Some challenges to adapt nuclear codes and standards to innovation

Focus on materials and coolants in nuclear reactors' environments

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1. **Basic definitions: nuclear codes and standards**
2. **Innovative systems, specificities**
3. **Connection between environment, materials and nuclear codes**
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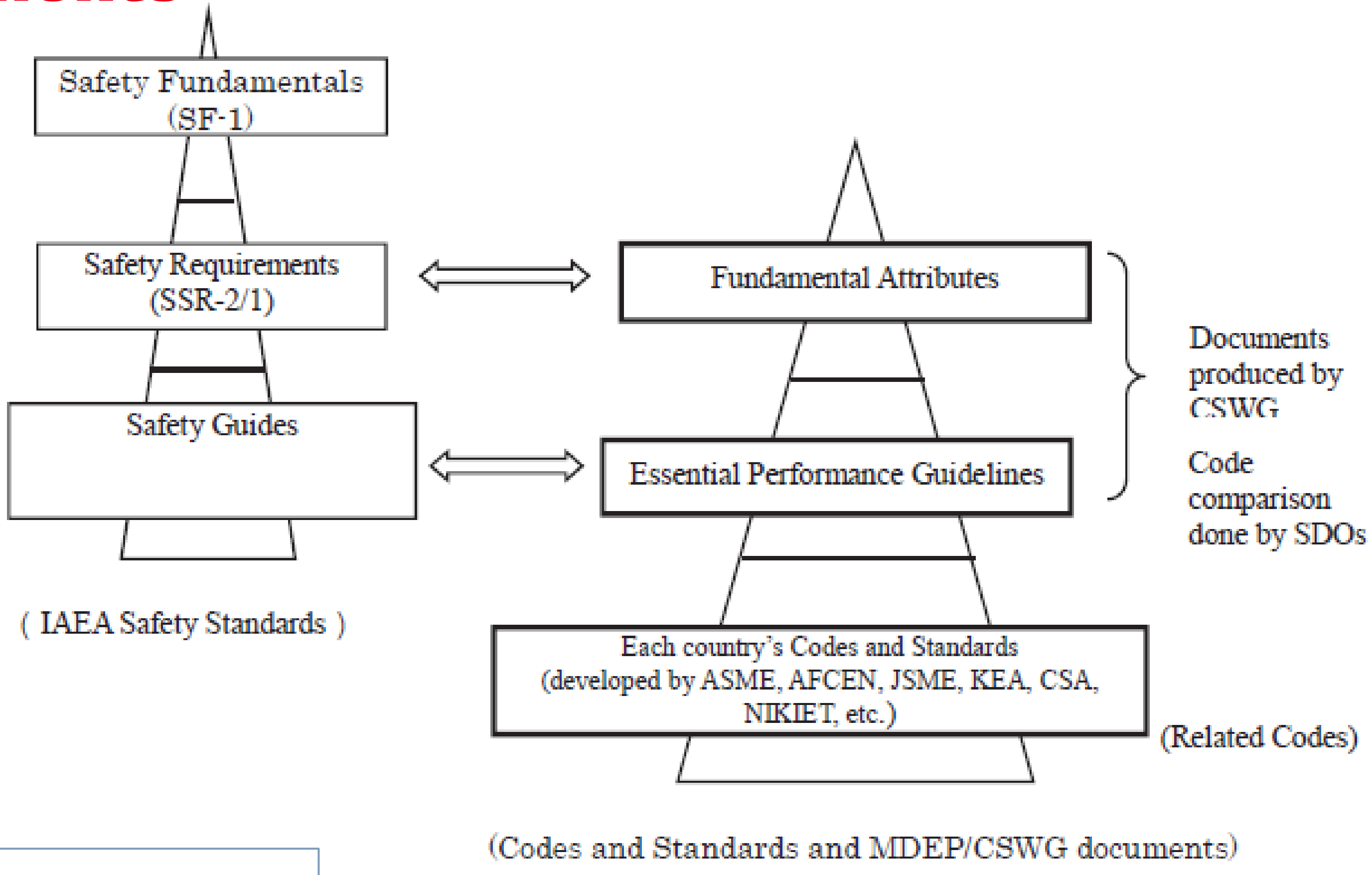
    b. Examples
4. **Conclusion**

C&S and safety requirements



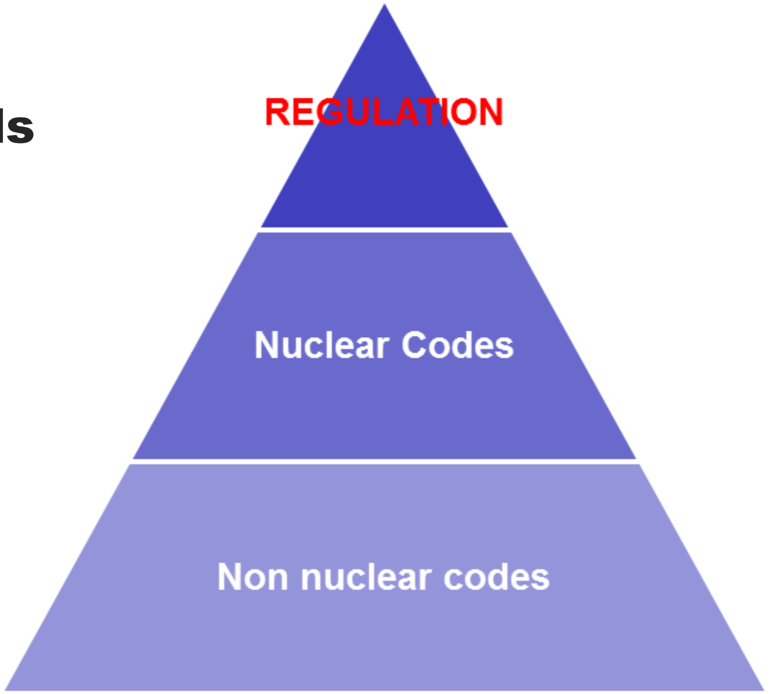
MDEP Technical Report TR-CSWG-04
Multinational Design Evaluation Programme : Codes and Standards Working Group, SDO Standards Development Organisations

1. Basic definitions: nuclear codes and standards

Codes &Standards use

For one reactor:

- **One regulation (depending one the country where you built your plant)**
- **Different codes/standards depending on**
  - **the part of the plant** (nuclear or not)
  - **the component** (mechanical or electrical component, civil work…)
  - …



Examples for mechanical components design
ASME Sect III RCC-M, RCC-MRx KTA 3211 R5,R6 SDC-IC, DDC-IC
EN 13480, EN 13445 ASME sect VIII

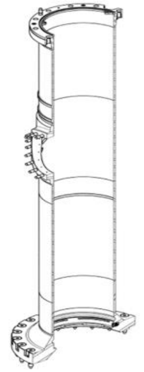
1. Basic definitions: nuclear codes and standards

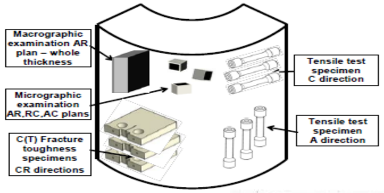
Example of a nuclear code

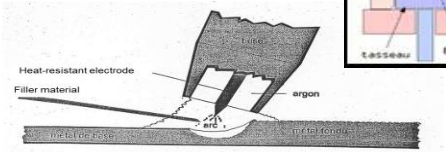
Code is a set of rules, not a software
A nuclear code is a coherent whole
…not only a process, a material or a design rule…

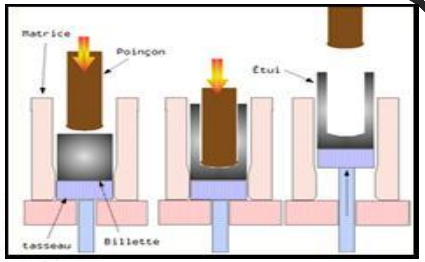
RCC-MRx

VOLUME I	VOLUME II	VOLUME III	VOLUME IV	VOLUME V
Design	Materials	Examination Methods	Welding	Manufacturing operations









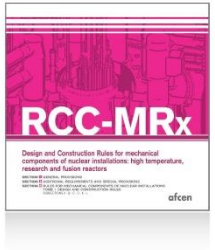
Shall reflect the state-of-the art and include improved technologies

1. Basic definitions: nuclear codes and standards

Example of a nuclear code

RCC-MRx
Design & Construction Rules for
Mechanical Components
of Advanced, Experimental and Fusion Nuclear Installations

Experimental, High-Temperature, Fusion Reactors



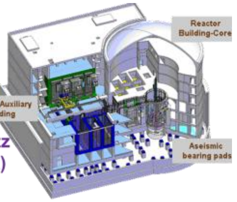
RCC-MRx
MECHANICAL COMPONENTS

- Design
- Materials & Examination Methods
- Welding & Manufacturing Operations

RCC-MR 2002

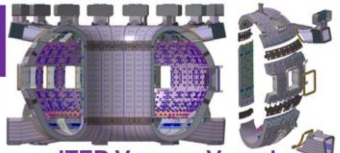
Indian PFBR

RCC-MX 2008



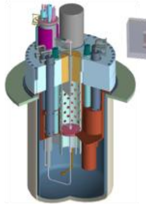
Jules Horowitz Reactor (JHR)

RCC-MR 2007

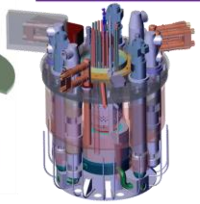


ITER Vacuum Vessel

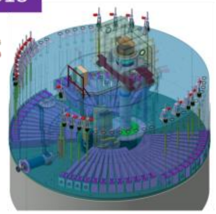
RCC-MRx 2012, 2015, 2018



MYRRHA Primary Cooling system



ASTRID

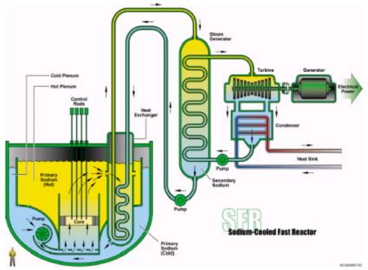


European Spallation Source target

2. Innovative systems, specificities

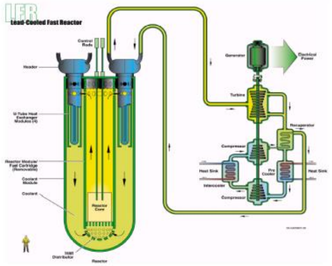
Strong diversities of innovative projects

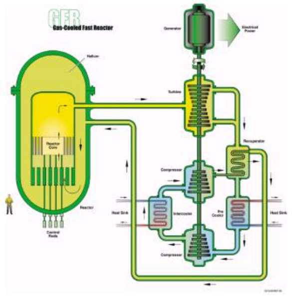
- **GENIV/ AMR concepts:**



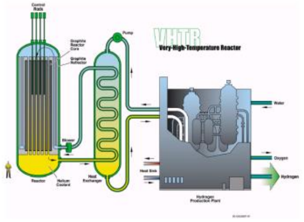
Sodium Fast Reactor

Lead Fast Reactor

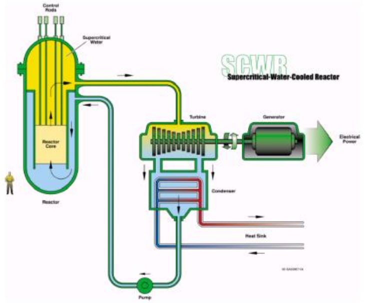




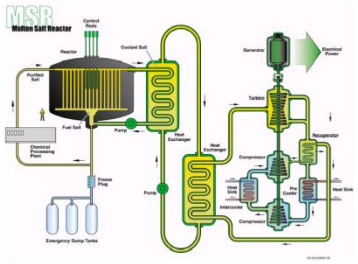
Gas Fast Reactor



Very High Temperature Reactor (Gas)

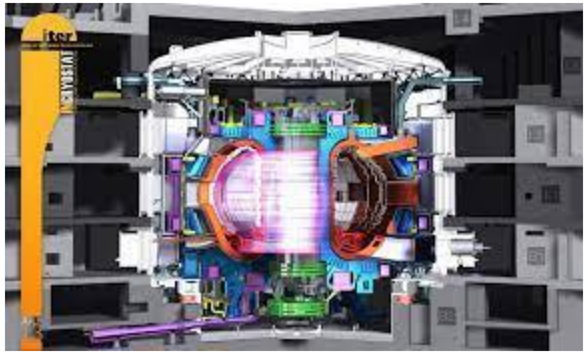


Supercritical Water Reactor

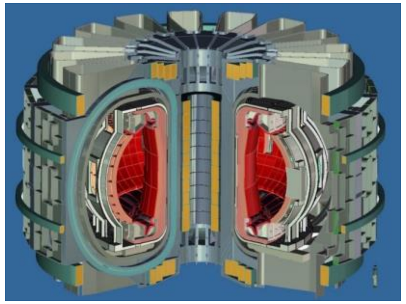


Molten Salt Reactor

- **Fusion concepts:**



Iter



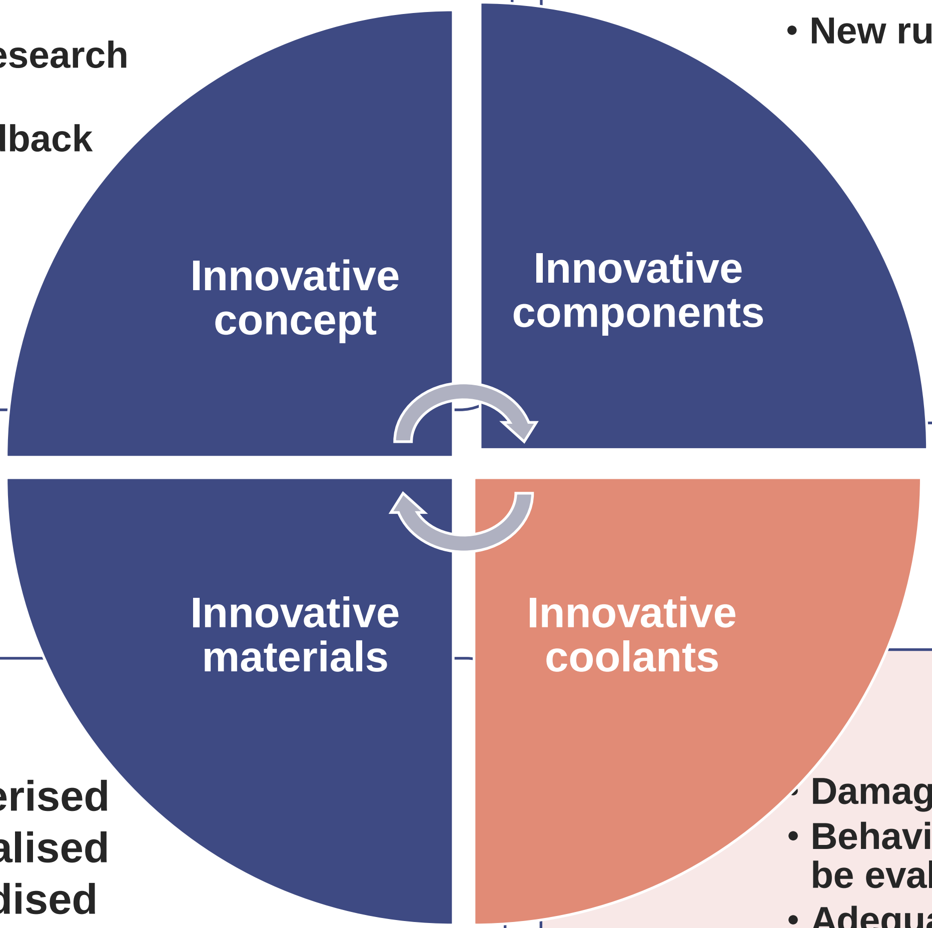
DEMO

Sodium, molten salt, lead, lead bismuth, high and very high temperature, high and very high irradiation, electromagnetic loads…

2. Innovative systems, specificities

- Non conventional systems
- Common approach to be adapted
- Diversity of the research world
- No industrial feedback

- New damages
- New designs
- New rules



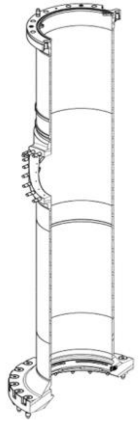
- To be characterised
- To be industrialised
- To be standardised

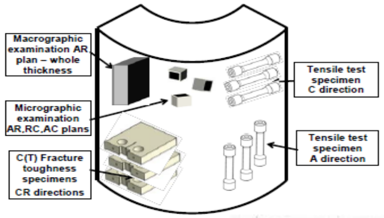
- Damages to be identified
- Behavior of materials to be evaluated
- Adequacy of the rules questionable

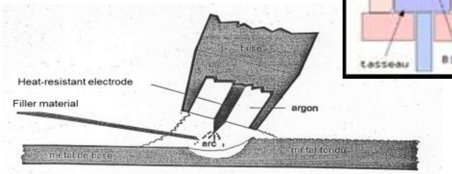
3. Connection between environment, materials and nuclear codes
a. General process

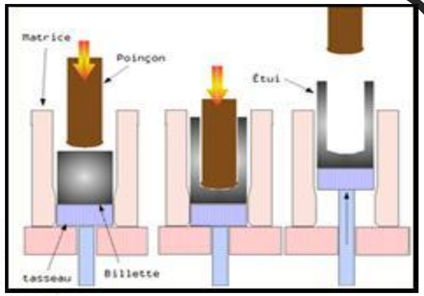
Mechanical design code

VOLUME I **Design**	**VOLUME II** **Materials**	**VOLUME III** **Examination Methods**	**VOLUME IV** **Welding**	**VOLUME V** **Manufacturing operations**









Environment effects: design (properties, corrosion), materials (selection, caracterisation), examinations (especially for in-service monitoring)…

Integration of environment effects

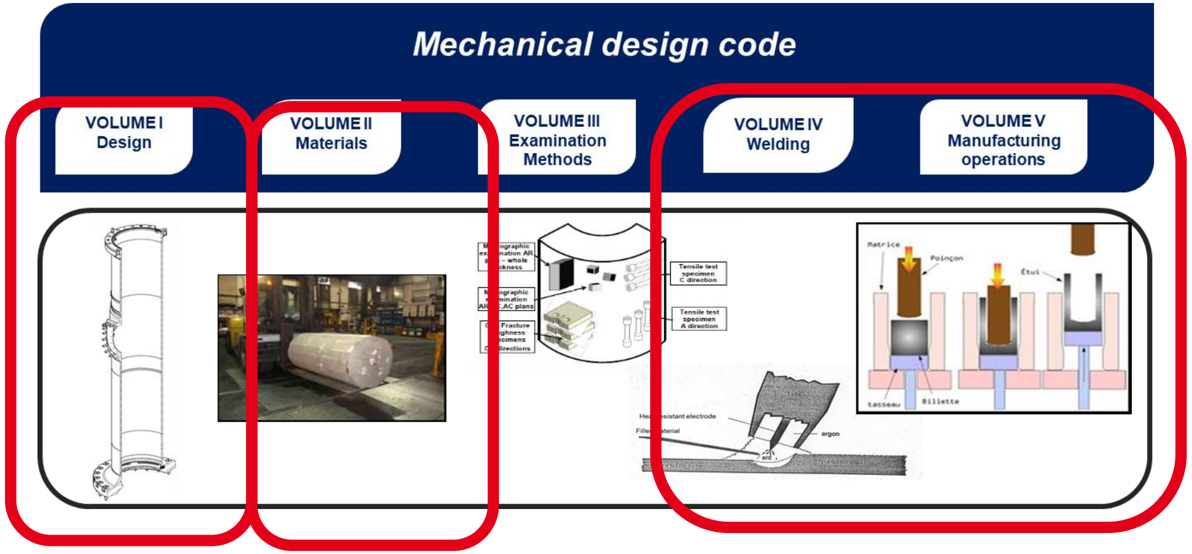
Environment effects are complex and depend on :

- Fluid nature and quality (control)
- Fluid Temperature and Pressure, velocity…
- Steel type and heat treatment associated

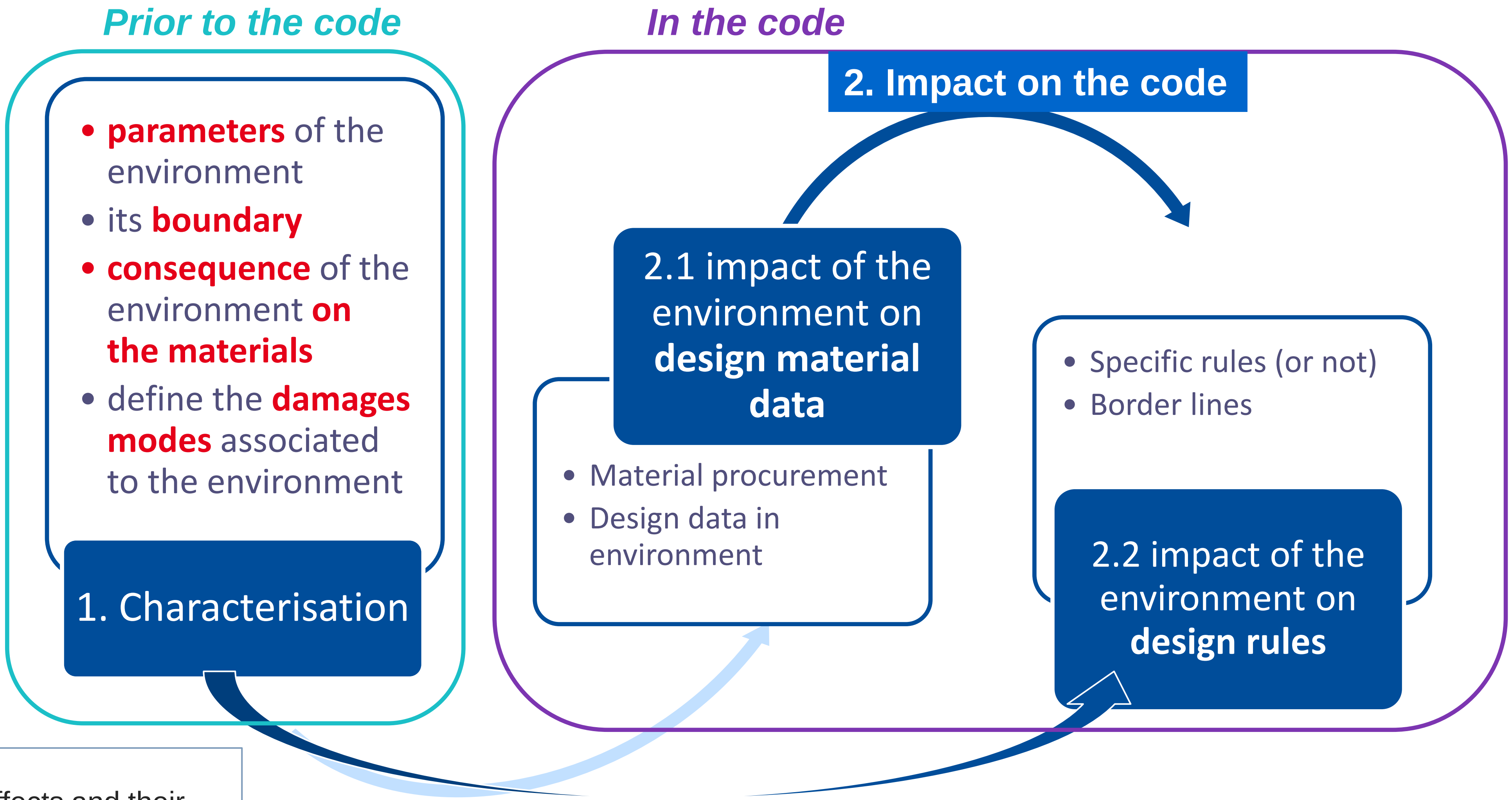
Not managed by the mechanical code

Only impacts of the fluid environment may be managed by the Code

- Impacts on **material properties**
- Impacts on **mechanical design rules**
- Impacts on **constructive disposition** (design thickness, choice of materials)



3. Connection between environment, materials and nuclear codes
a. General process



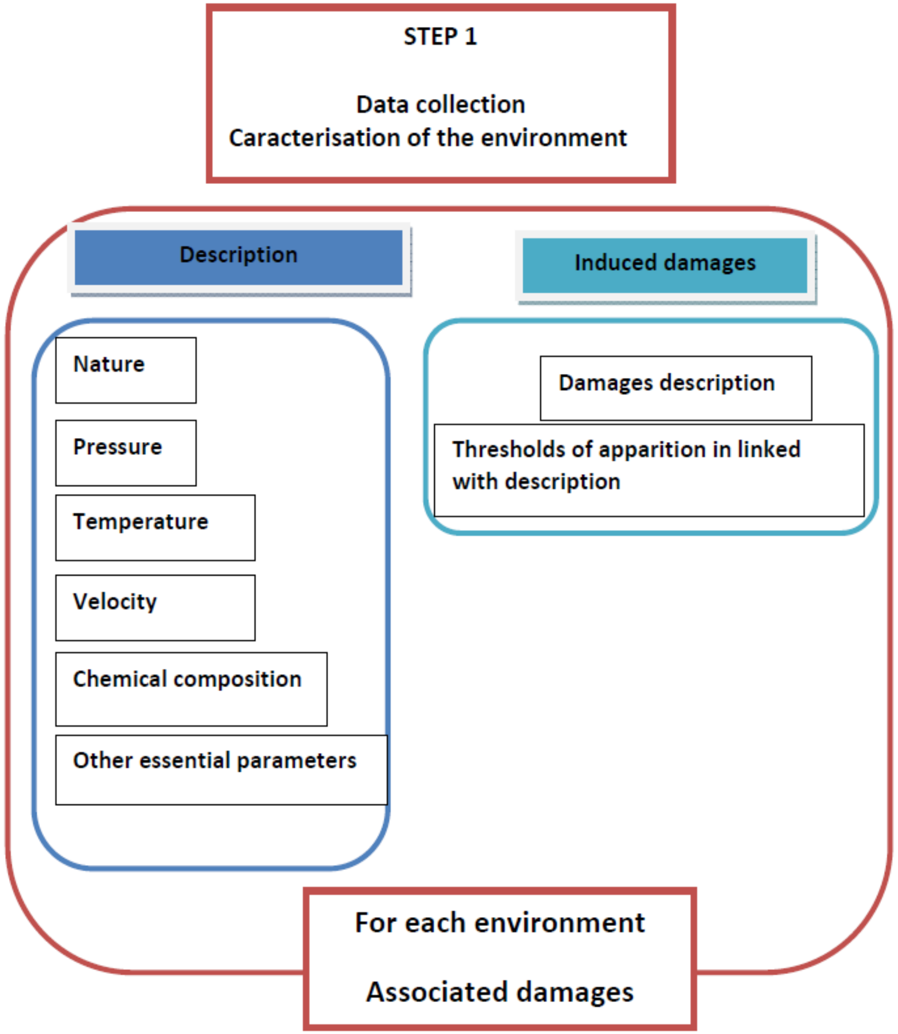
O. Gelineau, Framatome
RCC-MRx : environmental effects and their inclusion into the Code, MATTER, 2014

3. Connection between environment, materials and nuclear codes
a. General process

Prior to the code

1. Characterize the environment associated to the application

- define the **parameters** of the environment and **its boundary**
- Need to describe the **consequence** of the environment on the **materials**
  - Preferred materials may be chosen : SS, ferritic…
- Need to define the **damages modes** associated to the environment (and to material grades) with :
  - Description of each damage
  - Threshold initiating the damage
  - Link between the damage and the design rules

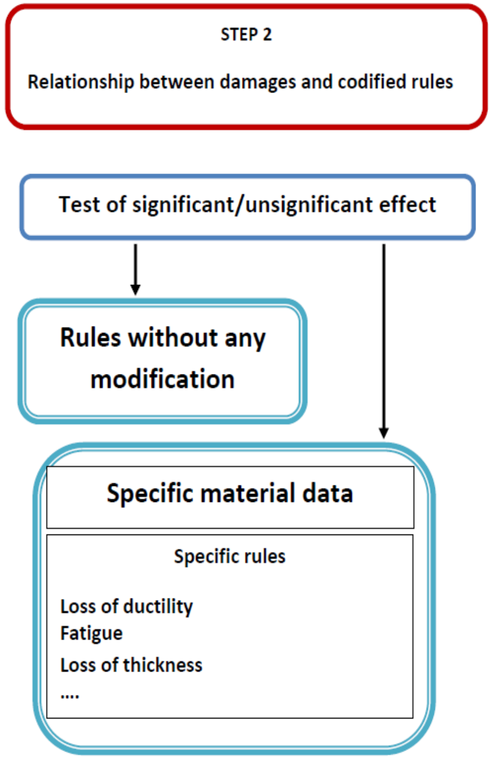


3. Connection between environment, materials and nuclear codes
a. General process

In the code

2.1 Impact of the environment on design material data

- Choice of **preferred material grades** (prescription, limitation ?)
- **Identification of the impacted material properties** (within the range of op. cond.)
  - Tensile properties, ductility
  - Fatigue
  - Rupture strength, creep law
  - Cyclic data, ….
- **Define material property as a function of a measurable parameter** :
  - Weigth loss ? (Div V ASME for Graphite, strentgh vs weigth loss)
  - Oxygen rate ?
  - …
- Define the **border lines**
  - from which the environment effect is significant
  - Beyond which the effect is considered as too important
    - Oxidation at more than xx % ?
    - Cumulation of oxidation with irradiation ??
    - …



3. Connection between environment, materials and nuclear codes
a. General process

In the code

2.2 impact of the environment on design rules

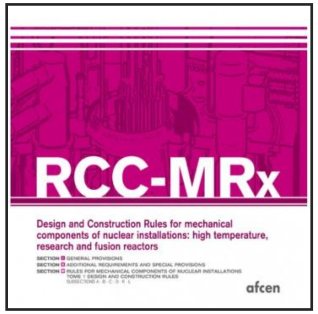
- Examine **all the possible damage modes** and define **adequate design rules**
  - Excessive defomation/plastic instability
  - Buckling
  - Progressive deformation
  - Fatigue
  - Creep rupture, creep-fatigue…
  - Crack propagation …
- **Confirme** the way stress/strain have to be calculated
  - Elastic/inelastic
  - Treatment of primary/secondary stress
  - …

!

!! Mechanical damages only *(avoidance of stress corrosion cracking by design in RCC-MRx but what about environment embrittlement ?)*

!! Necessary to have data on representative material parts, for the whole life duration

3. Connection between environment, materials and nuclear codes
b. Example



Consideration of the SFR environment in RCC-MRx:

Considering the operating conditions of a SFR, that is « normal quality Sodium » (Low Oxygen rate):

- **no effect** on properties, on damages
- **Same** results as in the air

But corrosion cracking risks exist :

In service

- Equipments in contact with cooling water
  - In Heat exchangers tubes, “design” thickness has to include possible loss due to generalised corrosion
- Equipments sensitized by welding operations

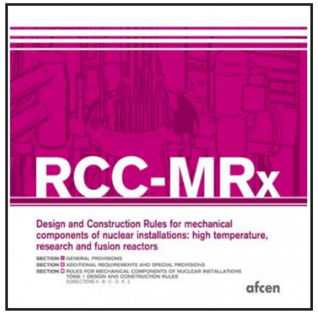
During storage

- Non controlled air environment

During in service intervening operations

- Washing and decontamination operations (concern component working in sodium as well !)

3. Connection between environment, materials and nuclear codes
b. Example



Consideration of the SFR environment in RCC-MRx

Intergranular Corrosion

- Preferential attack to the grains joints in water environments (electrolyte)
- Austenitic steels, mainly :
  - Chromium depletion [thermal sensitivity between 400 (450) and 800°C]
  - Thermal effect of welding

Solutions (where there are corrosion risks in service) :

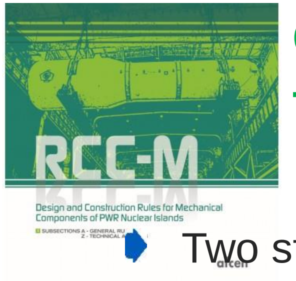
- Very low carbon content: **≤ 0,030 % for the austenitic steels**
- Titanium or Niobium stabilized steels
- Corrosion test according to RMC 1310 RCC-MRx chapter

Code doesn't cover directly intergranular corrosion of austenitic and austenitic-ferritic stainless steels except for:

- **Selection of austenitic steels in Tome 1**
- **Cleanliness requirements concerning contamination (Cl, F, S…) in Tome 5**
- **Corrosion test in Tome 2 (material) and 3 (examination)**

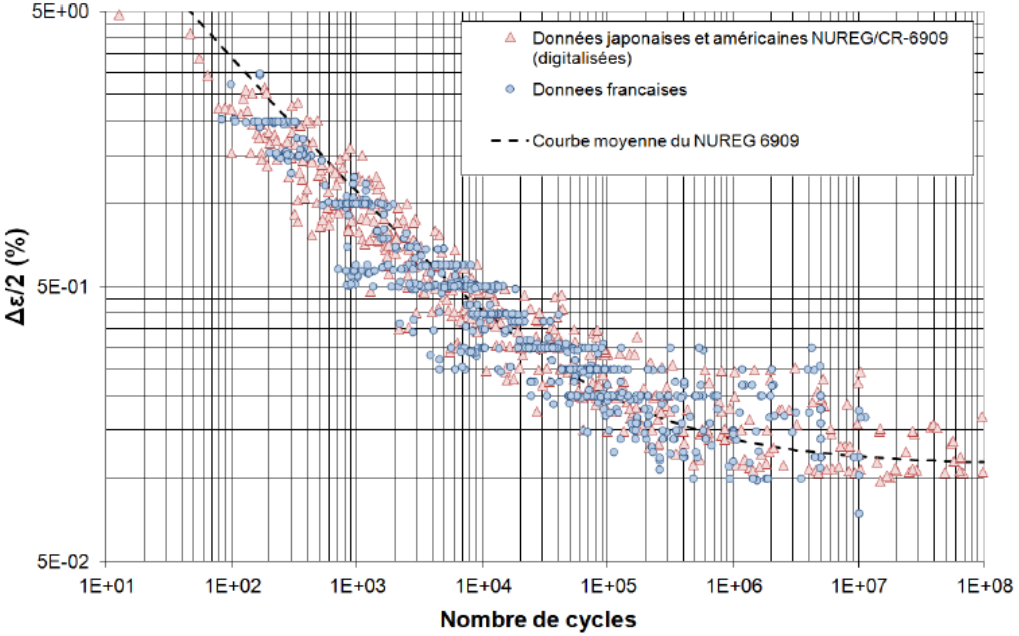
3. Connection between environment, materials and nuclear codes
b. Example

S Courtin, T Métais &all
Modifications of the 2016 edition of the RCC-M code to account for environmentally assisted fatigue, PVP, 2016

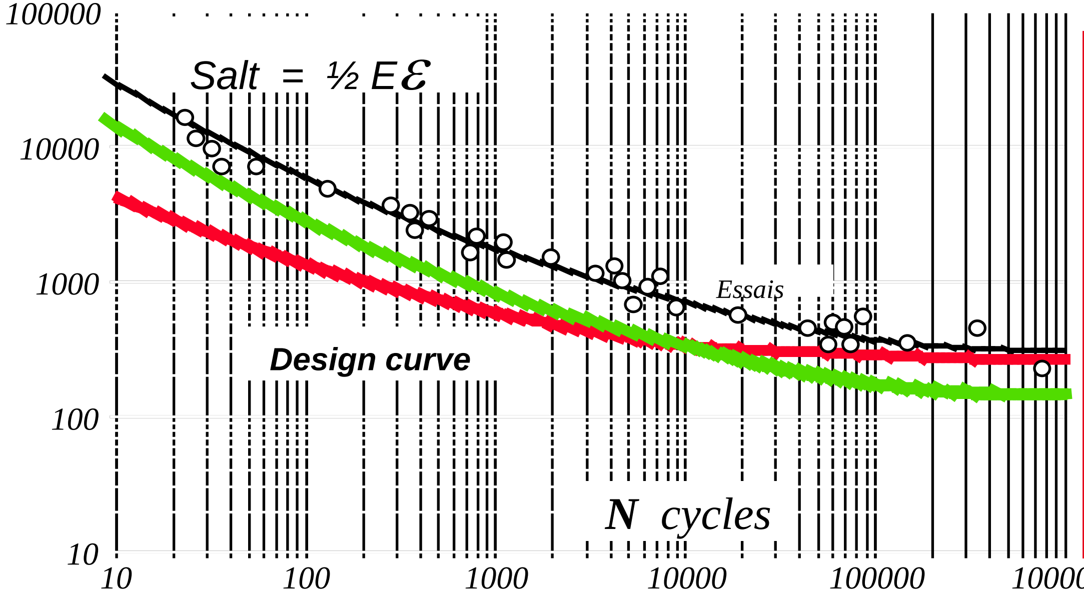


Consideration of PWR environment effect on fatigue design curves in RCC-M or ASME

- Two stages in the construction of the fatigue curves:
  - Stage 1: Definition of a mean air curve from laboratory tests
- Stage 2: Definition of a design curve by applying translation coefficients on the number of cycles and the strain amplitude



2 on stresses or strains / 20 on numbers of cycles



Cover the following effects:

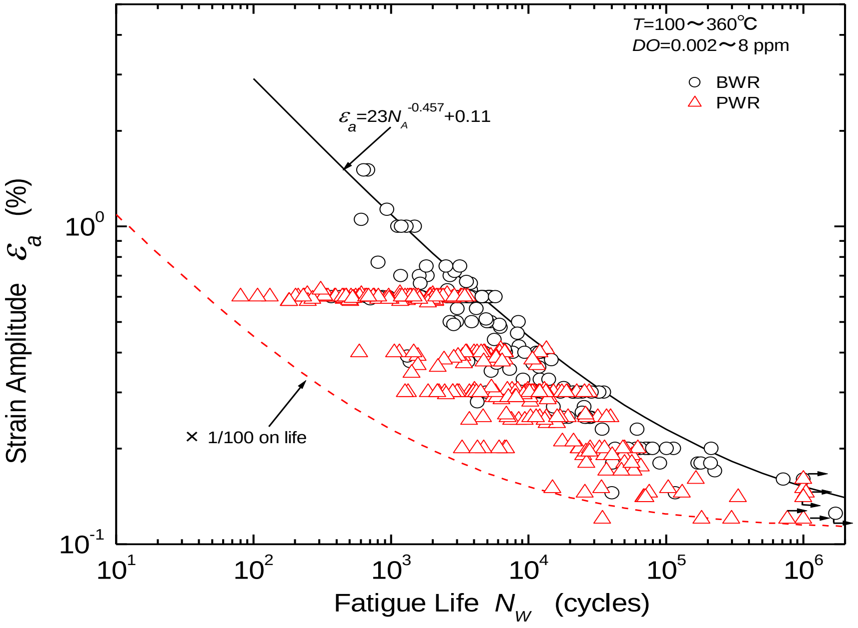
Material data scatter, Surface finish, Size effect /geometry, Mild environment, Damage accumulation /load sequence, Multiaxiality, Residual stress

3. Connection between environment, materials and nuclear codes

b. Example

Consideration of PWR environment effect on fatigue design curves in RCC-M or ASME

- **Effect of primary water environment** on low cycle fatigue lifetime of austenitic stainless steels : Comparison with reference “Air curve”



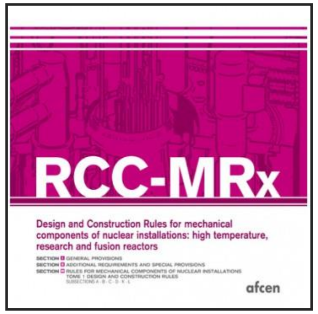
- **Environment effect characterisation**
  - laboratories assert that the effects of environment in PWR can be very significant and superior in reserves taken into account in the nuclear design codes
  - At the end of 1999, the NRC asked the " Board " ASME to treat in the code ASME III the effects of environment,
  - This led the NRC to get closer to the Argonne National Laboratory (ANL) and to support through Regulatory Guide 1.207 a methodology (corrective factor Fen) described in the **NUREG CR-6909.**

- **Design methodology and design data to be changed to integrate this environmental effect**
  - **New design curves** without environmental effect
  - **Environmental effect taken into account** through a penalised factor Fen

*Correction of the usage factor Fu: F.u. = f.u.p $_{(1)}$ * Fen $_{(1)}$ + f.u.p $_{(2)}$ * Fen $_{(2)}$ + f.u.p $_{(3)}$ * Fen $_{(3)}$ + …+*

Fen function of: Strain rate during transient, Temperature evolution during transient, Oxygen content during transient

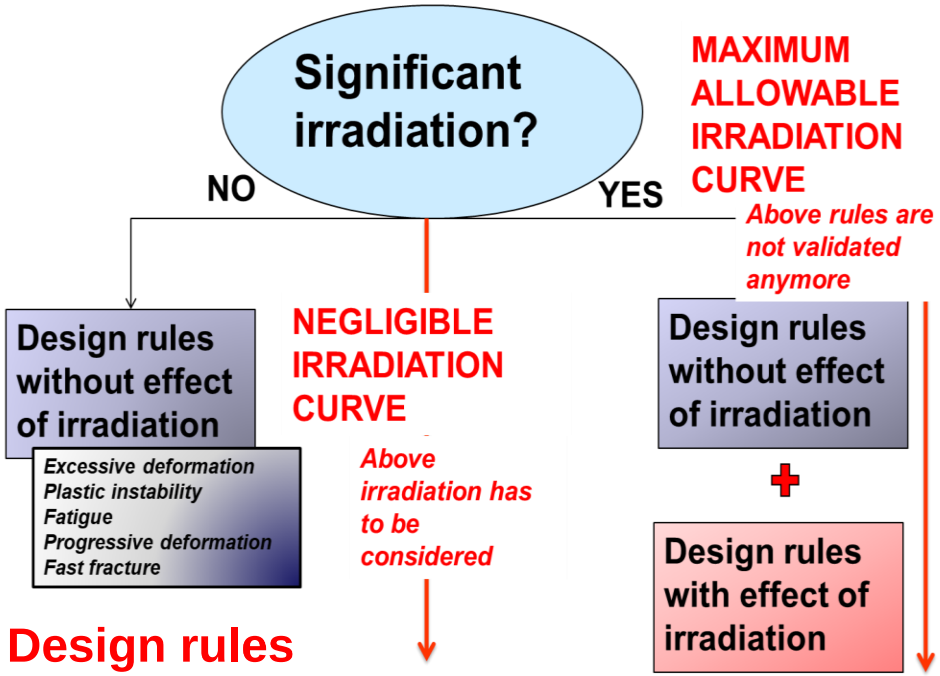
3. Connection between environment, materials and nuclear codes
b. Example

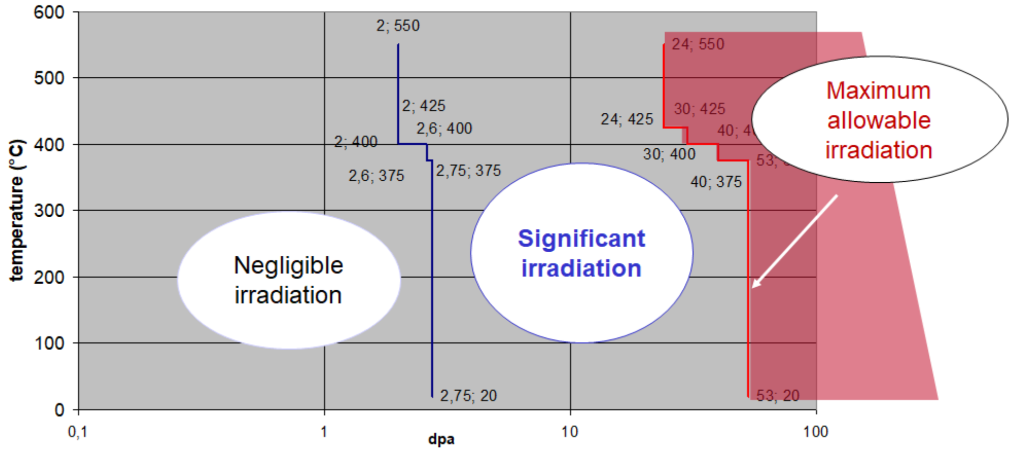


Consideration of Irradiation effects in RCC-MRx

Irradiation Effects are environment effects
Their treatment in RCC-MRx :

- Use of **Border lines**
  - In relation with the operating parameters of the concerned application : neutron irradiation range, temperature range





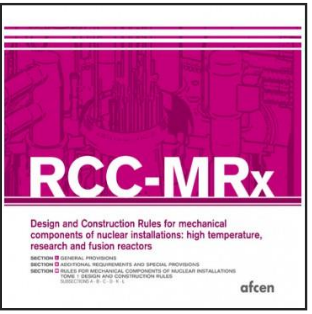
Specific Design rules

- According to the observation of damage modes under irradiation : toughness/ductility loss of materials
- Description/Introduction of « new » damage modes : P type damage are fully concerned

Specific Materials Data including irradiation effects, in the range of the operating parameters of the application

- in RCC-MRx : Stainless Steels, Aluminium alloys, Zirconium alloys

Connection between environment, materials and nuclear codes
b. Example



Consideration of Irradiation effects in RCC-MRx

A3.GEN.41 QUANTIFICATION OF IRRADIATION

A3.GEN.411 NON ALLOY AND LOW ALLOY STEELS

Irradiation damage is expressed as irradiation flux in fast neutrons E>1MeV per cm^2. Fast fluence Φ_{ra} (n_{ra} / cm^2) can be deduced by integration over time.

A3.GEN.412 HIGH ALLOY STEELS (NOT SUPPLIED)

A3.GEN.413 AUSTENITIC STAINLESS STEELS

Irradiation damage D is expressed using the displacements per atoms (dpa) NRT as defined by M.J. Norgett, M.T. Robinson and I.M. Torrens.

The experimental validation domain for the data provided in appendices **A3.1S**, **A3.3S** and **A3.4S** corresponds to:

- Total fluence (n/cm²): $9x10^{19}$ – $3x10^{23}$
- Fast fluence E > 0.1MeV (n/cm²): $3x10^{19}$ – $3x10^{23}$
- Produced Helium (appm): 10 – 6000
- Temperature (°C): 25 – 575

The experimental validation domain for the data provided in appendices **A3.7S** corresponds to:

- Fast fluence E > 0.1MeV (n/cm²): $2x10^{21}$ – $3x10^{23}$
- Produced Helium (appm): 20 – 6000
- Temperature (°C): 25 – 560

A3.GEN.414 ALUMINIUM ALLOYS

During projects, it is normal to characterize irradiation by the neutron flux. For aluminum alloys, thermal neutrons should be reviewed. To quantify the effects of irradiation, it was decided to use the % silicon content produced by irradiation because this production, as well as resulting Mg_2Si precipitates, are the key elements in mechanical property changes due to irradiation.

Fluence in conventional thermal neutrons (E = 0.0254eV), corresponding to the most probable neutron energy in water at 20°C, is that which represents the most direct relationship with ^{28}Si atom density created by neutronic capture under ^{27}Al irradiation.

Conclusion

- The consideration of the environment effect on material behaviour is a crucial point for the design of mechanical components dedicated to innovative concept

- The crucial point to be covered is the characterisation for a dedicated use of the coolant effect on material behaviour regarding the rules to be used

- Challenges are here:
  - consideration of corrosion in design codes
  - Introduction of innovative materials, processes required by stringent environments
  - Dedicated parts dealing with in-service monitoring
  - Dedicated rules for non covered effect

Conclusion

- Developments need a strong collaboration between all stakeholders (Scientifics, codes and standards, researchers, industry, manufacturers,…)

- CEN Workshop 64 initiative

Design recommendations (integrated in RPP14 in the 2018 RCC-MRx edition):

« The operator (Prime Contractor) should follow the recommendations hereafter in order to insure structural integrity under operating conditions (mainly coolant chemistry):

- The chosen material, in the chemistry controlled coolant, has the same behavior as in air except for the depletion of the corrosion allowance,
- All failure modes inside or outside of the design Code shall be identified and addressed,
- Flaws, local corrosion and local thinning will be detected before defects become critical, assuming a limited corrosion speed,
- The requested coolant parameters (composition, pressure, temperature, circulation speed…) will be satisfied all over the systems,
- Failure of the chemistry control system that could cause high speed corrosion is detected and the grace time is sufficient to take corrective action.”

CWA 17377
Design and Construction Codes for Gen II to IV nuclear facilities, CEN Workshop Agreement

THANKS FOR YOUR ATTENTION

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CEA Saclay

DES/ISAS/DM2S/SEMT/LISN