AGING OF MATERIALS DURING PLANT OPERATION

Preventive measures taken for EPR design

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SUMMARY OF THE PRESENTATION

① *Degradation modes of PWR components*

② *Principles of materials selection*

③ *Neutron irradiation*

④ *Thermal aging*

⑤ *Fatigue*

⑥ *Stress Corrosion Cracking*

⑦ *Conclusions*

DEGRADATION MODES OF PWR COMPONENTS (1/2)

(Source : European study – Safe management of NPP aging in the European Union – September 2000)

Potential degradation for			Metals	Concrete	Electronics	Polymers
1	**Irradiation**		X		X	X
2	**Thermal ageing**		X		X	X
3	**Creep**			X		
4	**Fatigue**					
	4.1	High Cycle Fatigue	X			
	4.2	Low Cycle Fatigue	X			
	4.3	Thermal Fatigue	X			
5	**Corrosion**					
	5.1	Corrosion without mechanical loading				
	-	Uniform Corrosion Attack	X	X		
	-	Local Corrosion Attack (Pitting, Wastage, Crevice Corrosion)	X	X	X	
	-	Selective Corrosion Attack (InterGranular Corrosion)	X			
	5.2	Corrosion with additional mechanical loading				
	-	Stress Corrosion Cracking (InterGranular SCC, TransGranular SCC)	X	X		
	-	Primary Water Stress Corrosion Cracking	X			
	-	Hydrogen Induced Stress Corrosion Cracking	X			
	-	Strain Induced Corrosion Cracking	X			
	-	Corrosion Fatigue	X			
	5.3	Flow Accelerated Corrosion (Erosion/Corrosion)	X			
	5.4	Irradiation Assisted Stress Corrosion Cracking	X			
	5.5	Microbiologically Influenced Corrosion	X			
6	**Wear** (Fretting, Abrasion, Vibration, Cavitation, ...)		X	X		
7	**Loss of prestressing**			X		
8	**Environment effects**					
	-	Freeze-Thaw Cycling, Wetting and Drying		X		
	-	Chemical Attack		X		
	-	Oxidation				X
9	**Concrete Degradation** (Shrinkage, Leaching of Calcium Hydroxide, Reaction with Aggregates)			X		
10	**Differential Settlement**			X		
12	**Oxidation**					X

DEGRADATION MODES OF PWR COMPONENTS (2/2)

- ***Main degradation modes of PWR components :***
  - *Embrittlement of materials by irradiation or thermal aging*
    - *Reduction of resistance to fast fracture*
  - *Local corrosion attack or stress corrosion cracking*
    - *Loss of thickness – risk of leakage*
  - *Fatigue cracking*
    - *Risk of leakage or of fast fracture*
- ***Good knowledge developed through international R&D programs and lessons drawn from the field***

PRINCIPLES OF MATERIALS SELECTION

- **Requirements:**
  - → *Ability to manufacture heavy components (forging, welding....)*
  - → *Avoid any significant fabrication defect*
  - → *Demonstration of fitness for purpose (materials files)*
- **Consequences:**
  - → *Avoid "high performance" materials*
  - → *Use commercial grades well known to the manufacturers*
  - → *Optimize these grades to get:*
    - ⇨ *Reproducible and homogeneous properties*
    - ⇨ *Good resistance to fast fracture (level of impurities, Charpy impact toughness, RTNDT < -20℃)*
    - ⇨ *Corrosion resistance in the anticipated environment and reduced release of corrosion products*

MATERIALS REFERENCE FILES FOR EPR

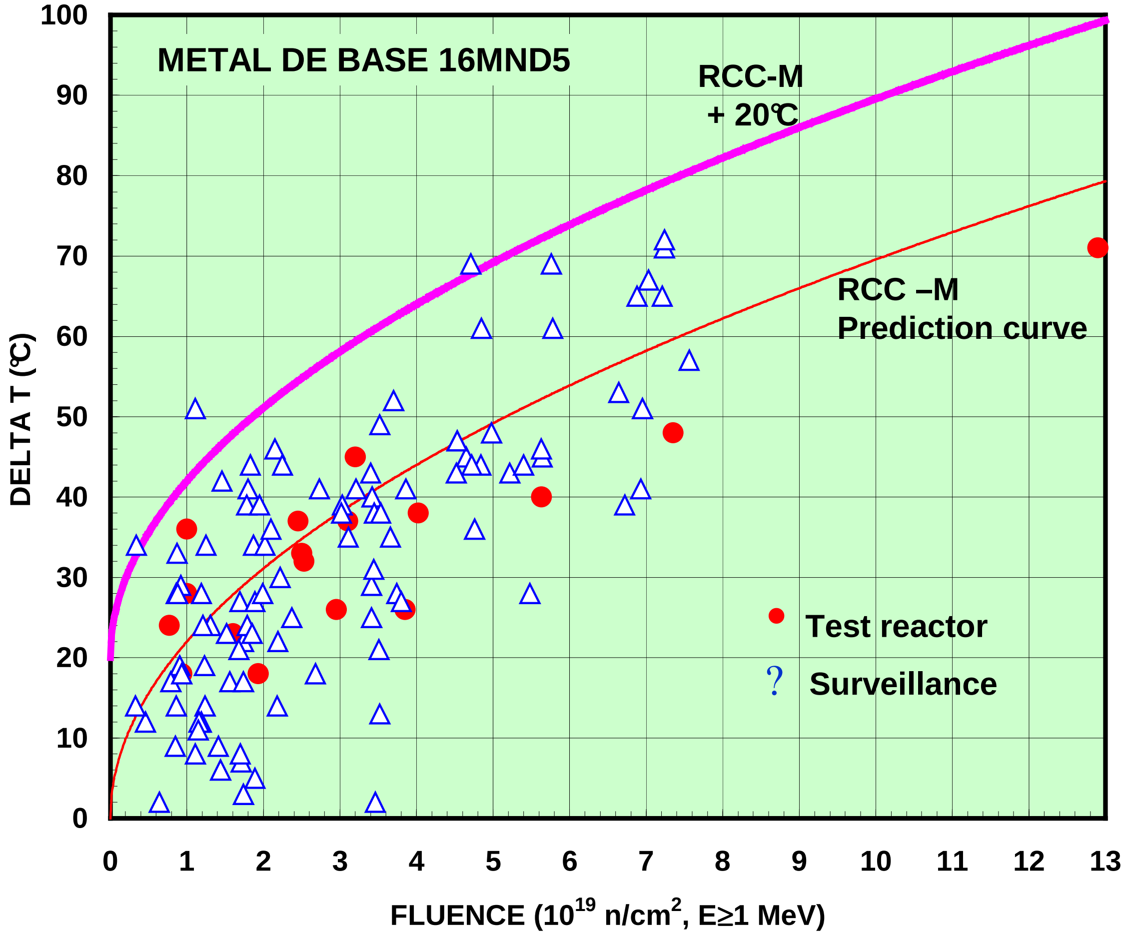
- ***Field of application dependent on the local regulation***
- ***Objectives***
  - → *Demonstrate that the selected materials are adequate for a given component*
  - → *Demonstrate that the designer masters all materials-related aspects*
- ***Contents***
  - → *Procurement specifications-comparison with international standards*
  - → *Manufacturing (steelmaking, casting, forging, heat-treatments, surface conditioning)*
  - → *Physical and mechanical properties*
  - → *Resistance to irradiation, thermal aging, fatigue, corrosion*
  - → *Industrial and field experience*

NEUTRON IRRADIATION (1/4)

- **Core region of the Reactor Pressure Vessel**
  - → *The shift of transition temperature is a function of Cu and P contents, of irradiation temperature and of neutron fluence (E > 1 MeV)*
    - ***Prediction formulae available for old and for modern materials***
    - ***Damage monitored by surveillance capsules submitted to a higher neutron flux***
  - → *Reduction of the neutron fluence and of the residual elements in the case of the EPR RPV*
    - ⇨ *P content ≤ 0.008 % and Cu content ≤ 0.080 %*
    - ⇨ *1.3 to 2.6 10^{19} n/cm^2 for 60 years*
    - ⇨ *End of life RTNDT < 30°C*

NEUTRON IRRADIATION (2/4)

Irradiation embrittlement of modern RPV Materials
(P ≤ 0.008 %, Cu ≤ 0.080 %)



NEUTRON IRRADIATION (3/4)

- **RPV internals**

  → The main concern today is IASCC, i.e. the cracking of some baffle bolts after more than 10 years operation (+ circumferential cracks in BWR core shrouds)

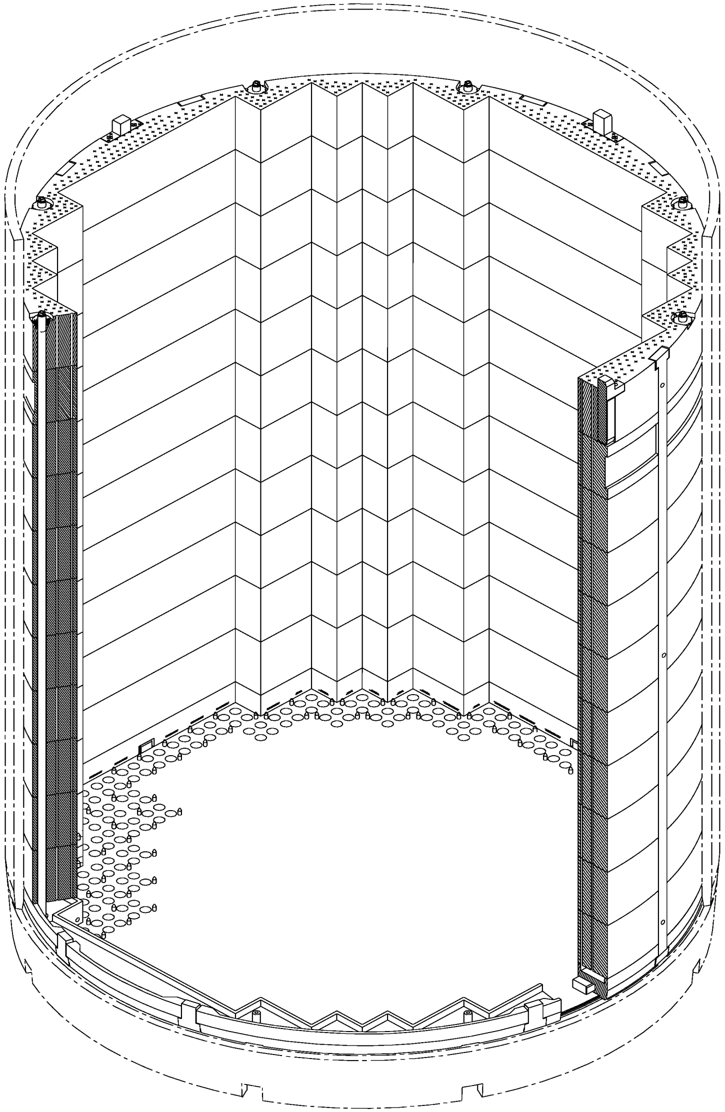
  - International cooperative program (CIR) managed by EPRI to improve our knowledge and identify more resistant alloys

  → Design changes for EPR with water cooled stainless steels heavy reflectors and tie-rods installed far away from the core

  ⇨ Reduction of neutron leaks and of neutron fluence on the RPV wall

  ⇨ Fluence on bolting material reduced by a factor of 10

IRRADIATION EMBRITTLEMENT (4/4)



Schematic of EPR lower internals

THERMAL AGING (1/5)

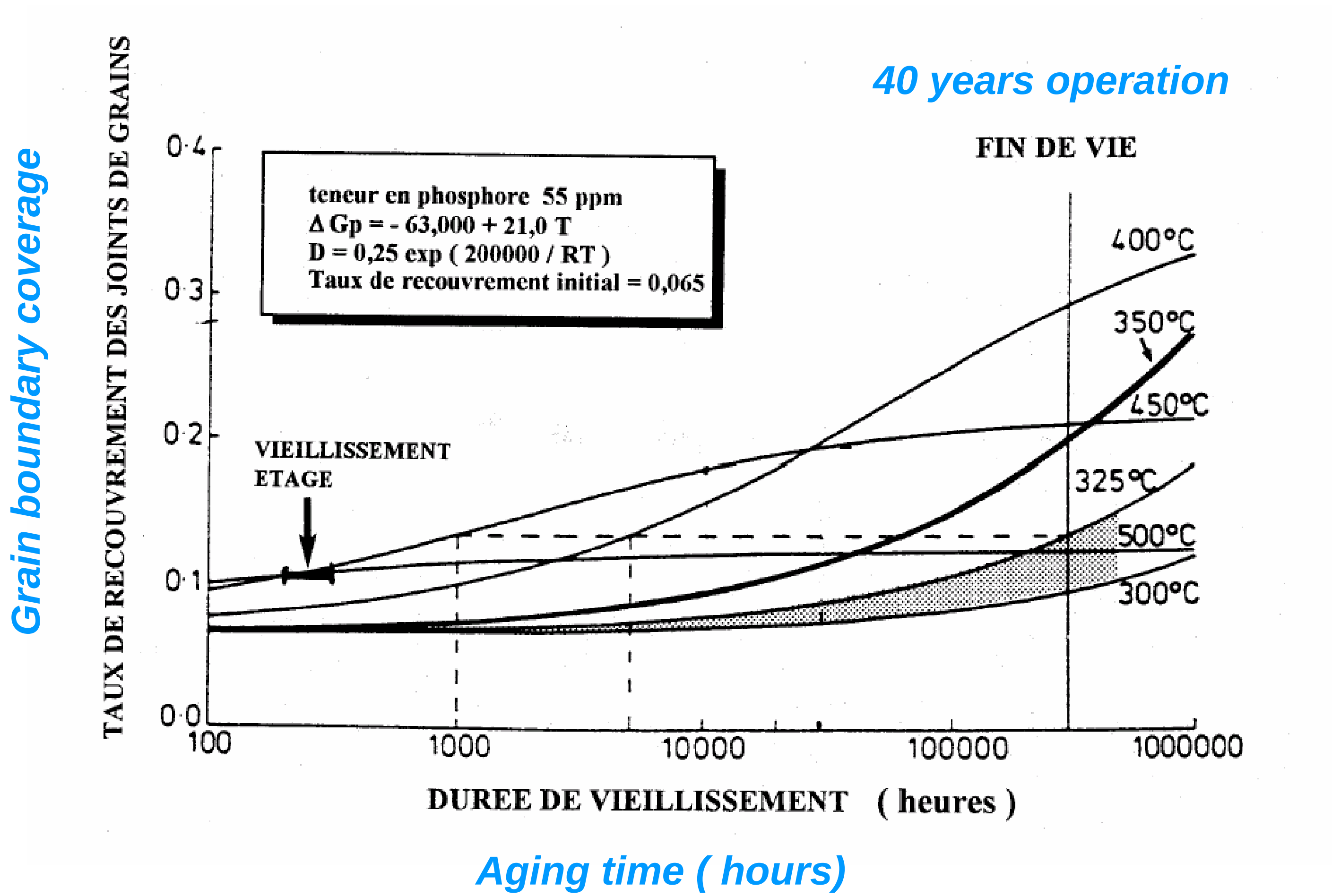
- **General**
  - → *All ferritic steels and alloys are potentially susceptible to various forms of thermal aging in the temperature range 20 – 350°C*
  - → *Austenitic stainless steels and Nickel-base alloys appear to be practically immune to thermal aging*
  - → *Thermal aging of stainless steels has been the subject of extensive studies for a long time, throughout the world. The underlying mechanisms are well understood and empirical laws were developed to quantify aging effects on the properties*
    - ***Martensitic stainless steels with 15-17 % Cr are highly embrittled by precipitation of Cr-rich particles at operating temperatures above 250°C***
    - ***The presence of high Cr ferrite in duplex cast austenitic stainless steels renders these alloys susceptible to thermal aging, which results in a decrease of the ductile fracture toughness***
    - ***The countermeasures in order to reduce or to avoid thermal aging in these materials are well known***

THERMAL AGING (2/5)

- **Pressure boundary of the pressurizer**
  - → *Shift of the transition temperature due to segregation of P and other impurities (Sn, As, Sb) to the grain boundaries*
  - → *Function of the operating temperature, P content and grain size, but accurate quantitative knowledge is lacking*
  - → *Could be significant in the coarse grain areas of the heat affected zone under the stainless steel cladding especially in the case of a single layer cladding)*
    - ⇨ *Optimization of the cladding procedure (2 layers, control of the position of the weld beads and of the energy input of the second layer) to reduce the grain size in the HAZ*
    - ⇨ *Reduction of the level of the harmful impurities (P < 0.008% and additional KTA requirements for As, Sn … in the case of EPR procurements)*

THERMAL AGING (3/5)

Kinetics of phosphorus segregation to the boundaries of large grain HAZ according to the model of Mc LEAN

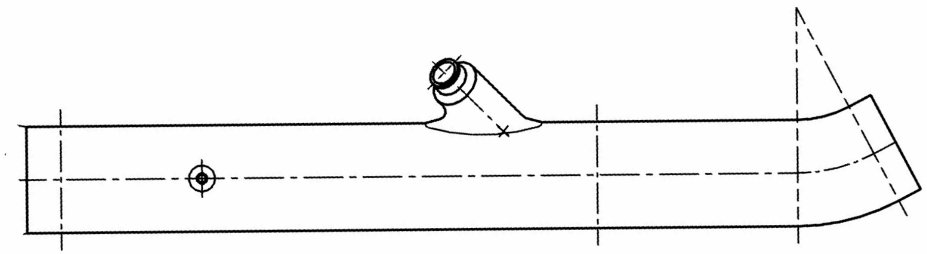


THERMAL AGING (4/5)

- **Cast duplex austenitic-ferritic stainless steels**
  - → Duplex microstructure (typically 80% austenite and 20% ferrite)
  - → Spinodal decomposition of the ferritic phase results in hardening and embrittlement which depend on:
    - ❖ Aging temperature and time
    - ❖ Chemical composition (mainly Si+Cr+Mo content)
  - ⇨ As a consequence, the Mo-bearing grade (CF8M) was abandoned in France at the beginning of the 80s
  - → In the case of EPR, the only application is the primary pump casing which operates in the cold leg:
    - ❖ Optimization of CF8 grade (ferrite content limited to 20%)
    - ❖ In-service aging well known through 100000h tests at higher temperatures (300 to 350°C) – remains moderate.

THERMAL AGING (5/5)

- **_Cast duplex austenitic-ferritic stainless steels_**
  - → *In the case of EPR, these materials are abandoned for the primary piping*
  - → *Manufacturing of primary loops with forged austenitic stainless steels (prevention of any aging)*
  - → *In addition, manufacturing of integral elbows and nozzles to reduce the number of welds*



Example of EPR primary piping cold leg

FATIGUE (1/2)

- **Fatigue damage: a function of operating time**
  - → *Good level of prevention through state of the art rules for design of circuits and parts*
  - → *Field experience shows cracking in locations where loadings were ignored or underestimated*
    - ❖ ***Mixing of hot and cold fluids***
    - ❖ ***Thermal fluctuations at the interface between cold stratification and hot vortex***
    - ❖ ***Unexpected vibrations of small piping***
  - → *Aggravating factors are well identified:*
    - ❖ ***Cyclic loadings associated with high mean stress***
    - ❖ ***Poor geometry or surface condition***

FATIGUE (2/2)

- ***Effect of high temperature water environment on fatigue damage : a controversial topic***

  → *Laboratory tests performed in USA and Japan show a strong reduction of number of cycles to crack initiation with :*

  - ***Slow strain rates associated with large transients***
  - ***Temperatures above 150℃***
  - ***High or low oxygen contents***

  → *Field experience does not evidence an environmental effect on fatigue resistance:*

  ⇨ ***This effect is probably included in the margins of the design methodology (definition and number of transients, definition of Ke....)***

  → *Need of some critical experiments to evaluate the real concern*

  → *Keep the same design methodology for EPR*

STRESS CORRECTION CRACKING (1/2)

- ***Primary water stress corrosion cracking of Alloy 600 components is the main corrosion problem in PWRs***
  - → *Started with cracking of SG tubing more than 25 years ago*
  - → *Cracking of pressurizer nozzles for about 15 years*
  - → *First reported cracking of vessel heads penetrations in 1991*
  - → *Cracking of Alloy 182 welds since year 2000*
  - ⇨ *The solutions are known (replacement with Alloy 690 components + 52/152 weld metals)*
  - ⇨ *A proactive approach appears necessary to maintain the safety*
    - ❖ ***Periodic efficient inspections***
    - ❖ ***Repair or, better, replacement of the component to prevent leakage***

STRESS CORROSION CRACKING (2/2)

- ***Qualification of replacement solutions***
  - → *International research proved the PWSCC resistance of Alloy 690 which was the prefered choice for SG replacements since 1985*
  - → *Development and optimization of Alloy 690 product forms and weld metals:*
    - ***Started in France after the failure of a vessel head penetration in Bugey (1991) – Cooperative studies involving EDF, CEA, Framatome and the steelmakers.***
    - ***Qualification (manufacturing and PWSCC resistance) of Alloy 690 vessel head penetrations, BMI penetrations, SG divider plates and core supports***
    - ***Qualification (welding procedures and PWSCC resistance) of Alloys 152 and 52 weld metals***
  - → *All these technologies were progressively implemented for components manufacturing and are used for EPR*

CONCLUSIONS

- ***The main physical degradation modes of PWR components are well identified through international R&D and field experience***

- ***Prevention of aging starts with optimized materials, well known to the manufacturers, resistant to fast fracture***

- ***Changes of materials only in the case of negative field experience (thermal aging or stress corrosion cracking)***

- ***EPR design takes into account all these damages which are prevented or mitigated through changes in manufacturing, optimization of materials, reduction of neutron fluence, modifications of systems or components***

- ***EPR lifetime relies upon the best solutions developed in France and in Germany, with improvements of operation mode and reduction of dosimetry***