JULES HOROWITZ REACTOR: RCC-MRx[1] APPLICABILITY FOR THE DESIGN PHASE OF EXPERIMENTAL DEVICES.

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Abstract.

The Jules Horowitz Reactor (JHR), currently being built at the CEA2/Cadarache in the south of France, will be a Material Testing Reactor (MTR) designed to perform irradiation experiments while complying with today's safety, quality and regulatory requirements. This paper introduces the fundamentals of the RCC-MRx[1], technical references and rules for designing, manufacturing & controlling of mechanical components for the JHR.

The RCC-MRx defines the rules and the recommendations for all the mechanical equipments, which will be used in the JHR, even the experimental devices which will have a safety and reliability functions. These rules must be applied, in particular, during the process of mechanical design and calculations. They are depending of the type of equipment (containment, structures, pumps, valves, etc.) and they are proportional of the safety/reliability levels defined by the safety studies.

1. General introduction

This paper describes the applicability of the RCC-MRx rules within the instructions for use, the input data, the general analysis for mechanical calculations and the criteria verifications. This process is illustrated by applications focused on experimental devices (presently) in development.

2. RCC-MRx introduction

In 1980, the AFCEN (French Association for Design and Construction Rules for Nuclear Island Components) was founded to define the rules for the design and the construction for mechanical components of nuclear islands. CEA joins AFCEN since 2009.

The purpose of the Association is, in particular, to:

- ✓ draw up detailed and practical rules for design, manufacture, installation, commissioning and in-service inspection of components for nuclear islands used for power generating stations,
- ✓ revise such rules on the basis of experience, technological advances and changes in regulatory requirements,
- ✓ publish such rules or revisions thereto.

The design and construction rules for mechanical components of nuclear installations (RCC Codes) published by AFCEN primarily apply to safety class components. These Codes are used as a basis for contractual relations between Client and Supplier, in which case they shall be accompanied by a list of components to which they shall be applied.

In particularly RCC-MRx, developed especially for Sodium Fast Reactors (SFR), Fusion Reactors (FR-ITER) and Research Reactors (RR) like the Jules Horowitz Reactor (JHR), will be used for the irradiation devices on the JHR

2.1. General plan

The code is split in three main sections. The first section is introducing the using methodology and defines how to manage the rules. The main subjects of the chapter are the quality and management systems during the design and the manufacturing of the equipment. The section make also the link to the other sections with the “entrance keys” which are described in § 2.2.

The second section approaches some specific points linked with specificities of the French or European regulations like the directive for nuclear pressured equipment (ESPN). This chapter introduces also the use of some European Standards for component with low safety level.

The third section is the main body of the code, with all the technical rules for the design and the manufacturing of the equipment. This section is split in two different parts:

- ✓ The design process: this part contains all the requirements and rules for the design and for the dimensioning of the equipment. This process is the main subject of this paper to understand the methodology through examples.
- ✓ The manufacturing aspects: This part contains the requirements linked with the material procurement (supplying), the welding aspects (production and controls) and applicable rules during the manufacturing like the cleanliness.

2.2. Classes and entrance keys

The code could be considered like a table with multiple-entry, named keys. These keys are depending of the equipment and the safety issues (based on the safety studies).

- ✓ *Key 1.* This key is applicable to define if the concern equipment or facility is:
  - components of nuclear reactor and its auxiliary systems,
  - or examination, handling or drive mechanisms,
  - or components of irradiation devices.

- ✓ *Key 2.* This key gives the required RCC-MRx class:
  - Class N1Rx,
  - Class N2Rx,
  - Class N3Rx.

For these classified components, the relations, between “Safety Classes” and “RCC-MRx classes” that must be applied, are defined before the application of this Code by the safety studies. Generally, a direct link is applicable like this: Safety class N1 = RCC-MRx class N1.

- ✓ *Key 3.* This key indicates the type of component to which the component is attached:
  - vessels, tanks, containers,
  - pumps,
  - valves,
  - piping,

- bellows,
- box structures,
- heat exchangers.

✓ *Keys 4, 5 and 6.* These keys indicate:
- whether "Catalogue Component" or not, for irradiation devices, class 3 components of nuclear reactor and its auxiliary systems,
- whether component is subjected to Pressure Equipment Regulations applicable in France,
- whether applicable European standards are used for class 3 components.

2.3. Calculations / Analysis rules

When the keys are defined, the design phase can start with the applicable chapters.
The code makes the link between the input data, like the operating conditions of the component and the analysis which must be used. It exists two types of analysis, the general one give for all components and specific analysis for component listed in key 3.
The analysis is concluding with the validation of the criteria defined in the rules, depending of these input data. These links between the criteria and the input data could be sum up like this:

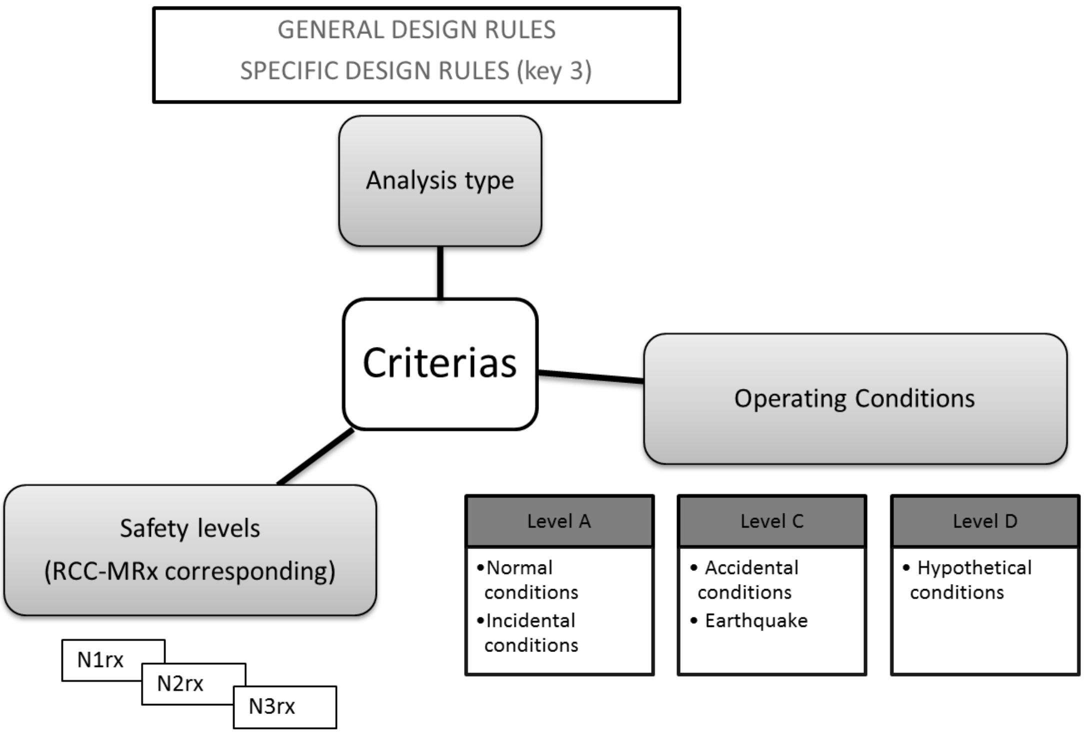

FIG. 1. Links between MRx Criterias and safety studies (levels and conditions)

Note: Generally during the design with these chapters of the code, the requirements, depending especially of the Rx class. The level of requirements is proportional to the level of class and, for the design phase, could be sum up like this:

$$N1 \approx N2 \geq N3$$

Three methods of analysis are acceptable in defining the significant quantities used in the criteria:

- ✓ elastic analysis (used the main time),
- ✓ inelastic analysis,
- ✓ experimental analysis.

The aim of the design (dimensioning) rules is used to define sufficient safety margins against damages like:

- ✓ Prevention of "Type P" damages - damage which can result of a steadily and regularly increasing loading or a constant loading = pressure, own weight, etc, at a mechanical structure,
- ✓ Prevention of "Type S" damages - damage can only result of a repetitive loadings = thermal loads (cycling), vibrations,
- ✓ Buckling,
- ✓ Fast fracture.

The final input data is used to determine the level of criteria to apply in regards at the different working conditions. The working conditions are determined by the safety analysis with 4 levels of importance: normal conditions, incidental conditions, accidental conditions and hypothetical conditions.

The first two are verified with a level A criteria, the accidental conditions with the level C and the hypothetical conditions with the level D. Mechanically, the difference between the criteria is :

- ✓ Criteria level A → only elastic deformation with sufficient margins with the limit of the elastic deformation of the material considered.
- ✓ Criteria level C → only elastic deformation with fewer margins with the limit of the elastic deformation.
- ✓ Criteria level D → margins with the limit of the plastic deformation.

Note: in JHR facility, the earthquake is defined like accidental conditions, the calculations must verify the level C of criteria.

2.4. Manufacturing issues

The manufacturing aspects are not the subject of this paper but it is important to precise this subject is developed in the code with specific items like material procurement, welding process, cleanliness aspects and controls, which are closely interdependent with the design phase.

These items could have a significant influence on the design, so the designer must be taking account these chapters during the design phase even if it is applicable only during the manufacturing. For example, the materials supplies involve requirements (chemical and mechanical requirements) to be in compliance with to the design phase. Also it can be noted, for manufactured products (serial production), it is more complicated to comply with the rules of the code.

3. Applicability for irradiation devices*

3.1 General analysis

The first step of the design for an irradiation device is to use the entrance key 1 for an irradiation device and define the type of component for specific rules. Generally for the analysis (design), this chapter sends to the general analysis for reactor component.

Note: the difference for an irradiation device is located in some particularity like small pipes and components for example, because it is not use in the reactor main facility.

** The irradiation device or experimental device is the equipment or the facility used to make some experiences (fuel, material, safety, isotopes) in the reactor core or reflector. These devices are design by the CEA.*

3.2 Materials

Many materials are referenced in the code with all the properties of the material to make the different analysis required. These properties come from experimental tests or from international standards if the commission has validated the values. The main materials are especially stainless steel alloys, aluminum and zircaloy.

The material, which is referenced in the code, must be privileged for the design of the device. Other material was not avoided, but the design team should justify the use and the conservative aspect of the material data used.

3.3 Applications

3.3.1 Field of application

To illustrate the process of the using of the code, some examples are useful. The first one is the MOLY facility**, which the status is given by the paper reference [3].

*** The Moly facility is composed of two main parts:*
- ✓ *the in pile part in the reactor pool, which includes the four Moly devices and the movable system,*
- ✓ *the out of pile part composed of the cubicle cooling circuit.*

The Main entrance keys for the in pile part of the Moly facility:

- ✓ Key 1: components of irradiation devices.
- ✓ Key 2 : class N2rx
- ✓ Key 3 : vessel or box structure

Particularity for MOLY device, the main parts are in aluminium for neutron performances.
When the material is defined, we must verify in the normal conditions and during the life of the equipment (with a percentage of accidental conditions) if the parts are determined in :

- ✓ Irradiation negligible or significant,
- ✓ Creep negligible or significant.

The code give material properties for some material (the properties must be available), it's the case for the aluminium 6061 T6 and stainless-steel like X2CrNiMo17-12-2, which are used for the JHR reactor or for PWR.

The first step defines the irradiation "area" applicable for the different components. The following figures illustrate two allowable areas: negligible irradiation and non-negligible irradiation. In negligible irradiation, the calculations don't take into account the impact of the irradiation on the materials. In non-negligible (or significant) irradiation area, the analysis must be taking into account the material data after irradiation. Above the maximum irradiation limit, rules are not available.

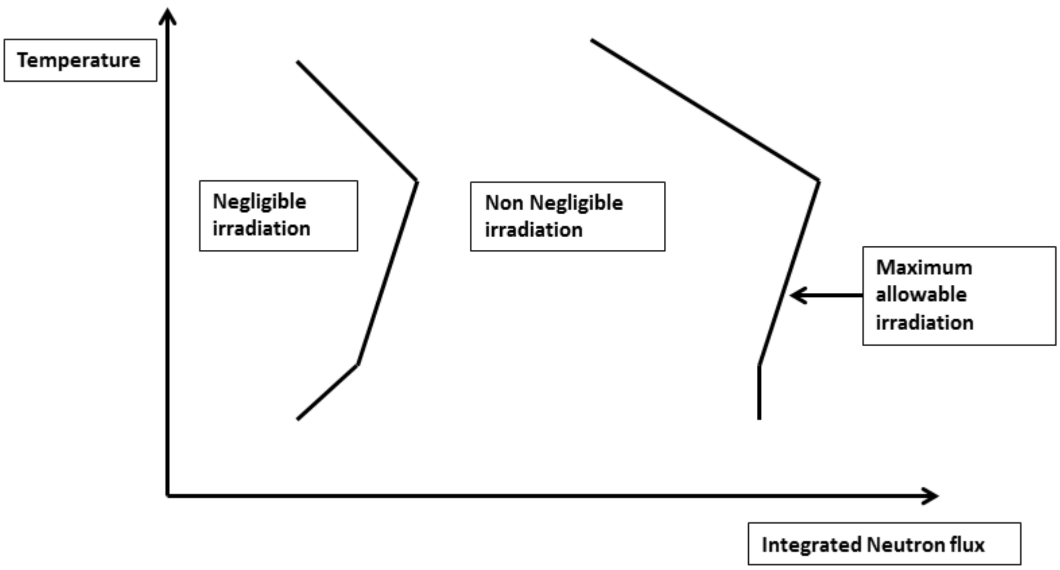

FIG. 2. Example of irradiation limits depending of the temperature and the neutron flux integrated on the operating time

In application for the MOLY in-pile facility, with the flux from the core and the operating time defined, the calculation illustrates the area in non-negligible irradiation (grey area in the figure 3).The analysis concludes that only the device and a part of the displacement system are in significant irradiation. The impact of irradiation on the material (mechanical performances, swelling) is taking into account only on these parts. The rest of the facility could be analyses without irradiation issues.

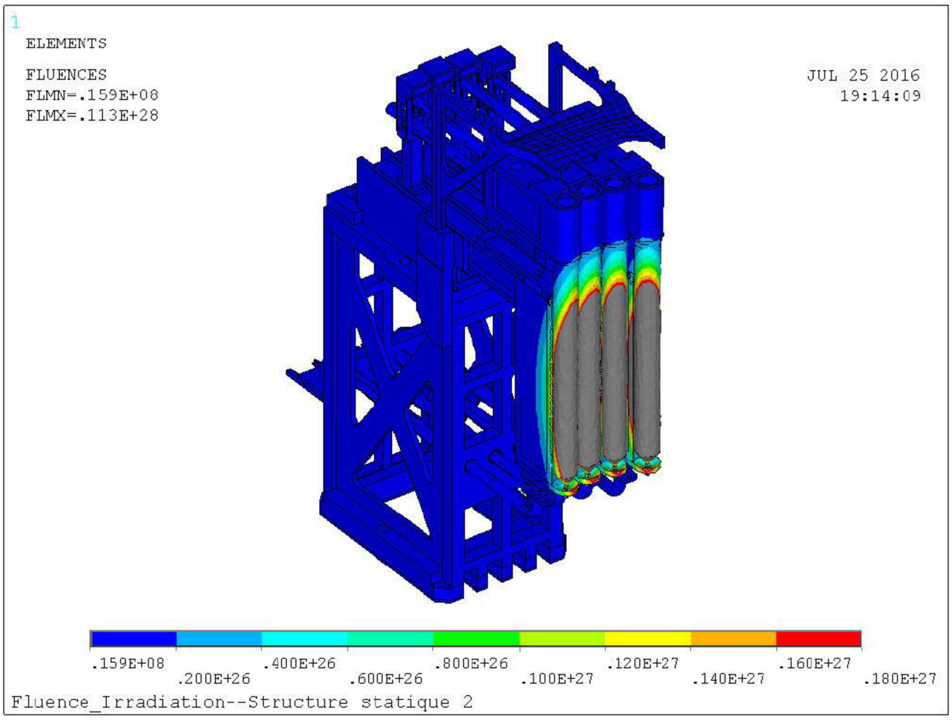

FIG. 3. Irradiation map from calculation on the MOLY facility

After irradiation, the thermal limits must be verified. For the device in example, which is in significant irradiation, the choice is to avoid creep regardless the operating time. Indeed, if the creep is significant, the analysis rules for significant irradiation are not all allowable for the aluminum.

So in respect of the next figure, the device must be in negligible creep regardless of the operating time. This need require the limitation of the temperature of each component of the device under the "creep temperature"***.

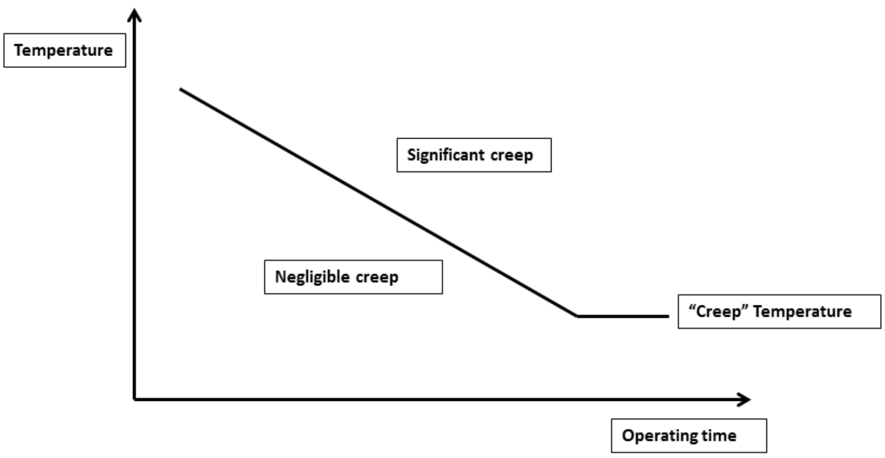

FIG. 4. Example of creep limit depending of the temperature and the operating time

For the components which the temperature cannot be verified under the "creep temperature", the operating time should be reduced and the part replaced.

**** The "creep" temperature is the temperature limit under which the operating time could be to infinity.*

3.3.2 Mechanical calculations

For the mechanical structure in negligible irradiation, the conservative calculation is generally the seismic load. The first step is to do the modal analysis of the facility to determine the Eigen frequencies to compare to the seismic spectrum on the JHR. The high frequencies are selected to avoid the acceleration spike < 5Hz for horizontal spectrum.
For the seismic calculation, two types of analyses are used “pseudo-static approach” or “spectral analysis”. The second one is preferable for complex system but the first one could be used for “mono-modal” structure.

The Stresses in the main parts are determined with finite elements software, for each mode or combination of several mode.

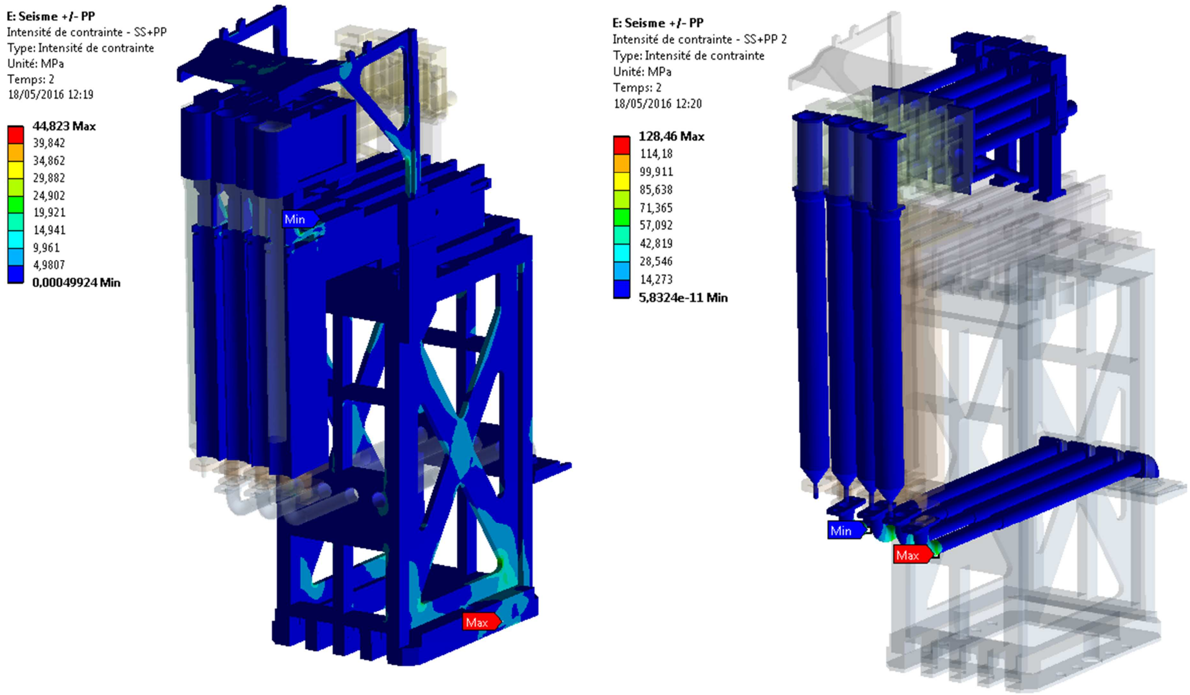

FIG. 5. Results of spectral analysis

On the local level (regarding the high strain areas), the linearization of the stresses is needed to determine independently bending stress and membrane stress. Each value must be compared with the RCC-MRx criteria depending of the working conditions. For example, C-level criteria are used for the seismic load.

$$\sigma_m(P) \leq S_c$$
$$\sigma_m(P) + \sigma_b(P) \leq 1{,}5xS_c$$

Note: with m for membrane, b for bending and Sc for mechanical limit of the material for C-level criteria.

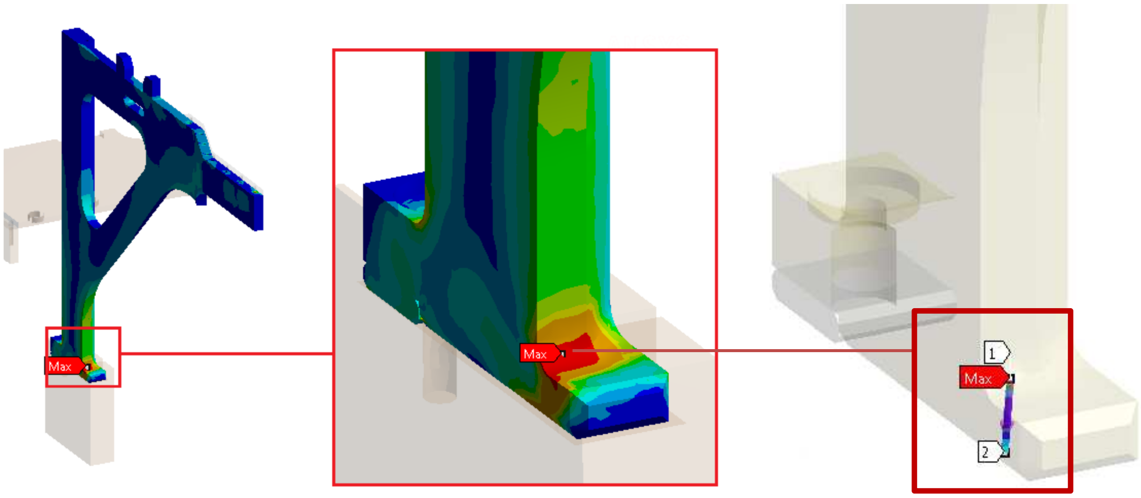

FIG. 6. Stresses analyses with stress linearization in thickness (illustration)

3.3.3 Thermomechanical calculations

For the calculations and the results, the seismic loading is not necessary the conservative dimensioning for all the components. Indeed, some mechanical or thermal loadings, considered in incidental conditions (with level A criteria), could be more conservative. For the Moly application, the thermal conditions, in regards of the power of targets, are more important and are considered in normal conditions and in incidental conditions (overpower). To consider the impact of the thermal loading, the stresses must be calculated as follows : the total stress is the addition of the primary stress (pressure, own weight) and the secondary stress mainly due to the thermal stress in the component (temperature gradient). The following table illustrates the decomposition of the total stress, useful for the dimensioning:

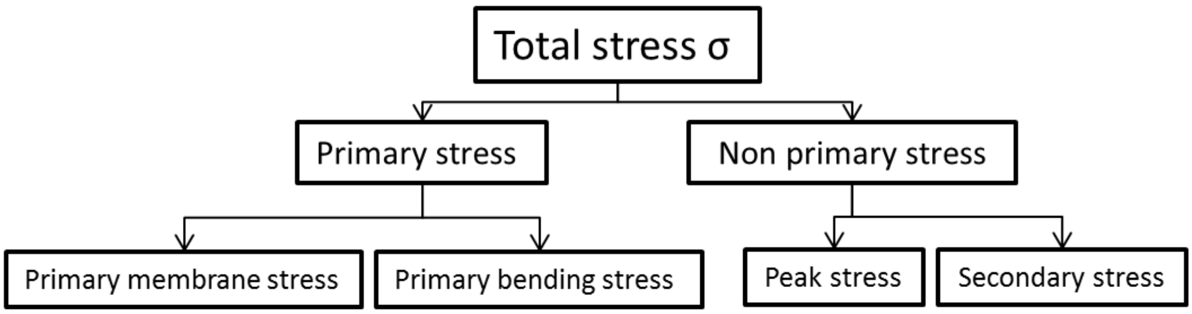

FIG. 7. Classification of stresses for analysis and calculations

The methodology of the analysis is to abstract primary stress and secondary stress separately. The designer has to do two different analyses. The first one is the mechanical calculation (cf. § 3.3.2) with the primary loads like pressure, weight and seismic. The second one is to make a thermomechanical analysis with the thermal loading obtained by a thermal calculation. The stress results of each analysis are compared each one to the RCC-MRx criteria, (primary for the first and secondary for the second) and also by addition together.

The methodology of calculation is sum up in the figure 7.

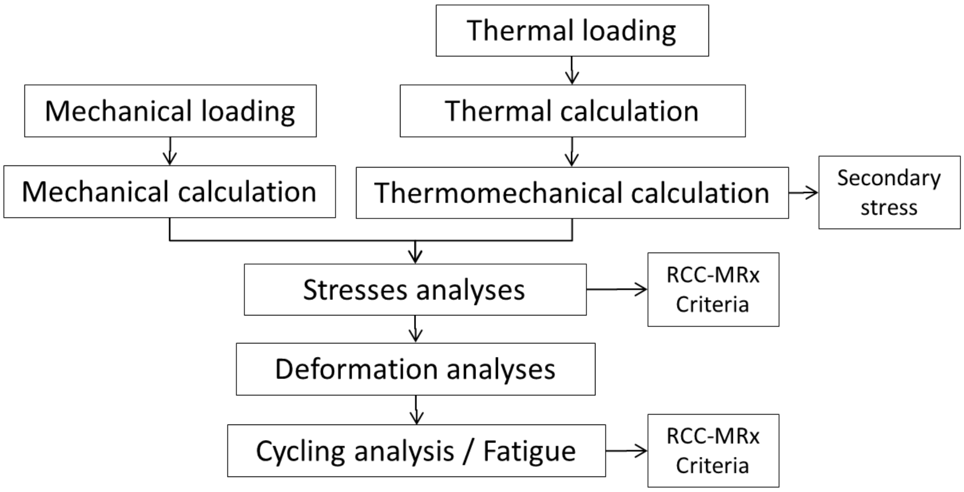

FIG. 8. Methodology of calculation for thermomechanical analysis with fatigue issue

3.3.4 Others calculations

The code gives specific rules depending of the key 3 of the code. These rules are in addition to the general analysis, described previously to take into account the particularity of the equipment, like a pump to complete the design and the criteria. The code gives also some rules for "common" parts like the bolts and for the welds. Some examples are given below:

- The RCC-MRx defines the welds authorized according to the safety level and the type of component (shell, box structure…). Generally for high safety issues and irradiation aspects, only butt welding, full penetration, two sides accessible is authorized. For other welding, for low safety issues, partial penetration or back side-inaccessible are authorized but, in this case, the calculated stresses must be reduced by a safety factor (up to 50 % of decrease). The non-destructive controls are also defined with the recommendation for manufacturing and for ultrasounds and X-Ray controls.

- For the bolted assemblies, the forces and torques are determined with the finite elements calculations. After this action, the analytic determination of stresses in the bolts, nuts and structures to validate bolted assemblies. The values must be comparing to criteria for screw core, screw threads and head.

4. Final Remarks - Conclusions

The RCC-MRx gives many technical rules for the design and the manufacturing of JHR facility and for the experimental devices. These rules provide a shared technical framework with the French safety authorities to work safely for the design, the dimensioning and the manufacturing.

For the studies, the main part of the code is the rules to make the mechanical and the thermomechanical calculations to extract the good stresses. These rules are also adapted to the safety studies and to the type of equipment (pipping, shell, pump…) by providing many criteria adapted to each case.

5. References

[1] Design and Rules for Mechanical Components of Nuclear Facilities (RCC-MRx), AFCEN[2] - v2015.

[2] French Association for Design, Construction, and In Service Inspection Rules for Nuclear Island Components.

[3] MOLY production in the Jules Horowitz Reactor : Capacity and status of the development, 18th IGORR, M. Antony and Al, CEA, France.