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**Titolo**

**Valutazione degli effetti dinamico-strutturali indotti dal fenomeno del "core compaction"**

**Ente emittente** Università di Pisa (CIRTEN)

# PAGINA DI GUARDIA

## Descrittori

**Tipologia del documento:** Rapporto Tecnico

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**Argomenti trattati:** Reattori Nucleari Veloci, Sicurezza nucleare, Analisi incidentale

## Sommario


Lo scopo dell'attività è stato analizzare in dettaglio il Cylindrical Inner Vessel e le componenti più importanti, in particolare i "fuel assemblies"- FAs. A causa dell'elevato onere computazionale legato al dettaglio con il quale è stato realizzato il modello FEM le analisi di transitorio dinamico sono state eseguite su un semi-modello (condizione di simmetria assiale). L'esecuzione delle analisi dinamiche è consistita: 1) Upgrading dei modelli numerici (realizzati mediante l'utilizzo del codice MSC®Marc) sviluppati in maniera preliminare nel corso del PAR2013 con un dettaglio tale da poter rappresentare con maggior accuratezza la propagazione dei carichi dinamici fino ai FAs. 2) Nello studio è stato utilizzato un FRS coerente con l'input sismico usato nel PAR2012. 3) Determinazione delle condizioni al contorno, iniziali e della tipologia di interconnessione delle strutture (vincoli di contatto).4) L'analisi dinamico-strutturali di modelli geometricamente complessi ha previsto l'esecuzione di analisi non lineari. Sono state prese in considerazione le condizioni di contatto che si ritengono possano influenzare il comportamento dinamico delle strutture mediante fenomeni di vibrazione e/o di natura hertziana.
I risultati, in termini di spostamenti, tensioni, e accelerazioni, indotte dalla sollecitazione sismica hanno evidenziato una deformazioni localizzata di aluni FAs, dell'inner vessel e dell'upper plate. L'analisi ha messo in luce le problematiche ancora aperte, i cui aspetti più importanti sono sintetizzabili in: analisi del sistema di bloccaggio dei FAs, dei sub-assembly, influenza delle forze e tipologie di contatto esistenti, delle vibrazioni, e influenza delle variazioni delle proprietà del materiale la variazione radiale e assiale della temperatura.


## Note

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**Autori:**

R. Lo Frano, A. Sanfiorenzo, G. Forasassi, G. Pugliese – UNIPI-CIRTEN


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**DICI**

# Structural-dynamic evaluation of the effects caused by the core compaction

**Authors**

**R. Lo Frano**

**A. Sanfiorenzo**

**G. Forasassi**

**G. Pugliese**

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# Content

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# Summary


Nuclear stability dictates that the geometry of the core be closely controlled at all times.

This means that a core deformation, caused by dynamic condition like the seismic motion, could determine, to a large or small extent, a radial inward displacement, and be accompanied by a possible insertion of reactivity.

This safety issues is therefore of meaningful importance particularly for the next generation LMRs core design because of high inertia of the metal coolant.

In the PAR 2012-2014 the deformations of core (and restraint system) geometry caused by dynamic perturbations has been investigated. In particular in doing that it was referred to the Advanced Lead Fast Reactor European Demonstrator - ALFRED (300 MWth).

After a revision of the state of art, found to be lack of such a type of study, an analytical and numerical investigation was carried out.

The core compaction issues were treated by means of a deterministic approach;. In this framework numerical analyses have been performed by the finite element MSC©Marc code to simulate the mechanical behaviour of the overall reactor system and, specifically, of the most important components constituting the inner vessel, such as the lower and upper grid, the inner vessel, the support skirt, the assemblies, etc.

Due to the complexity of modelling and especially due to the limitation of calculation resources available to solve such a type of complex phenomenon, the substructure approach was adopted.

A special attention, of course, was paid to those solicitations that could deform the behaviour of core system and of each fuel assembly: therefore the propagation of seismic loading from the ground to the fuel elements was analysed.

Indeed, suitable boundary and initial conditions, such as that one related to the fuel mass, the restrictions imposed by the geometrical in-structures connections and restraints, etc. have been assumed to adequately simulate the dynamic response of structures. To characterize the interaction among the components, surface-to-surface contact condition has been implemented along with the “deformable body” one.

In addition, the mesh was designed to be appropriate for the purpose of the analysis; due to the nature of the problem it is significantly finer, with a more refinement at areas where high stress gradients or large deformation gradients are expected.

The results indicate that stresses overcome the yielding limit particularly in the upper part of the inner vessel, close to the flange support, in the upper grid and in the annular area neighbouring the nozzle penetration. In this latter case it was observed that the section ovalizes, highlighting therefore that a circumferential buckling is occurring. All these zones plasticize largely as an obvious consequence of the prolonged stress state without any cycling (dynamic) relaxation.

The assemblies undergo to a bending deformation that looks like the beam inflexion type. This is a consequence of length of the elements, the larger deformation of which is localized at half height of the structures.

The displacement varies along the vertical axis (direction of main flexibility of structure) reaching at some instant a maximum value of about 9 cm.

# 1. Introduction

One of the objectives of advanced liquid metal reactors (LMR) is to maximize the safety of reactors in any design and (beyond) design condition for all plants lifetime, so LMR designs are expected to significantly increase the safety [1] [2].

As indicated in the PAR 2012-13, to attain this intent becomes important also the knowledge of the core behaviour, especially in deformed configuration, because of its safety relevant aspects, particularly related to the reactivity excursion, fuel life prediction, etc.

Nuclear stability considerations dictate that the geometry of the core be closely controlled at all times: therefore any modification of it must be predictable, compatible with the requirements of the interfacing reactor systems and safely manageable by means of (intrinsic and engineered) control mechanisms. The compaction of core assemblies is so a crucial aspect of the core system design because of the consequences and effects (e.g. loss of flow, etc.) on the net reactivity, especially, during transient conditions caused by external events [3][4]. In fact, as a result of a ground motion, the core assemblies may distort in the axial (along the height), radial and circumferential directions, as shown in Figure 1: generally the deformation is radially inward (flexion + constraint on pads), of small or large extent.

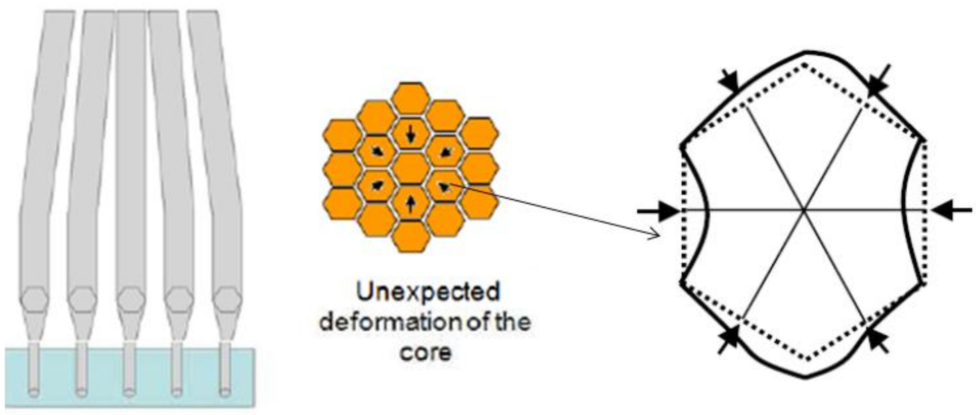



Figure 1 – Scheme of core compaction.

It is notably necessary to ensure that [2]:

- in any situation, a large compaction of the fissile material must be prevented/avoided. It shall be demonstrated that the reactor must safely shut down without any insertion problem of control rods.

- Core cooling capacity of the core assemblies must be demonstrated under dynamic loading.
- Material containment is assured, particularly during earthquake;
- it must be demonstrated that the fuel pins are not damaged [4].

In consideration of that, the dynamic behaviour of the core assemblies [5] [6] [7] (and restraint system) geometry of the ALFRED reactor is investigated in this study with respect to seismic event. This assessment will give information for the safety control of the reactor and the upgrading of the core region design.

## 1.1. Problems to be addressed in the core compaction

As indicated in [3] the several sources of dynamic loading that could determine the core compaction may be originated by the internal or external accidents. In this latter case the most important source of solicitation  is the earthquake event. As for the Fast Reactor concerns, major threats are related/arise from the large amount of metal coolant retained in the vessel pool: the inertia force caused by the seismic solicitation impacting on the internal structures might deform at less or large extent them. As a consequence of that a (partial) loss of flow (LOF) from fuel sub-channels, nominally may occur determining possibly an increase of the fission rates (notably in the “even” nuclides, having a threshold fission cross section) and a reduction of the capture rates. A rapid insertion of reactivity may occur determining instability of reactor.

Since it is not possible to exclude core compaction by design, it becomes important to limit the compaction, through passive, simple and reliable means, so that the associated reactivity insertion can be safely managed. The three fundamental safety functions to take into account in core design are [3] [4][7]:

- Reactivity control: it must be demonstrated that under any kind of possible dynamic loading the core volume will not be decreased above a given limit. To limit the possible insertion of reactivity, relative movements between fissile subassemblies and absorber rods should be limited, and fuel pins break prevented. Moreover, it shall be demonstrated that the control rods are able to fall within the core during a dynamic excitation;
- Removal of heat from the core: under dynamic loading, it must be demonstrated that the cooling capacity of the assemblies is not hindered;

- Radioactive material containment: mainly under seismic loading, it must be demonstrated that the fuel pins are not damaged to a level at which significant radioactive release from the core to the primary coolant could occur.

# 2. CORE COMPACTION ANALYSIS

## 2.1. System design

Figure 2 illustrates the configuration and location of major components in the ALFRED reactor. The Reactor Vessel (RV) adopts a compact pool type solution with a simplified and innovative primary circuit characterized by the integration of all the internals, such as the Steam Generators (SGs), Primary Pumps (PPs), etc. The primary system design temperature ranges between 400°C and 480°C, while the design pressure is about 1 bar (primary system not pressurized). The operational condition range of the secondary side, entering the RV through the SG tubes, is between 335°C and 450°C at about 18 MPa.

The reactor vessel, having 8 m internal diameter, the skirt and SGs outlet are made of SA 240 316LN, whereas SGs support box and the base plate are made of SA 516 Gr 70 carbon steel [7].

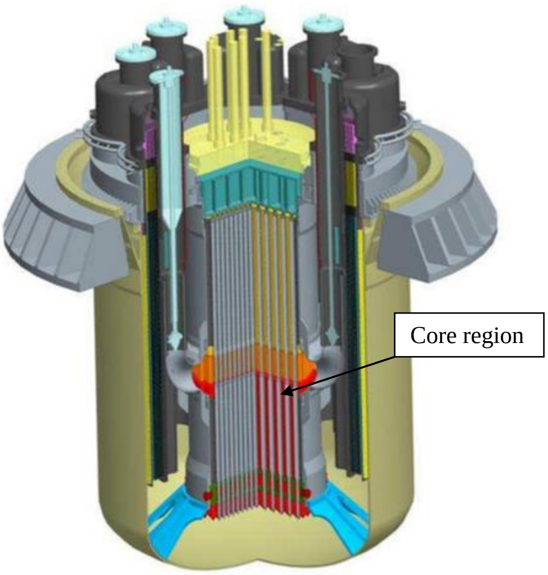



Figure 2 – Advanced Lead-cooled Fast Reactor European Demonstrator - ALFRED scheme [3].

Core assemblies are axially positioned and supported by upper and lower core support plates.

The bottom core diagrid is constituted by two horizontal perforated plates connected and stiffened by vertical spokes; plates holes are the housing of FAs foots while the plates distance allows guaranteeing the verticality of FAs.

The upper plate seems a box structure as the lower grid but more stiff. It has the function to hold down the Fuel Assemblies during the reactor operation. Furthermore, upper restraints

allow to maintain the vertical position and guaranteeing the correct positioning and insertion of the control and safety rods systems.
Lateral supports are also provided at two elevations by the core barrel.

## 2.2. ALFRED core design

The reactor core is made of 171 Fuel Assemblies surrounded by a shroud of 108 Dummy Elements (Figure 3), in which 16 control elements are included [12].
Figure 3 shows a planar view of the arrangement of assemblies of the ALFRED core. The active zone of the Fuel Assembly is yet defined and each hexagonal FA contains 127 pins; the main dimensions of which are reported in Figure 4.

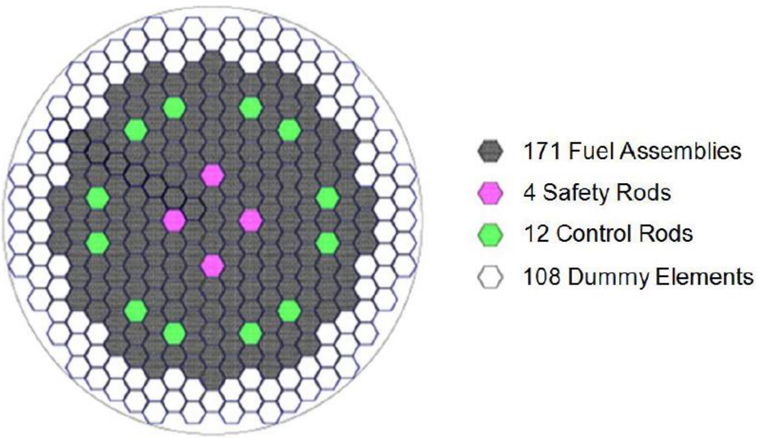
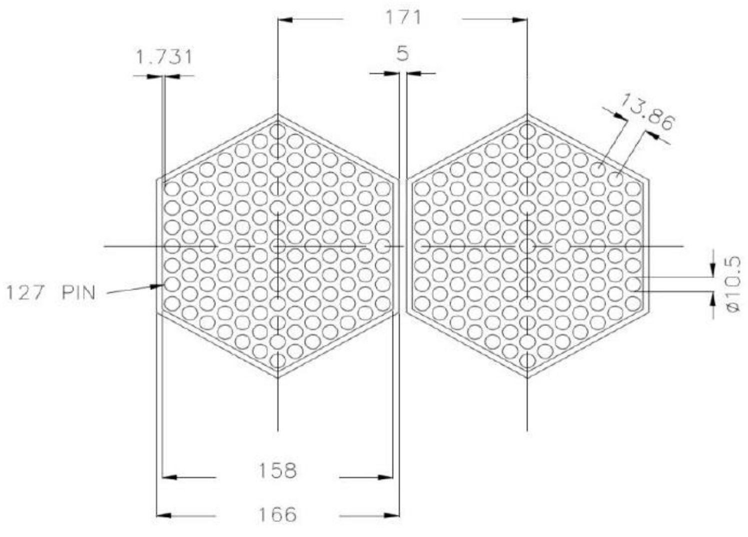



Figure 3 – ALFRED core configuration.

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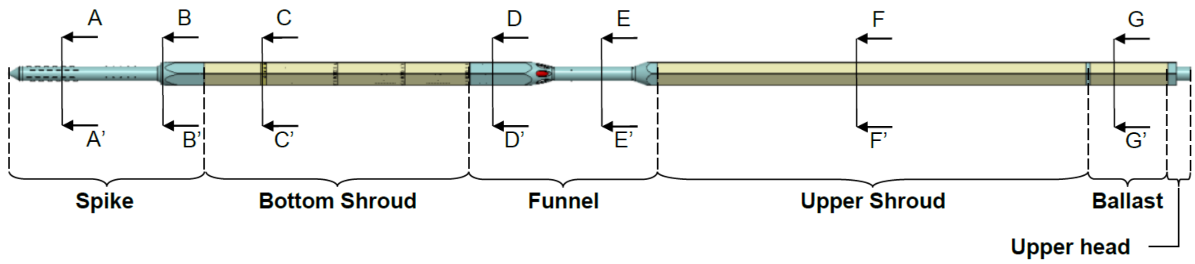



(b)

Figure 4 – Hexagonal FA geometry (the dimensions are in mm) (a), and an overview of the element parts (b) [12].

Moreover as indicated in [12], the FA structure of ALFRED is made up of the following parts (from the bottom to the top):

- The Spike, to guarantee the lead flow inlet both into the FA sub-channels and into the by-pass region between adjacent FAs.
- The Bottom Shroud, in which the core active zone is included.
- The Funnel, in correspondence of the outlet region.
- The Upper Shroud, above the outlet region, allows overcoming the lead free level.
- The Ballast, in the upper zone, maintains the FAs in position during the refuelling operation.
- The Upper Head allows to guarantee the correct position during normal operating condition, and the connection of FAs to the refuelling machine during refuelling operations.

## 2.3.Strategy to core compaction analysis

In the PAR 2012 and PAR 2013, with reference to the earthquake event, a preliminary methodology capable to simulate the dynamic behaviour of the inner vessel/core region was set up along with a preliminary evaluation of the effects caused by the core compaction. In the methodological approach the following several steps have been identified:

1. Definition of the peak ground acceleration of the input earthquake, since effective isolation characteristics would be obtained by the chosen artificial seismic waves. The input PGA was consistent with requirements requested by the NRC RG 1.60 Rev. 1 and 2. The seismic solicitation in terms of time histories of accelerations are showed in Figure 5.

2. Definition of type and number of isolators based on a fixed frequency. To this purpose HDRB isolators type (2 s isolation period), have been considered and represented by means of an iso-elastic approach.
3. Seismic analysis of the isolated reactor building (RB) of LMR, having 44 m diameter, 48.5 m height and about 1 m wall thickness. The layout considered in this assessment was the same proposed for the ELSY project since the design of Alfred has not to date involved the part relating to the building of the reactor.
4. Dynamic analysis of the reactor vessel including some simplified components (Figure 6). The dynamic behaviour is of course the result of the transmission of dynamic loads propagated through the RB.
5. Analysis of the global dynamic response of the inner cylindrical vessel (Figure 7).
6. Investigation of dynamic behaviour of fuel assemblies. A detailed model of FAs has been implemented in order to determine the deformation and deflection they undergo under the reference seismic solicitation, that during the propagation from the ground to the upper restraints of IC amplifies along the vertical direction of 40% (Figure 9).

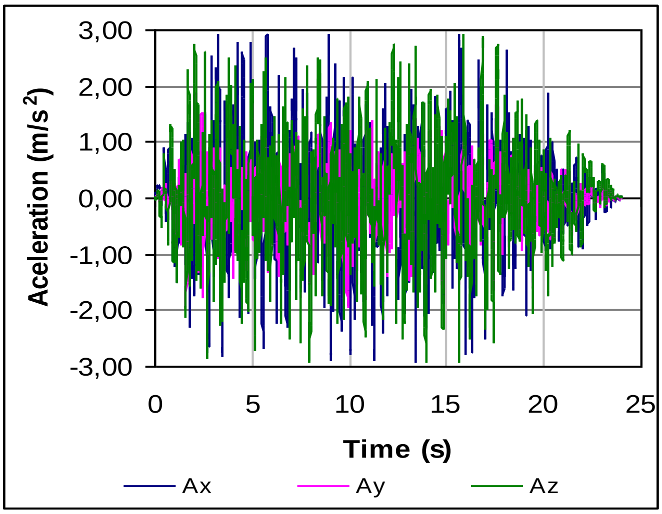



Figure 5 – 0.3 g PGA ATHs ground motion.

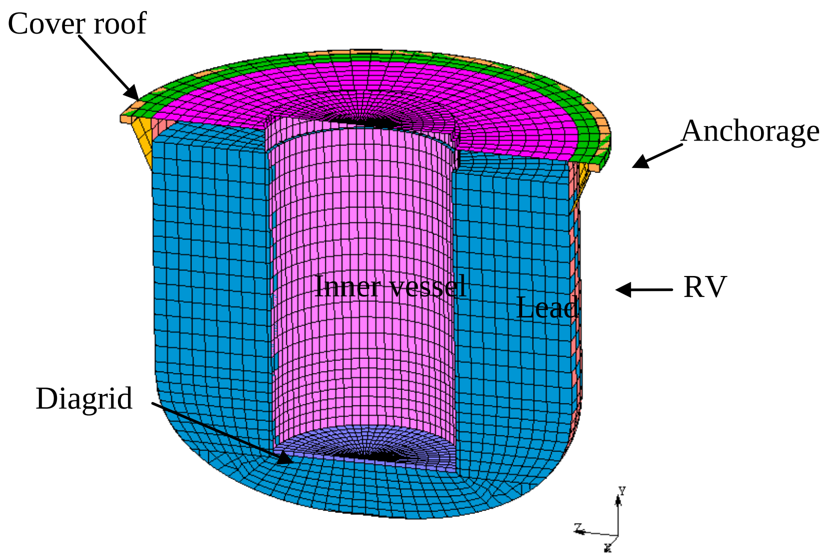



Figure 6 – FEM model of the RV.

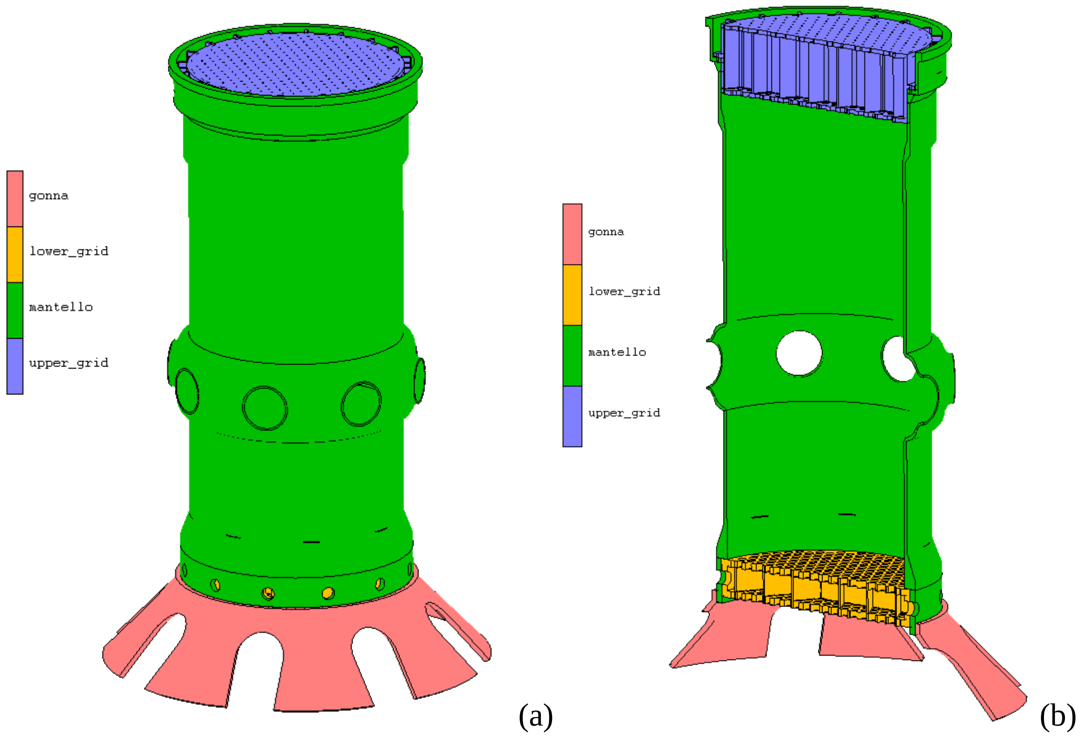



Figure 7 – FEM model of the inner cylindrical vessel: view (a) and vertical section (b).

# 3. Core Compaction Analysis

In respect to the past approach based on the two dimensional modelling [13]÷[20], in this study a 3D modelling was adopted. Therefore to evaluate the effects of the compaction on FAs an adequate 3D solid model including fuel assemblies, screws, upper and bottom plates along with the spacer grid, and IC shell has been set up and implemented.

Because of the geometrical complexity of the structure to represent and considering that some design data are currently missing, some assumptions have been made mainly for what concerned the geometrical shape and restraints characteristics.

Furthermore to reduce the computational costs (more than 4 days calculation in multiprocessor workstation) it was decided to execute the analyses on a symmetric model profiting of the fact that the full model has a double symmetry Figure 8.

Suitable boundary conditions have been imposed: the double symmetry condition was applied at the centre line of the structure along the vertical axis; clamp restraints was instead adopted for the diagrid foots and for the upper part of upper plate and IC shell.

No piping or primary coolant was considered at this stage.

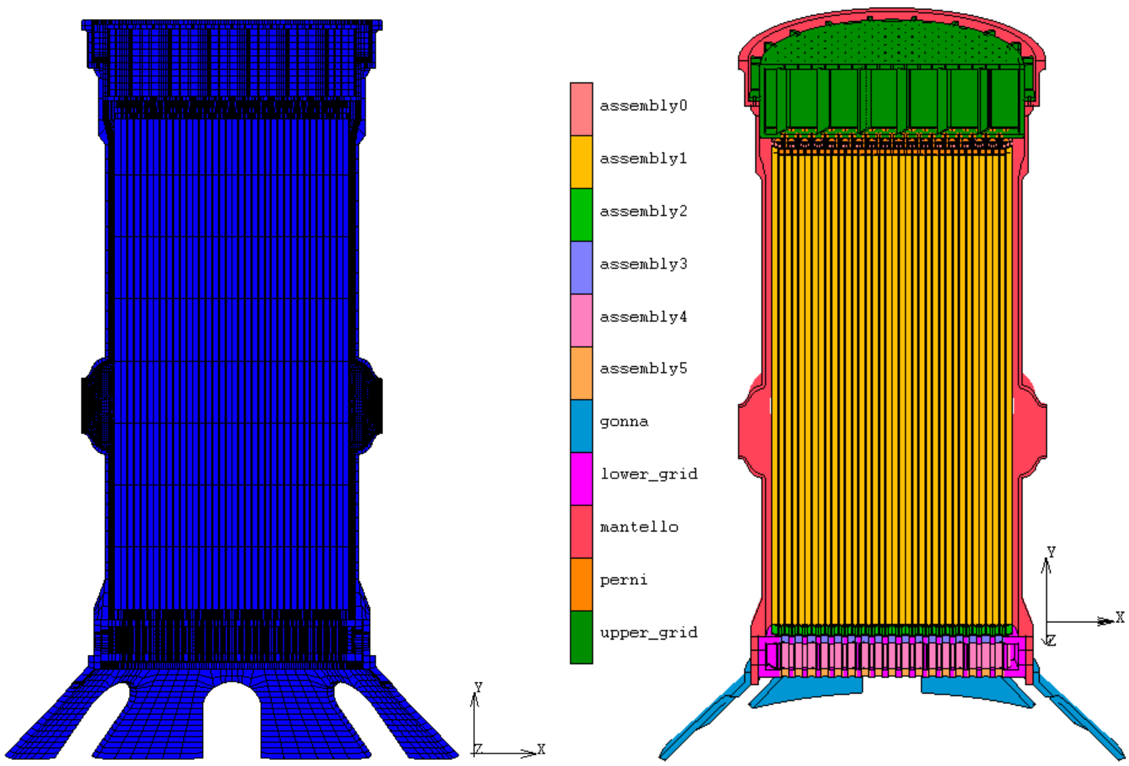



Figure 8 –Model of the inner cylindrical vessel with FAs

The model consists of more than 68.0003-D solid brick. The development and upgrading of the modelling profit of the sensitivity analysis results carried out in Lo Frano, 2014.
In the following a brief description of the model components is given.

## 3.1. Description of components

The lower grid is a 550 mm height cylindrical shell, with 3420 mm external diameter and 100 mm thickness. It was supposed to be made of austenitic stainless steel AISI 304. This component, showed in Figure 9, is enclosed by two identical cylindrical perforated plates, each one 100 mm thick. The distance between the two plates is guaranteed through an internal grid with an hexagonal geometry.
On the lateral surface are obtained eight holes, four of which are used for the insertion of plugs that allow to connect the lower grid to the bottom part of the inner vessel.

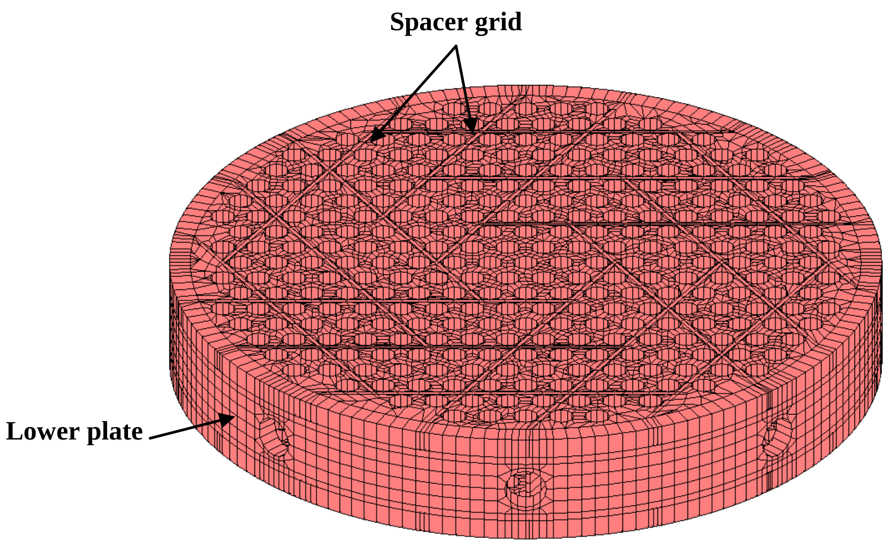



Figure 9 – Details of the lower grid model with plates and spacer grid.

The inner vessel is a cylindrical shell of diameter variable along the overall height.
The main values of the diameter and thickness are, respectively, 3320 mm and 50 mm; the height is 9070 mm. Figure 11 shows the detailed model of the overall inner vessel: its lower portion has a diameter slightly greater than the main value in order to allow the insertion of the lower grid, while in the middle part of this structure it can be seen a further increase in the diameter and thickness due to the presence of eight outlet nozzles.

In this study the piping, connecting the inner vessel, through the nozzles, to the pump are not represented in order to reduce the number of the element of the overall model and subsequently reduce the computational cost of each analysis. In its upper part, finally, is present an inner flange that allows to support the upper grid.

The upper grid (Figure 10) is a 1000 mm high and 60 mm thick cylindrical shell, enclosed at the ends by two perforated cylindrical plates.

The diameter of the holes in the upper plate is 20 mm, while the one of the holes in the lower plate is 90 mm. An inner grid separates the two plates, its geometrical shape is similar to that one of the lower grid.

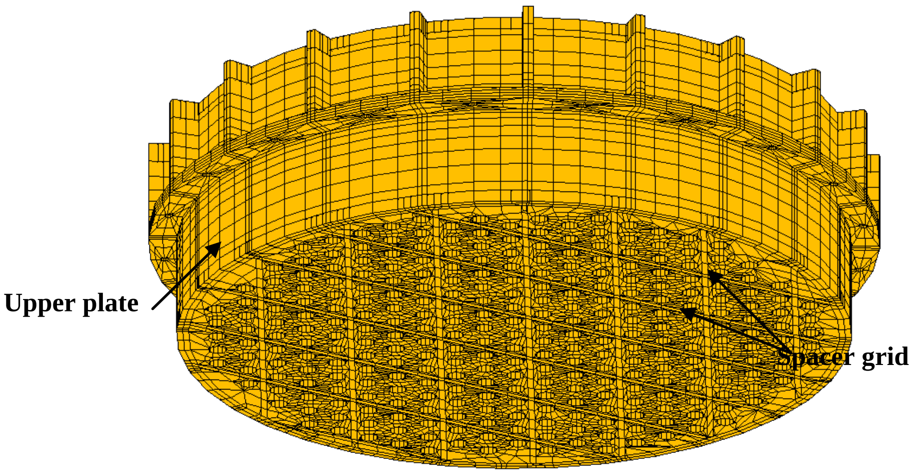



Figure 10 – Details of the upper grid model with plates and spacer grid.

A middle height positioned crown surrounds the upper grid, at the base of the crown twenty holes are obtained for the insertion of the screws used for the connection of the upper grid to the inner vessel.

Like the other components, also the upper grid is assumed to be made of AISI 304 steel.

The upper grid and inner vessel are linked together by means of twenty screws, as it is possible to observe in a detail of the model implemented and shown in Figure 11.

The inner vessel is linked at the bottom of the reactor vessel through the diagrid, which anchors it (in a removable way) on the inner bottom surface of the reactor vessel. The diagrid has a truncated cone profile; the circumferential surface has several openings in order to allow the coolant lead to flow upward.  Both the inner vessel and the support skirt are supposed to be made in AISI 304 steel.

Each <u>fuel assembly</u> has an hexagonal shape which contains 295 total fuel element, as shown in Figure 12. It is 8.15 m long and about 171 mm width. The pitch between two adjacent assembly is 171 mm, while the gap is 5 mm (Figure 12 b). The FAs are also restrained to each other's in order to avoid/limit vibrations. The FAs has been assumed to be made of T91 (yielding value of 375 MPa). The spike (bottom part of the assembly) has 0.115 m diameter. It is inserted for about 1 m into the bottom plate allowing lead to flow into the sub-channels: it restrains FAs to the bottom plate. The ballast, linked to the upper plate, together with the Upper Head represents instead the upper restraints.

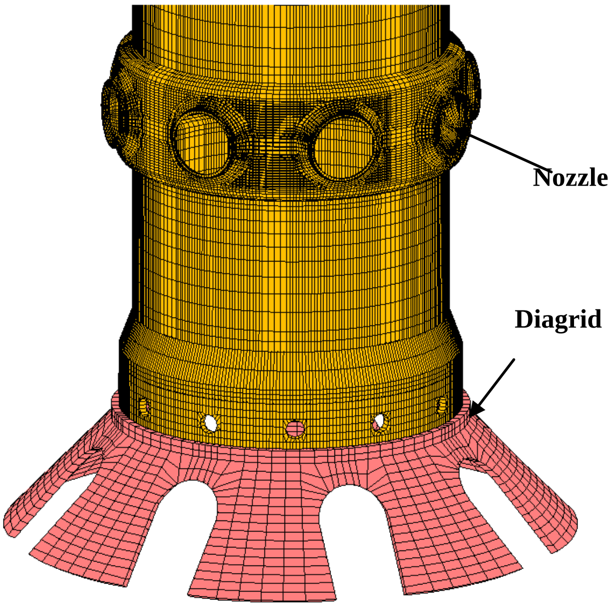
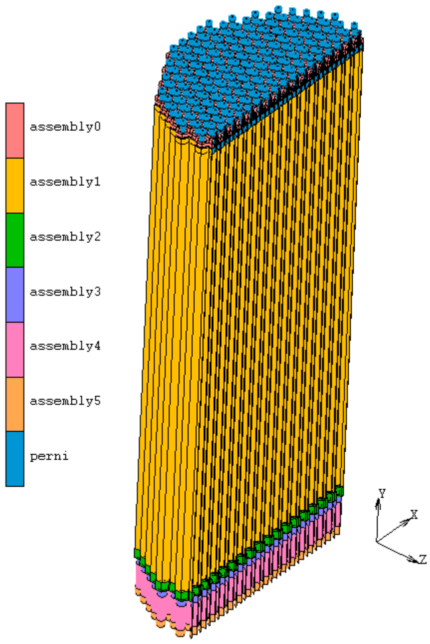



Figure 11 – Details of the bottom part of the inner vessel with lower late and diagrid.

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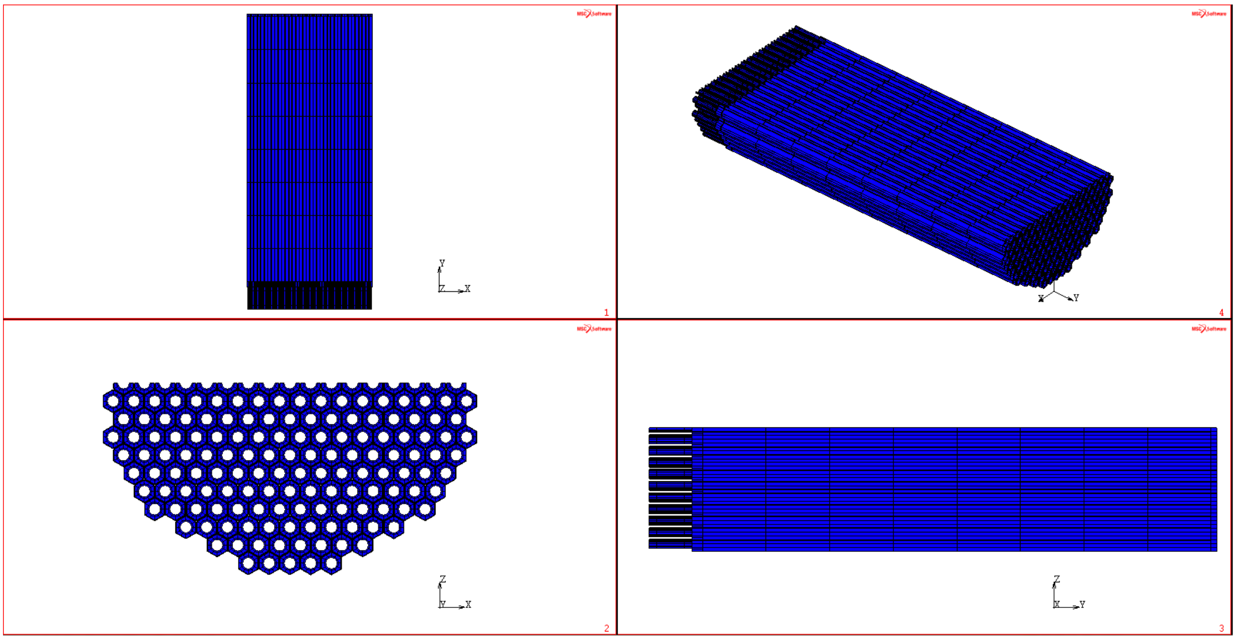
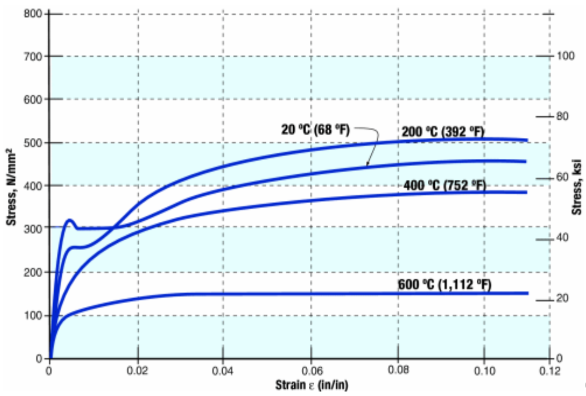


(b)

Figure 12 –Vertical section and orthographic views of the fuel assemblies.

In order to correctly simulate the dynamic behaviour of the structure taking into account the interaction between the different components, single-side contact was also assumed. This was used to easily set the contact type and the contact detection method between all contact body pairs defined in the contact table. A contact table was created so to represent the existing touching at the beginning and during the analysis. The minimum contact distance (below which two bodies get contact) was assumed $10^{-5}$ m.

The mechanical properties adopted are consistent with the operation conditions (1 bar and 480°C): for steel the yielding stress and the Young modulus are calculated accordingly to the correlations of Figure 13.



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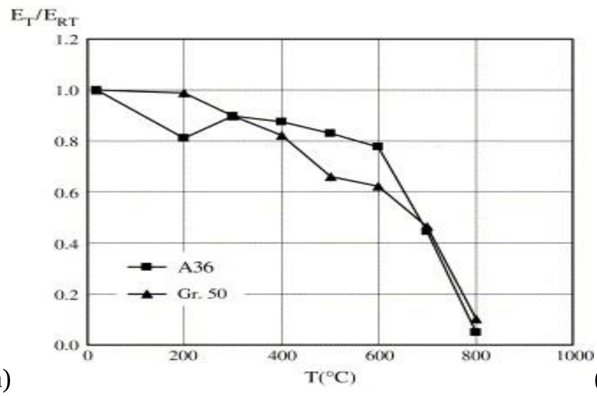


(b)

Figure 13 – Stress-strain curve (a) and Young's modulus (b) vs. temperature.

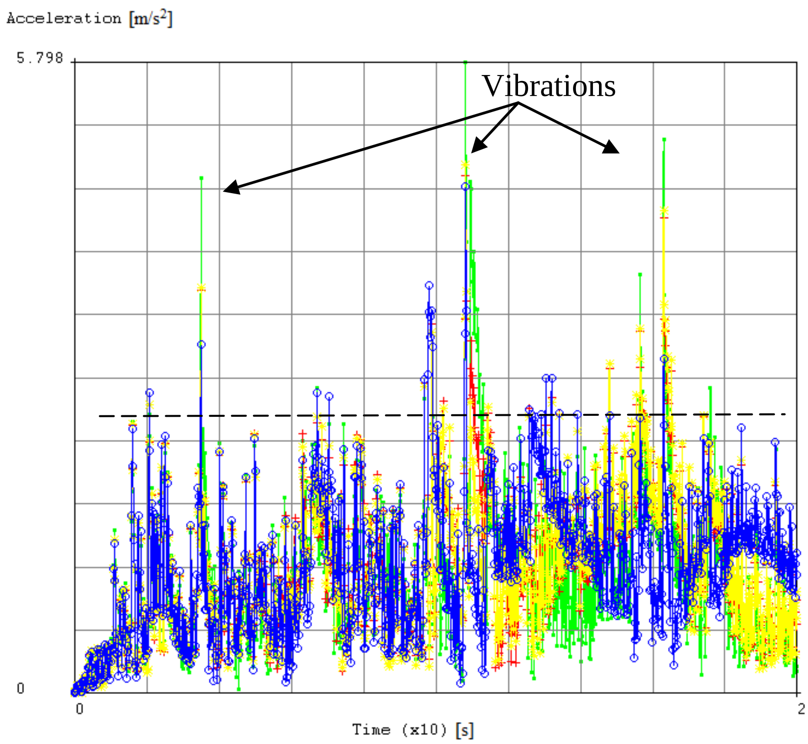
# 4. Discussion of results

In what follows the results obtained are herein presented and discussed.

They are in terms of acceleration, stress and displacement as shown in the diagrams and distribution of Figure 14 ÷ Figure 17: the inward displacement, with respect to the nominal position, heightens the radial deformation resulting in the compaction.

The contact forces determines a change of the compression rigidity of structures, and influences the deformation of the element cross-section and subsequently the stress state in the structures thickness.

The structure, hit by the seismic motion, amplifies the input acceleration (0.21 g and 0.28 g at the upper plate and IC restraints) that reaches 7 $m/s^2$ and 5 7 $m/s^2$ respectively at the radial peripheral and central FAs positioned along x axis (Figure 14). Vibrations also characterises the response of considered structures: high spikes (f > 65 Hz) are also visible in the acceleration time history showed in the Figure 14 below.



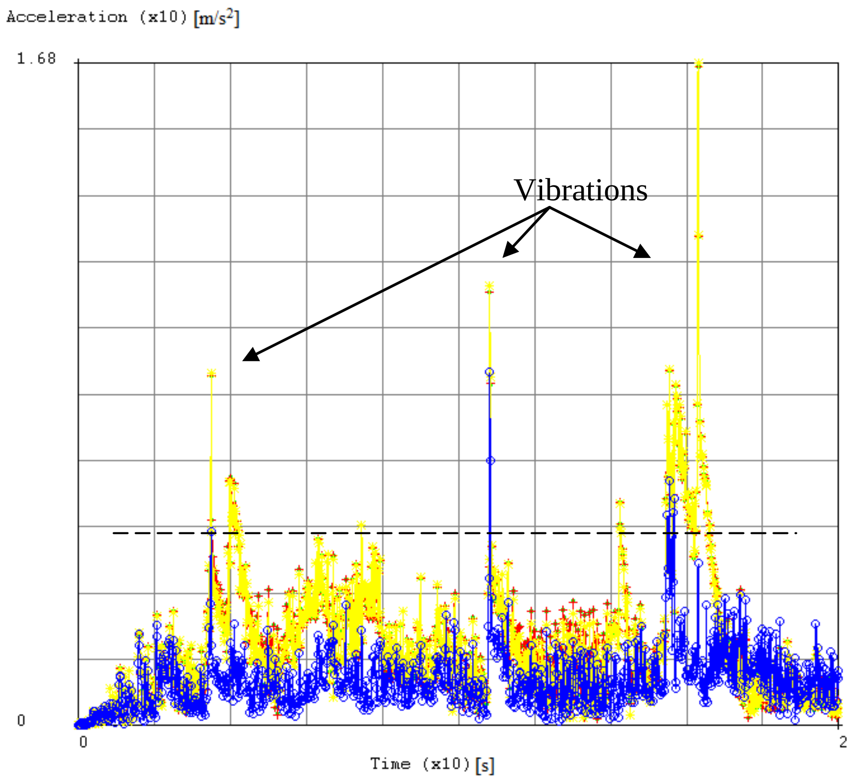
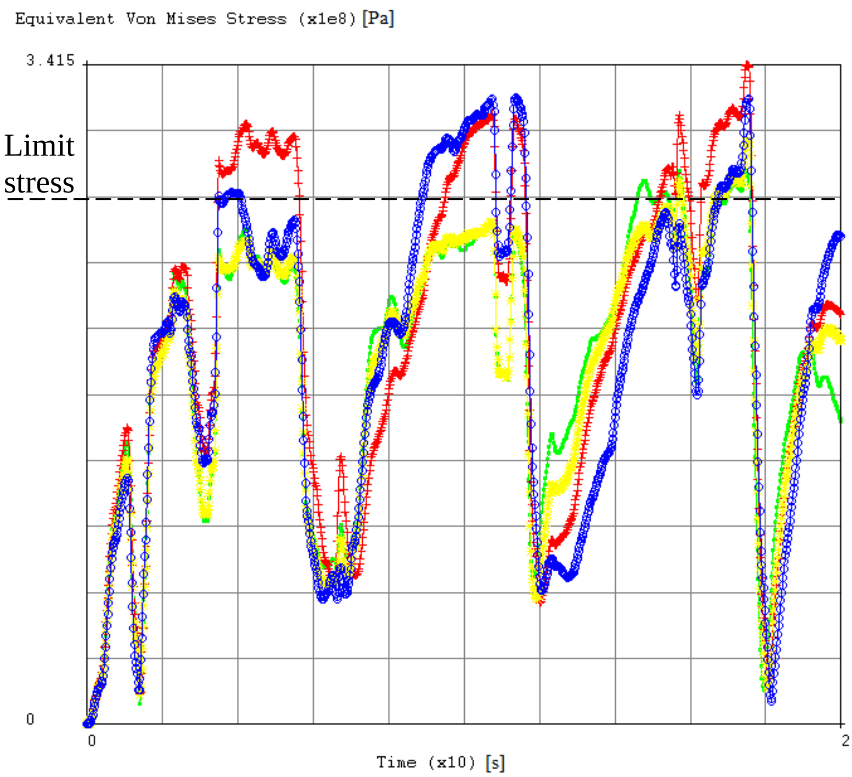
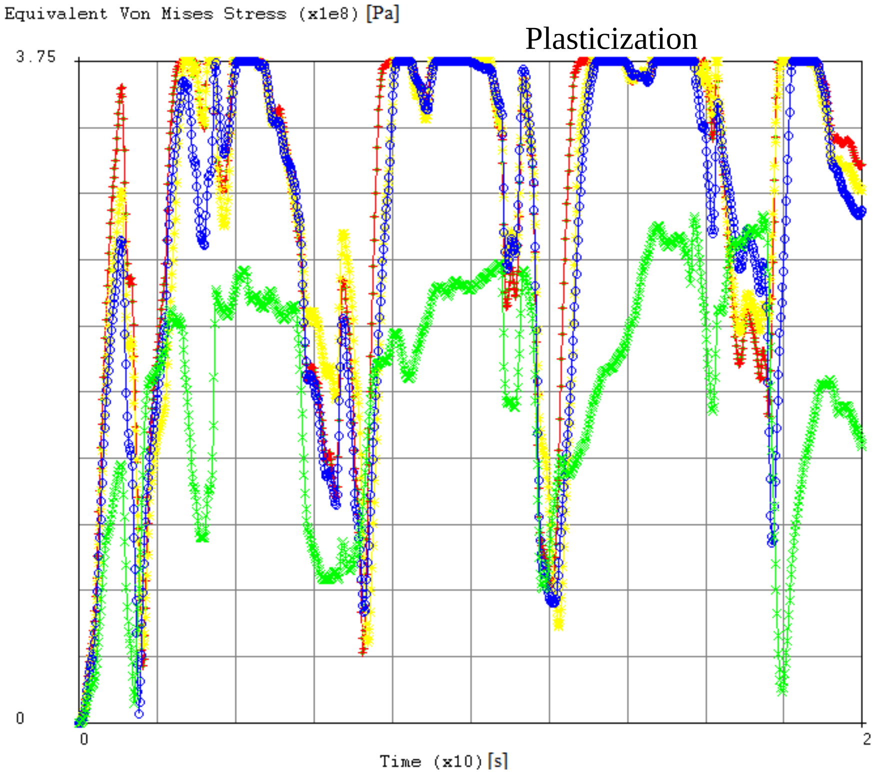



Figure 14 – FAs acceleration time history.

Analysing the Von Mises stress behaviour at the same FAs, it is possible to observe that the stress sometimes overcome the yielding for a prolonged time duration.



(a)




(b)

Figure 15 – FAs Von Mises stress vs. time.

This clear indicates that these components are plasticising; precisely a wide plasticisation appears in correspondence of the upper part of the upper plate, at the nozzle penetration area of the inner cylindrical vessel even if smaller plasticised area appears in and along the overall structure.

In addition the area surrounding the nozzle penetration ovalizes: this means that a circumferential buckling is occurring; to avoid which an upgrading of design will be necessary.

The horizontal displacement of the FAs is ranging from 1 to 8 cm (Figure 16); the mean vertical displacement is instead about 2.5 cm. The complex deformed shape along the FA elements is characterised by an inflexion which determine the inward displacement, as shown in Figure 17.

Finally taking into account that the gap between two adjacent assembly is 5 mm it is possible to conclude that the compaction is affecting mostly part of FAs (and LOFA could therefore occur).

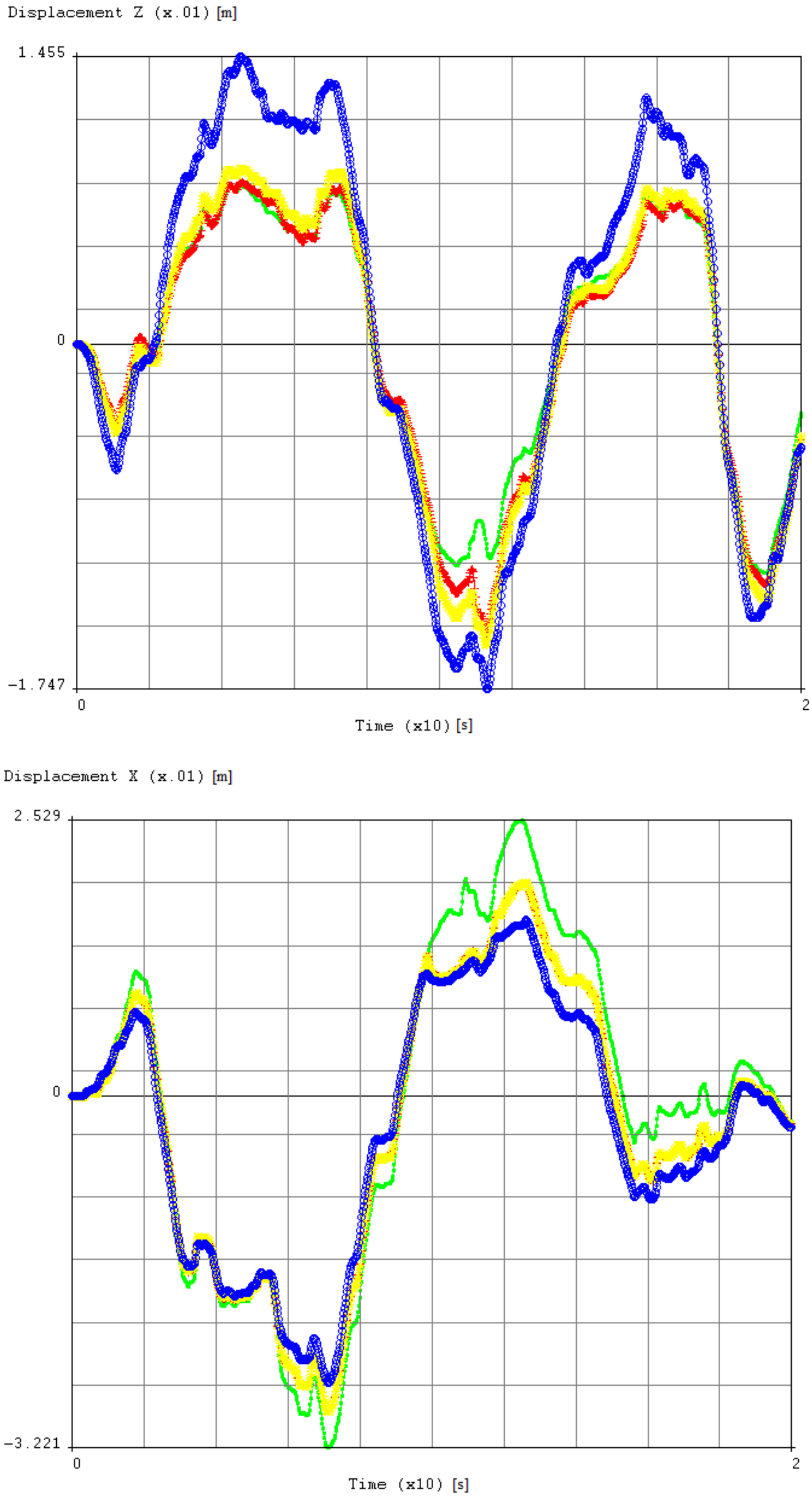



Figure 16 – FAs horizontal displacements.

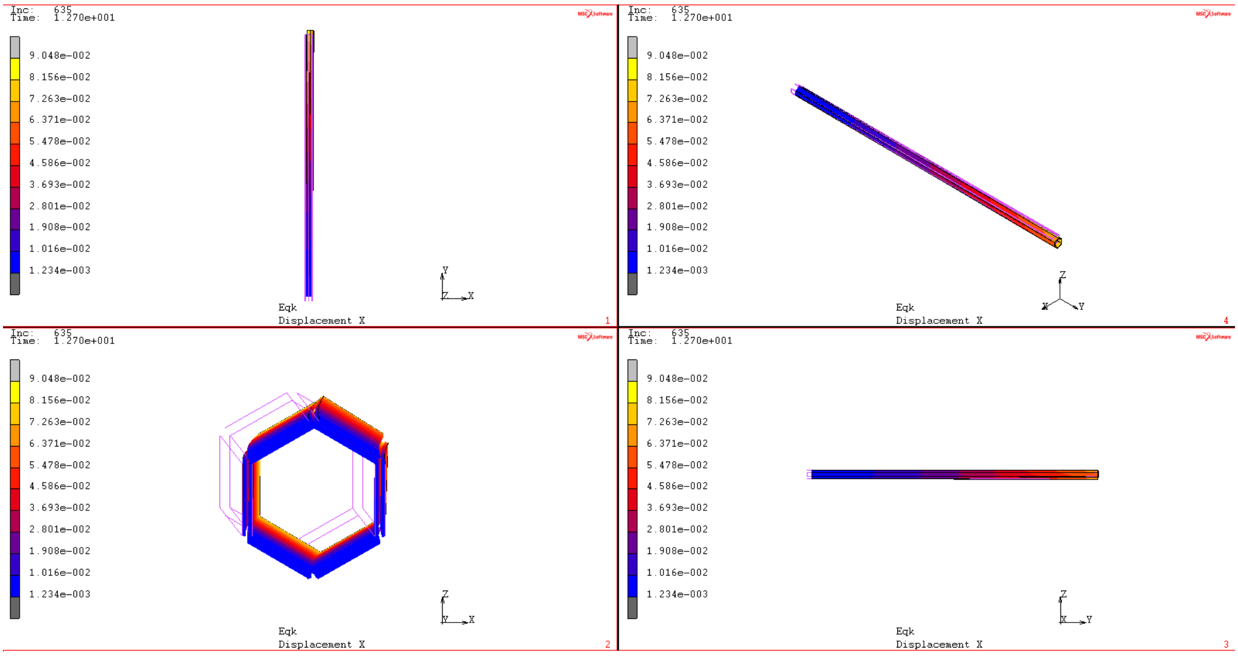



Figure 17 – FAs deformed shape.

It is important to emphasize that in this study there was no comparison with experimental data; this is due to the fact that to date no such data are available in the scientific literature neither specific experiments have not been conducted on the phenomenon studied.

Future development are also needed to investigate deeply the effects on the fuel element taking into account the constraints of the pad, such as the variation of the cross-section flexibility or that of the mechanical properties with the temperature along the height and radius, etc.

# 5. Conclusion

The core compaction phenomenon was studied with reference to the ALFRED reactor geometry and taking into account the influence of contact between structures.

Because of the complexity of the geometry of internals and considering the limitation imposed by the lack of information related to the geometrical shape of some components, the design data and some restraint characteristics, the dynamic of the core region necessarily has been made on a 3-D model of the IC.

Suitable boundary conditions have been imposed: the double symmetry condition was applied at the centre line of the structure along the vertical axis; clamp restraints was instead adopted for the diagrid foots and for the upper part of upper plate and IC shell.

No piping or primary coolant was considered at this stage.

In order to correctly simulate the dynamic behaviour of the structure taking into account the interaction between the different components, single-side contact was also assumed. This was used to easily set the contact type and the contact detection method between all contact body pairs defined in the contact table. A contact table was created so to represent the existing touching at the beginning and during the analysis. The minimum contact distance (below which two bodies get contact) was assumed 10-5 m.

The mechanical properties adopted are consistent with the operation conditions (1 bar and 480°C).

The results indicate:

- the contact forces determines a change of the compression rigidity of structures, and influences the deformation of the element cross-section;
- the input acceleration (0.21 g and 0.28 g at the upper plate and IC restraints) amplifies till to at reach 7 $m/s^2$ and 5 7 $m/s^2$ respectively at the radial peripheral and central FAs positioned along x axis.
- Vibrations also appear and characterise the response of structures with high spikes at f > 65 Hz.
- Von Mises stress that sometimes overcomes the yielding for a prolonged time duration, indicates that plasticization at small or large extent occurs.
- The horizontal displacement ranges from about 2 to 9 cm (going from the bottom to the upper plate).

It was also observed that the lower and upper plate did not suffer a wide plasticization, the opposite occurs instead in the nozzle-piping region that, for the geometry considered, undergoes large deformations that would unavoidably influence the normal reactor operation.

taking into account that the gap between two adjacent assembly is 5 mm it is possible to conclude that the compaction is affecting mostly part of FAs (and LOFA could therefore occur).

Further insights are needed for a better understanding of the phenomenon also in consideration of the other factors not considered in this study.

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