OCDE/NEA Workshop on LTO beyond 60 years
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Long Term Operation
EDF Nuclear French Fleet

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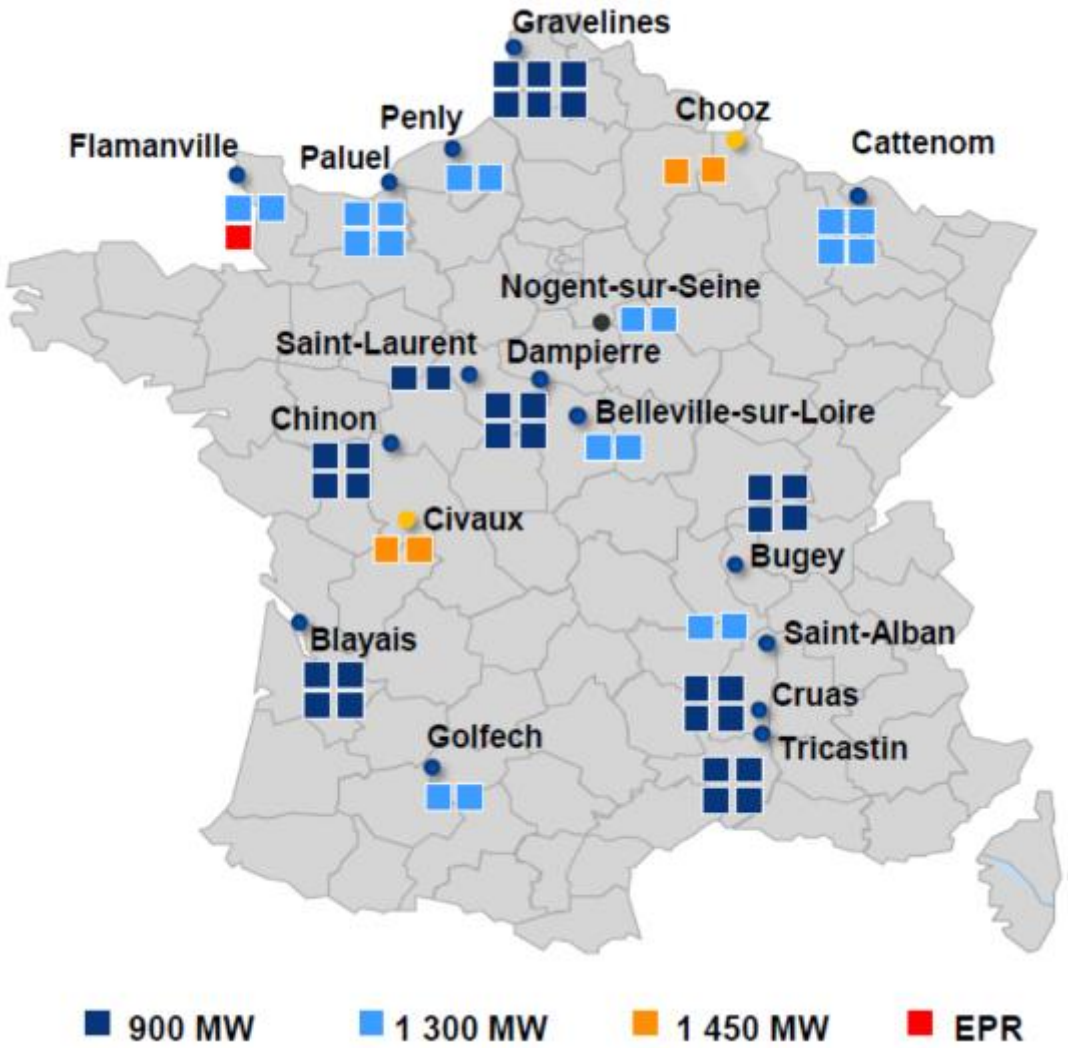
1.1. Context - EDF Nuclear Fleet

- **56 PWR in operation on 18 sites**
- **Standardized fleet :** 32 x 900MWe
  20 x 1300 MWe
  4 x 1450 MWe (N4)
  1 x 1650 MWe (EPR)
- **By the end of 2023 :**
  - Average age : **37 years**
  - **17 x 900 MWe NPP beyond 40 years**



Dates of commissioning	1979-1988	1985-1993	1994-1997	Final phase

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1.2. Context - French Energy Landscape in 2050

- **Government Policy – Belfort Speech – Feb. 2022 : "**Within 30 years, make France the first major country in the world to end its dependence on fossil fuels and strengthen our energy independence while setting an example in terms of climate care"

Consume less energy and be more energy efficient -40% of energy consumption by 2050	Produce more low-carbon energy +60% additional electricity by 2050	EDF industrial Programs To support the energy transition

Industrial & residential energy efficiency – Reduction of fossil fuels – Uses electrification

Development of one of the major hydrogen industrial pole

Development of Renewables & Batteries in France

Development of renewable energies
Consolidation of nuclear fleet

LTO > 60 years

> 25 GW by 2050 out of which 6+8 EPR2 and SMR

100 GW

40 GW

37 GW

GRAND CARÉNAGE Phase 2

EPR2

NUWARD

LE PLAN MOBILITÉ ÉLECTRIQUE

LE PLAN excell Excellence nucléaire

LE PLAN HYDROGÈNE

LEPLANSOLAIRE

EDF

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1.3. Context - French Regulatory Framework

- **No formal time-limited operating license but a regulatory process based on 10-year Periodic Safety Review (PSR)**

- **Periodic Safety Review of Plant Safety & Environmental Protection**
  - Aging management
  - Environmental Qualification
  - Compliance with applicable requirements and rules
  - Plant Safety and Environmental Protection Reassessment towards increased requirements and levels

- **Detailed technical assessment of EDF PSR related reports**

- **Regulatory position on continued operation until the next PSR with regulatory requests ("technical resolutions")**

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2.1. LTO beyond 40 years - EDF current major renovation program

- **4th PSR** allows achieving a major step in safety at a full fleet scale, bringing the safety of EDF 56 GEN-2 PWR up to levels compatible with GEN3 safety goals.
  - At the end of 2023, 22 “4th ten-yearly outages” (VD4) have been completed for the 900 MW series

Hazards

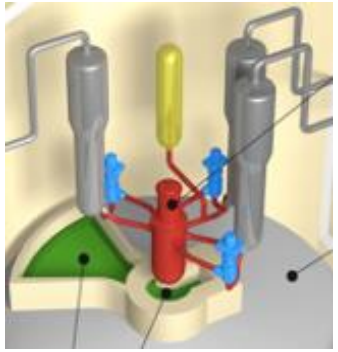
Ultimate diesel generator (DUS)

Diversified heat sink (water source for emergency supply to steam generator and fuel pool)

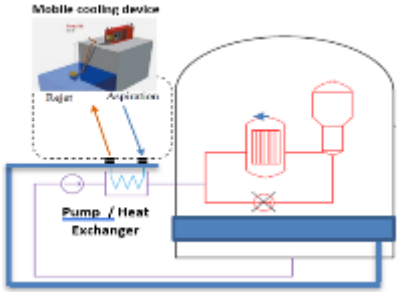
FARN Team

Examples of 4th PSR plant modifi-cations

Severe Accidents



Corium spreading area



Corium extra cooling system (EASu)

Spent Fuel Pool

Third train for fuel pool cooling (PTRbis)

- **5th PSR** will target mitigation of global warming impacts.
  - Safety and Environmental protection objectives under discussion with ASN
  - First 'fifth ten-yearly' (VD5) outage in 2029 (first unit reaching 50 years)

2.2. LTO beyond 60 years - French Roadmap

➢ **LTO Roadmap targeted at safe & high-performance operation <u>beyond 60 years</u>**

- <u>2023 : EDF strategic roadmap</u> pointing out technical topics to be addressed as part of LTO program
- <u>2024 : EDF technical reports</u> to support LTO related issues identification (as relevant) and associated solutions
- 2025 ⇨ mid-2026 : technical review of EDF reports and proposed solutions by regulator ASN, its Technical Support Office (IRSN) and the Standing Group of Experts
- <u>End of 2026</u> : ASN position on technical conditions for LTO beyond 60 years (up to 80 years)

⇩ ***Work program & industrial investments for LTO beyond 60 years***

- <u>2039 : First 6th decennial outage</u> (= first unit reaching 60 years)

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2.3. LTO beyond 60 years – French Roadmap

➢ **Main topics examined with a view to LTO beyond 60 years**

- Non or difficultly replaceable components
  - Vessels / Vessel Internals / E-type CASS Elbows
  - Biological Shield / Containment buildings
  - Electric Cables / Instrumentation & Control

  } Items described in the following slides, plus a topic on AFCEN codes

- Harvesting Programs
- Climate Change

→ **For these topics, the French LTO roadmap is based on R&D work and specific studies. In certain cases the development of new methods is necessary and will be carried out by EDF in 2024-25.**

→ **No generic technical element for PWR technology is likely to lead to the end of operation of these reactors before 60 or 80 years.**

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3.1. LTO beyond 60 years – Focus on RPV

Physical ageing

From a plant lifetime point of view, the main aging mechanism for RPV is embrittlement of the ferritic steel core zone due to irradiation.

Schematic view of RPV

Inspection and diagnostics methods

- In service inspection to detect and size potential indications by UT: 100% of the core shell of each RPV is inspected every 10 years using an automated machine called MIS (25mm depth of base metal under cladding are inspected).
- Pressure Vessel Irradiation Surveillance Program (PVISP) and decennial mechanical assessments

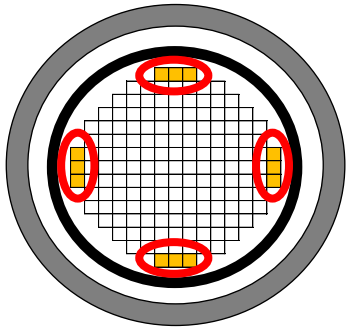
Repair, refurbishment and replacement solutions

RPV shell is not replaceable.

Mitigation strategy to reduce the irradiation damage of the shell:

- Low leakage fuel management (low neutron flux)
- Progressive introduction of Hafnium rod absorbers, starting from the oldest NPPs (900 MWe)

If needed: continuous heating of PTR tank water to reduce thermal shock in case of safety injection



Insertion of hafnium rods in 900 MWe Reactor Pressure Vessels

Fuel assemblies equipped with Hf rods (4 x 3)

Identified gaps for LTO beyond 60 – Action plan

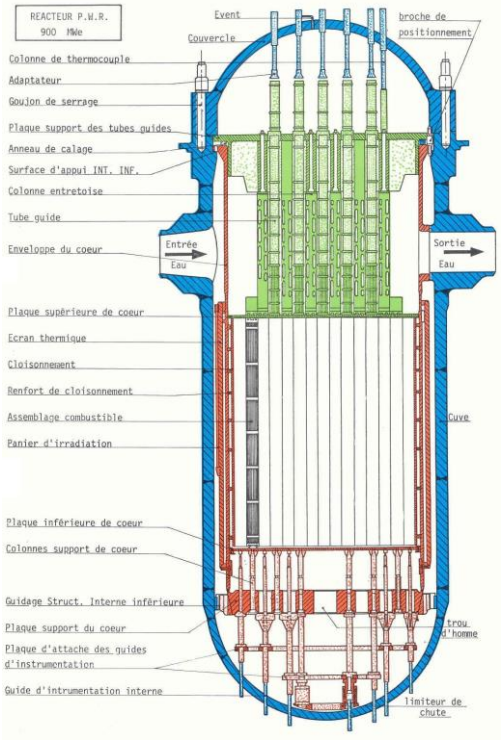
Continue the implementation of hafnium rods and of aging management program.

Study higher levels of fluence (up to 8.10^{19} n/cm²): possible impact on Embrittlement Trend Curve and on sample retrieving calendar.

Develop advanced methods for mechanical assessment: Warm Pre-Stress effect model, Master Curve, BEREMIN local model.

Nota Bene: At longer term, investigate other methodological levers: Two parameters approach (J,Q), PFM, Crack arrest criterion.

3.2. LTO beyond 60 years – Focus on RPV internals



Physical ageing

- **Stress corrosion cracking, whether or not assisted by irradiation**. IASCC observed on Baffle Former Bolts in one NPP
- **Wear** that affects several components: lower guide parts, upper guide tubes, thermal sleeves and cluster guides.
- In the long term, **potential swelling phenomenon** (never observed in France or in any Westinghouse design reactor)

Inspection and diagnostics methods

For SCC, IASCC, wear:

- VT : main inspection method
- UT in some specific cases (Guide Tube Support Pins, or baffle bolts for instance)
- Advanced technics as phased array (wear of the flange of thermal sleeves under vessel head)
- Neutronic noise monitoring for vibratory surveillance
- Different metrology tools (VT, UT, laser) for wear measurements

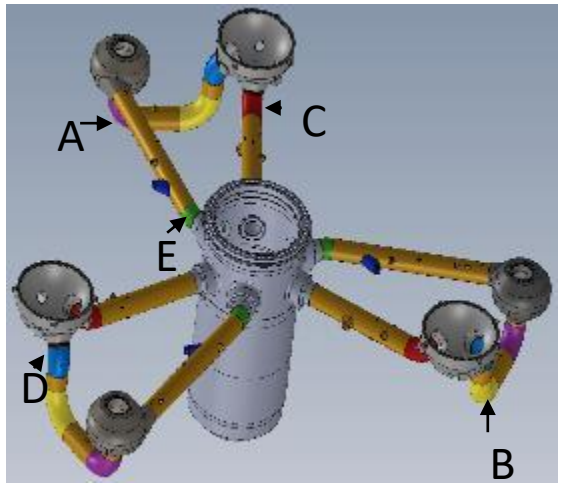
Repair, refurbishment and replacement solutions

Replacement of parts of RPV internals has already been completed (original hold on spring, baffle bolts, fuel pins, thermal sleeves, guide tubes, thermocouple guides, Guide Tube Support Pins…).

Identified gaps for LTO beyond 60 – Action plan

- Continuation of aging management program (in service inspections)
- Acquisition of material data at high doses to anticipate the occurrence of damage (susceptibility analyses to SCC, IASCC and wear)
- R&D actions to understand and model phenomena. Concerning swelling, the last 20 years of research lead us to consider a lower risk (in particular the international GONDOLE project conducted by CEA).

3.3. LTO beyond 60 years – Focus on Class 1 Pipes



Physical ageing

From a plant lifetime point of view, the main aging mechanism is thermal aging of CASS primary piping.

Inspection and diagnostics methods

- End of manufacturing NDE : RT, dye penetrant
- Maintenance strategy: material sampling to check aging predictions and targeted NDE (RT, dye penetrant, replica)
- R&D material aging program (prediction formulae cover up to 80 years), decennial mechanical assessments

Repair, refurbishment and replacement solutions

The main issue is CASS cold leg elbows close to RPV (E-elbows) that are not replaceable.
Several other elbows have been replaced, as well as a SIS nozzle.

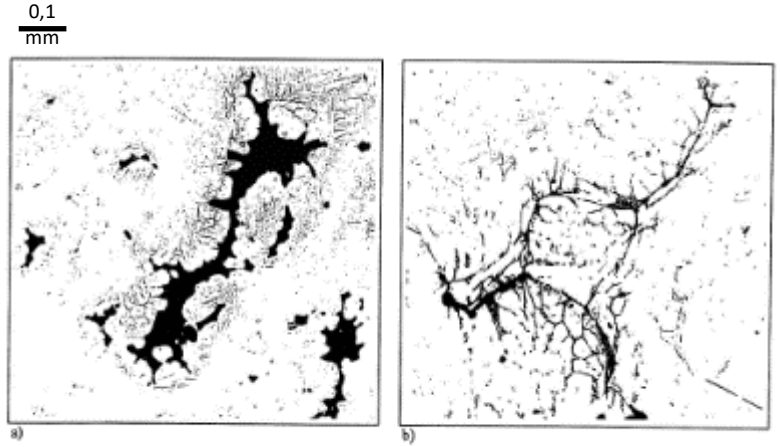


Fig. 1. Micrographs of the shrinkage cavities of plates A. (a) Large cavity surrounded by smaller ones (× 25). (b) Example of fine lines (× 100).

Identified gaps for LTO beyond 60 – Action plan

In addition to continue aging management, EDF roadmap about E-elbows includes the development of:

- A NDE to control the entire inner wall of E-elbows over several millimeters
- A repair solution by elimination of indications, if necessary
- A feasibility study to replace E-elbows
- New mechanical assessment methods:
  - ✓ For flaw initiation: a specific criterion to value the lower harmfulness of casting defects compared to a postulate plane crack.
  - ✓ For flaw instability: Gfr parameter, which is more accurate than J parameter thanks to a distinction between plastic and fracture energies
- Investigations in the long term: probabilistic fracture mechanics (PFM) and local approach models of ductile fracture

3.4. LTO beyond 60 years – Focus on Containment and Biological Shield (1/2)

Physical ageing

Ageing mechanisms (all equipment) :

- concrete: cracking, creep, shrinkage, carbonation and internal swelling pathologies
- containment steel liner: corrosion and blistering
- pools stainless liner: weld cracking, stress corrosion
- prestressing tendons: relaxation and corrosion
- passive rebars: corrosion
- containment instrumentation system: malfunction of certain instruments
- paints and composite coatings: ageing and behavior in accidental situation and severe accident
- biological shield: impact of fluence
- differential settlement occuring between containment building and spent fuel building

Inspection and diagnostics methods

Containment:

- Continuously monitored, to check creep, shrinkage and relaxation
- Visual inspection
- Tightness tests (tests designed to measure the tightness of the inner containments on a 10-years basis and at the design-basis pressure)

Other equipment:

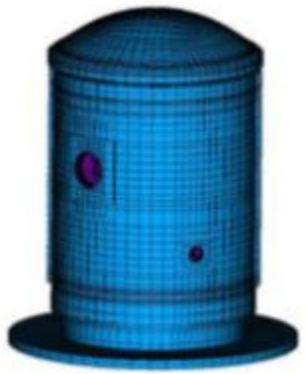
- Maintenance based on scheduled periodic monitoring (inspection, test)

3.4. LTO beyond 60 years – Focus on Containment and Biological Shield (2/2)

Repair, refurbishment and replacement solutions

Containment is not replaceable but repairs can be made:

- For single wall containments (900 MWe reactors), the liner can be repaired with steel patch.
- For double wall containments (1300MWe and N4 reactors), the leakage evolution is mitigated with polymer coating



Vercors Mock-up Model

Identified gaps for LTO beyond 60 – Action plan

Concrete containment mechanical behavior

Based on current knowledge, the behavior of containment and steel liner in case of severe accident will be demonstrated at 80 years. Efforts to improve modeling will continue.

Concrete pathologies

Given their very slow kinetics, concrete swelling pathologies are not a safety issue but could be a factor limiting operating life because no repair solution is currently known. Objectives are to better understand and model physical reactions, predict their effects on structures and maintain the best international state of the art.

Double-wall containments leaktightness

Future efforts concern the robustness of coatings, the methods to detect and quantify leakage and the numerical models to predict the evolution of leakage rates.

Biological shield mechanical behavior

Calculations taking into account fluence effect will be made with published data. If necessary, the properties of in-place concrete will be investigated.

Differential settlement occuring between containment building and spent fuel building

This phenomenon seems not to be critical but the assessment must be done for 80 years of life span.

Non-destructive testing (NDT)

NDT is useful where the structure is not instrumented, or when the instrumentation is not relevant to the phenomenon. The main actions are:

- Detection of corroded thickness and corrosion activity for coated reinforcement and liner,
- Detection of stone nests, delaminations, cracking, concrete defects, with an application for swelling pathologies,
- Measurement of the concrete stress.

3.5. LTO beyond 60 years – Focus on electrical cables

Physical ageing

Ageing mechanisms of polymers: Oxidation, Additives migration, Water trees linked to moisture, Dehydrochlorination, Macromolecular chain cutting and welding

Inspection and diagnostics methods

Various methods are available to characterize the ageing of an electric cable :

- Visual inspection
- Insulation resistance measurements
- Tangent Delta (TD) and Partial Discharge (PD) measurements, for HV cables only
- Time Domain Reflectometry (TDR)

In addition, a program of on-site cable sampling has been put in place for several years.

Repair, refurbishment and replacement solutions

Repair and replacement: not a technical issue for cables.
Only the massive replacement of cables, in case of cliff effect, could be an issue.

Example of cables taken from site for expertise (chemical, electrical and mechanical properties).
End of life criterion : 50% elongation at fracture (absolute value)

Identified gaps for LTO beyond 60 – Action Plan

<u>Prediction of the evolution of cable characteristics over time</u>
This needs research to understand in-depth degradation phenomena and their kinetics and to develop a new analytical "multi-scale" model.
<u>On site cable sampling for expertise</u>
<u>Research on Non-Destructive Techniques that can be used on site</u>, especially for LV cables (today LV cables are monitored mainly with visual checks).

3.6. LTO beyond 60 years – Focus on AFCEN Codes

AFCEN codes cover the design and construction of the main safety classified SSCs:

- Civil work structures (RCC-CW code),
- Mechanical pressure equipment (RCC-M code),
- Electrical equipment and I&C systems (RCC-E codes)

They also cover in service surveillance and maintenance rules (RSE-M).

The codes are periodically updated to align with the latest regulatory and safety requirements and to integrate OPEX and R&D.

For LTO beyond 60 years, AFCEN nuclear codes will take into account:

- The potential effect of longer material aging.
- Advanced methods for margin assessment: state of the art criteria can be an alternative to initial design criteria.

For example, RCC-M and RSE-M codes already provide:

- Warm Pre-Stress effect model for the PTS analysis of RPV irradiated zone.
- GFr criterion to evaluate the risk of ductile instability for piping. GFr represents energy dissipated specifically by fracture.

The development of other advanced fracture mechanics methods is underway, with the purpose of providing more precise and physical (but still conservative) margin estimates:

- BEREMIN and J-Q methods take into account local plastic effects at crack tip (constraint effects), which enables to model geometry effects between specimens and equipment.
- Master Curve is a way to better make use of RPV irradiation surveillance programme.

These three methods will be added to next edition of RCC-M code at the end of 2024.

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