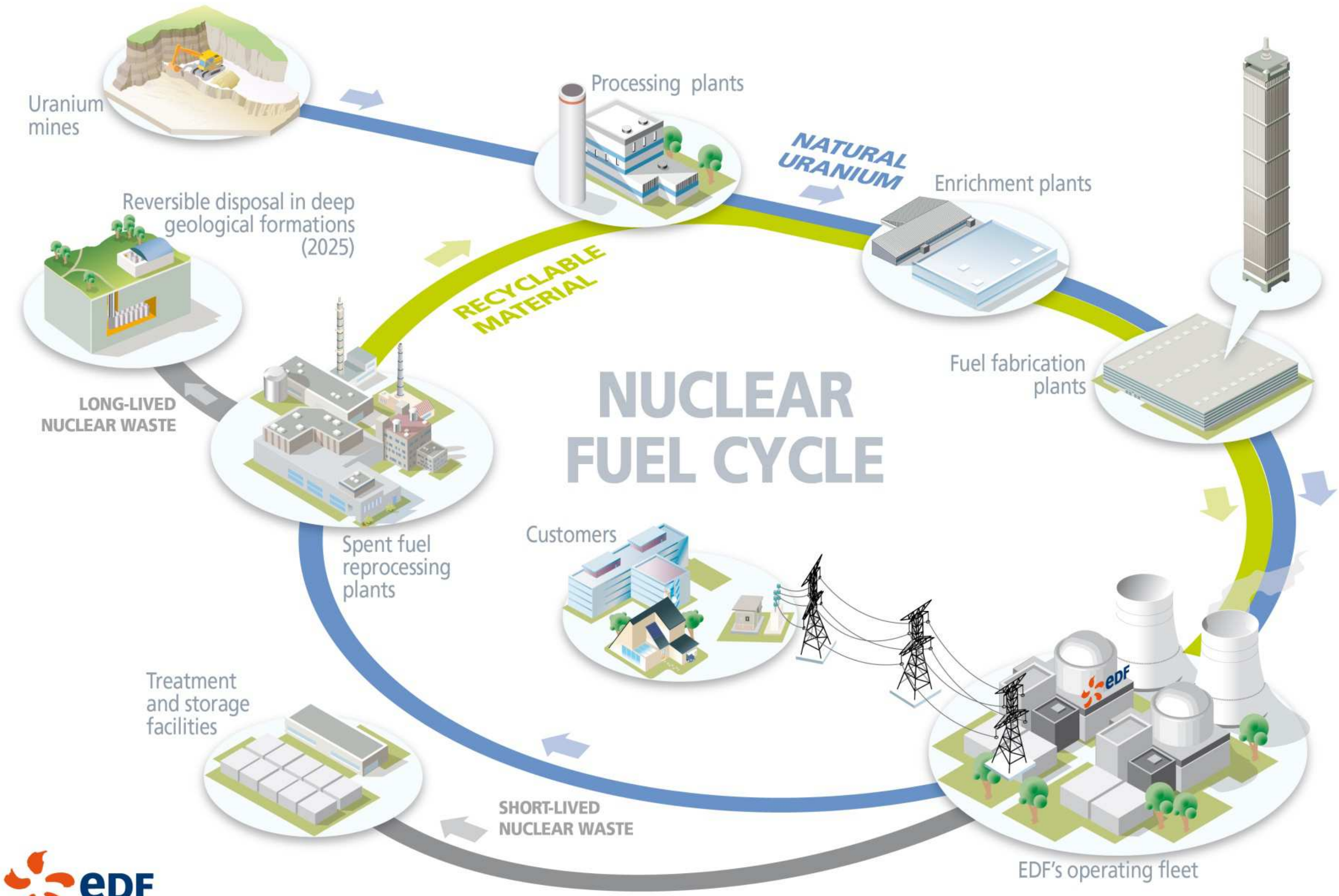
THE FRENCH FUEL CYCLE STRATEGY



THE FRENCH BACK END FUEL CYCLE STRATEGY

- **Since 1980, in accordance with the French Energy Policy, EDF decided to implement a "one-through" closed fuel cycle.**
  - The irradiated fuels are sent to La Hague reprocessing plant where uranium, plutonium are separated from waste (fission products and minor actinides).
    - The reprocessed uranium is enriched to produce ERU fuel
    - The plutonium is mixed with depleted uranium to produce MOX fuels in MELOX plant at Marcoule.
  - Once irradiated, MOX and ERU spent fuels are safely stored in pools, waiting for the achievement of multi-recycling in GEN IV fast breeder reactors

- **Reprocessing allows reduction of waste in volume and saves uranium ressources**
  - MOX fuel and ERU fuel utilization enabled to save approximately two years of uranium consumption
  - Reduction of the volume of nuclear waste by a factor of 4
  - The "one-through" closed fuel cycle is a first step towards the fully closed fuel cycle with Pu multi-recycling in GEN IV fast breeder reactors

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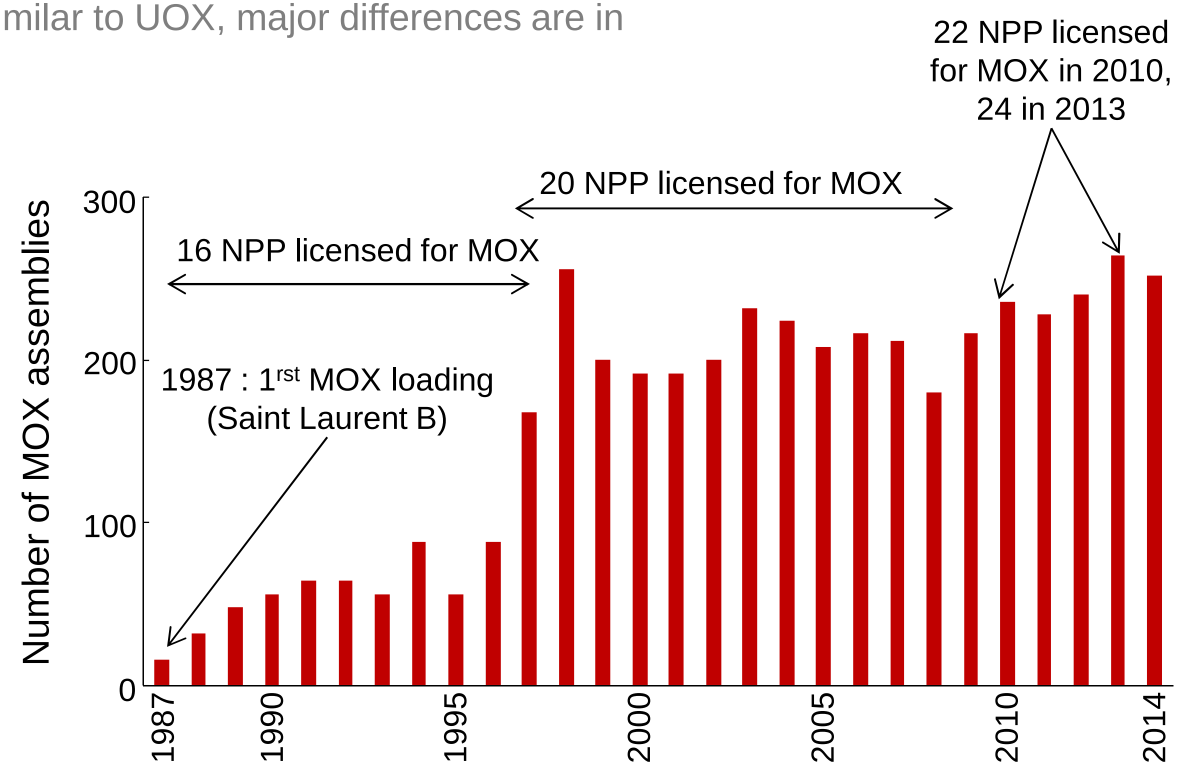
MOX USE IN FRENCH POWER REACTORS

- **The amount of about one annual discharged fuel is processed each year to produce Pu for the manufacture of MOX (Mixed Oxide) fuel:**
  - About 1,000 t of heavy metal from spent fuel give 10 t of Pu and 120 t of MOX
  - It is required to reduce interim storage of Pu, because of progressive creation of americium reducing its quality; so recycling separated Pu is not delayed
  - MOX assemblies fabrication is similar to UOX, major differences are in radioprotection arrangements

- **24 PWR 900 MWe units licensed for MOX utilization**
  - Licensing began in 1987
  - The two last units (Blayais 3 and 4) were licensed in 2013, MOX loading is planned in 2017-2018.



REACTOR ADAPTATION FOR MOX UTILISATION IN PWR

REACTOR ADAPTATION FOR MOX

- **With 30% MOX in the core => higher Pu content (0.5% -> 2%)**
  - ⇒ Higher energy spectrum
  - ⇒ Reduced efficiency of reactivity control devices (boron, RCCAs)

⇒ **To compensate for this effect**

- **In the primary circuit**

For reactivity control in operation and during shutdown

- Reinforcement of the control rods pattern (8 new RCCAs added)
- Increase of boron concentration in the boron make-up tank up to 7500 ppm

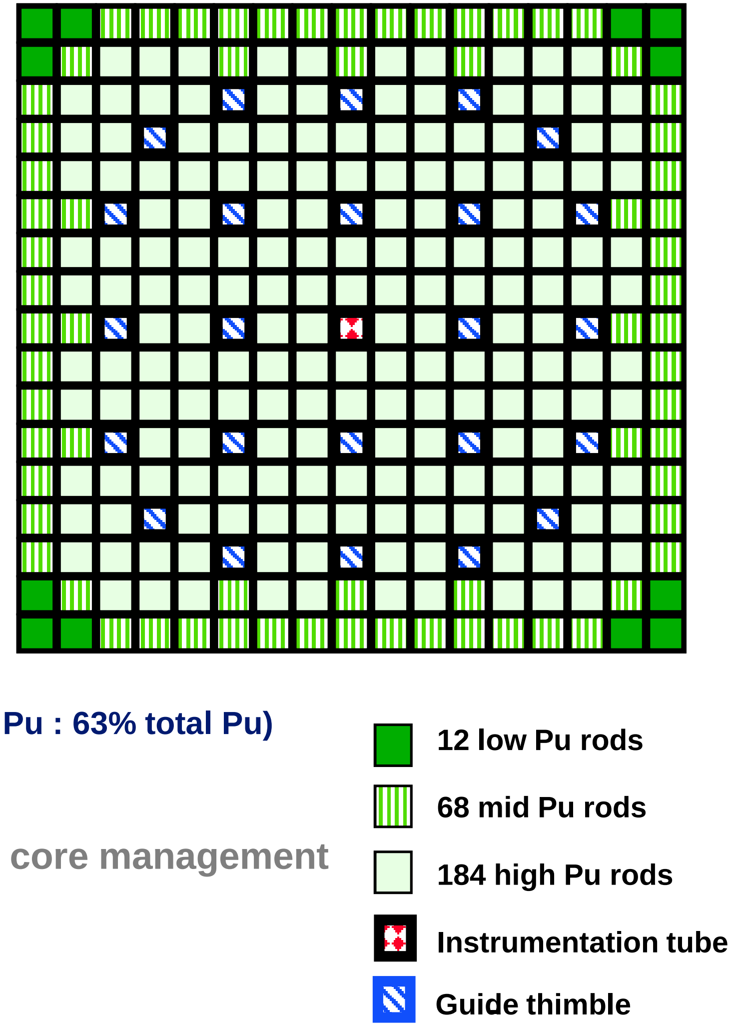
- **In the safety injection system**

To meet safety criteria for over cooling accidents and LOCA

- Increase of boron concentration of the refueling water storage tank (up to 3000 ppm)

CORE MANAGEMENT

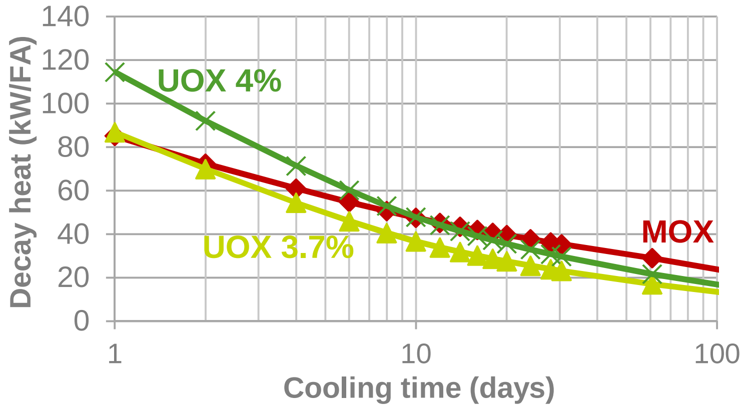
- **History of core management**
  - 30% of MOX fuels in the core
  - ⇒ Zoning of fuel for MOX / UOX flux interface :
    - 3 zones with specific Pu content
  - Energy equivalence increase :
    - From 1987 to 1995 :
      3 batches for UOX and MOX, annual cycle
      - Each reload : 16 MOX (3.25% equivalent) + 36 UOX (3.25%)
      - Pu content : 5.3% (fissile Pu : 70% total Pu)
      - UOX max BU : 36 GWd/t, MOX max BU : 42 GWd/t
    - From 1995 to 2007 :
      4 batches for UOX and 3 batches for MOX, annual cycle
      - Each reload : 16 MOX (3.25% equivalent) + 28 UOX (3.7%)
      - Pu content : 5.3% (fissile Pu : 70% total Pu) **then 7.08% (fissile Pu : 63% total Pu)**
      - UOX max BU : 52 GWd/t, MOX max BU : 42 GWd/t
    - From 2007 to 2014 :
      4 batches for UOX and MOX, annual cycle **"Parity MOX" core management**
      - Each reload : 12 MOX (3.7% equivalent) + 28 UOX (3.7%)
      - Increase of Pu content : 8.65% (fissile Pu : 63% total Pu)
      - UOX/MOX average discharge : 48 GWd/t
      - UOX/MOX maximum BU : 52 GWd/t



- **Decrease of fissile Pu content in reprocessed UOX fuel when BU increases**
  ⇒Necessity to increase Pu content in MOX for energy equivalence

FUEL BUILDING ADAPTATION FOR MOX

- **Gamma and neutron activities of MOX fresh fuel (Pu238, Am241)**
  - ⇒ Risk of higher exposure of the operators during transportation and handling
- **Fuel receipt and storage adaptation (for radiological reasons)**
  - Handling crane reinforcement (hardware and software) : capacity, reliability, safe and limited movements
  - Direct storage under water
  - Visual examination by video camera of each fresh MOX FA under water
  - Emergency switch on the fuel building ventilation (red mushroom head switch)
  - Reinforced safeguards on the plant during MOX handling (sensor cameras, fuel building access, …)
- **Spent fuel transport after 3 or 4 years cooling time**
  - Slower decrease of decay heat in MOX



STRAPONTIN calculations

TRANSPORTATION OF FRESH MOX FUEL

- **Fresh Fuel transportation by MX8 Cask : design similar to spent fuel cask**
  - In operation since July 2004
- **Main goals :**
  - Improved transport safety and nuclear materials safeguards
  - Reduced doses during unloading
- **Doses reduction achievements :**
  - Average value in 2012 : 0.7 mSv / shipment
  - Maximum value : 1 mSv / Shipment (half gamma, half neutron)
  - Thanks to handling automation, limited number of operators and biological protection use

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MX8 for fresh MOX transportation

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FCC for fresh UOX transportation

TRANSPORTATION OF IRRADIATED MOX FUEL

- **Spent MOX fuel transportation in standard spent fuel casks**
  - Each cask load with 4 MOX (center zone) and 8 UOX (peripheral zone)
  - About 40 to 60 shipments per year to La Hague reprocessing plant
  - Similar average dose for UOX and MOX shipments
  - Less than 1% of the annual collective dose due to spent fuel transport

- **TN 112 ; new spent fuel cask dedicated to MOX fuel**
  - Capability : 12 MOX FAs
  - Better protection regarding neutron flux than TN12
  - To obtain more flexibility in spent fuel transport
  - First TN112 in operation from 2008, second TN112 in 2015

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TN 12

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TN112

MOX LICENSING AND REGULATION

- **Safety reports needed for a new core management licensing with MOX fuel**
  - Accidental transients studies review
  - New Operating technical Specifications
  - Material and documentation modifications technical reports

- **Safety reports needed for licensing of a new fuel assembly (MOX)**
  - Neutronic design report
  - Thermo-hydraulic design report
  - Mechanical design report
  - Rod thermo-mechanical design report
  - LOCA

- **Operation feed-back experience : yearly report during MOX fuel irradiation**
  - Core physics start-up tests and flux maps : good agreement between predicted and calculated values
  - Assembly visual examination during outage : geometry, corrosion (as expected)
  - Doses during fresh fuel deliveries and in operation

- **Parity MOX :**
  - Implementation decided in 2001, 2 years needed to perform the safety studies and 4 years for licensing (cladding corrosion, Fuel Gas Release,…)

MOX IMPACT ON REACTOR OPERATION

IMPACT SUMMARY

- **No change regarding plant availability of the PWR 900MWe fleet :**
  - Same annual cycle
  - Light increase of outage duration due to increase of decay heat
- **No significant impact regarding operational maneuverability**
  - For all units with MOX fuel, load follow has been authorized in 1995, after 5 years of smooth operation on Saint-Laurent 1 and 2
  - Better axial flux stability during power transients (reduced Xenon efficiency)
- **No increase in the small amounts of waste release in the environment**
  - 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 sensibility to fuel (BU or Pu content)
- **In case of disruption in the supply chain, MOX fuels can be replaced by UOX fuels in reload batches.**
- **No impact of Fukushima event specific to MOX**

CONCLUSION

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- **The different steps of the nuclear fuel cycle are strongly connected**
- **The whole strategy saves nuclear material and allows to reduce waste in volume**
- **Burning MOX fuel in reactor is a routine operation for EDF, nevertheless some operation aspects are specific to MOX, mainly regarding logistics**
- **From 2007, implementation of MOX Parity fuel management achieves the balance of MOX and UOX fuel performance**
- **Every stage is involved in technical and economical performance of the nuclear generation**
- **Burning MOX in PWR is a first step towards the sustainable fuel cycle that will lead to Pu multi-recycling in GEN IV fast breeder reactors.**

THANKS