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# Methods for the Seismic Verification of a Fast Reactor Core

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## Abstract

The paper presents the main features of the numerical and experimental methods applied by the Fast Reactor Department of ENEA to the seismic verification of the core of the Italian PEC fast reactor test facility, which is in advanced construction at the Brasimone site. It also points out the problems which in general remain open in the fast reactor core seismic analysis. The aim is to contribute towards a generally acceptable philosophy on core seismic verification techniques and suggest items of possible co-operation for future developments.

## 1. Introduction

One of the main objectives of the design of nuclear plants in countries in which earthquakes are real events is to satisfy the seismic safety and operational requirements. This is especially true for a fast reactor, in which the presence of flexible structures may lead to considerable amplification of the seismic motion of safety relevant components /1/. For these reasons the greatest care is devoted by the Fast Reactor Department of ENEA to the seismic verification analysis of the PEC fast reactor test facility, which is in advanced construction at the Brasimone site /2,3/. Particular attention is obviously paid to the core, which largely affects the safety of the reactor in an earthquake /4,5,6/.

Due to the large reference earthquakes, the considerable flexibility of the vessel supporting structure and core elements, and the presence of non-negligible gaps among these elements and in their feet, sophisticated numerical and experimental techniques had to be developed for the analysis of the PEC core response to the horizontal earthquake components.

After a brief description of the PEC core and some remarks on the requirements to be satisfied in an earthquake, the paper will deal with the mentioned methods, with the aim of contributing towards a generally acceptable philosophy on core seismic verification. In fact, no well defined procedures exist yet on this subject, although a great amount of work has been carried out and published: the available papers (see, for instance, those presented at the two last SMiRT Conferences /4-11/) do not provide a clear and complete comparison of the methods applied in the various countries. For the above cited purposes, the paper will also point out the open problems, which need further studies, possibly in the framework of a wide international co-operation.

## 2. The PEC core

The PEC core is characterized by an outer diameter of 2.5 m and an overall element height of 3 m. It is surrounded by three neutronic shields, the most interior one having an inner diameter of 2.75 m. 622 elements of different types are present in the core most probable configuration. The 78 fuel elements surround the test channel, which occupies, when it is inserted , the seven most central diagrid positions.

Two levels of pads are fitted to the core elements: beside the original ones, located close to the element midplane, a second set of pads was recently applied at 2.6 m from element base (above the active zone), to reduce internal core clearances (and thus, element seismic relative motions) to very small (although non-zero) values : this limits neutronic-seismic interac tion effects to an acceptable level (see ref. /12/).

The core inner elements are arranged in groups of seven forced together at the contacting pads.

The control rod absorbers are inserted into guide-tubes (fixed to the vessel plug through the Control Rod Drive Mechanism) in the upper part, and enter guide elements located in the core in the lower part /13/.

A "core-restraint" ring was recently inserted in the vessel at the core element upper pad level, in order to reduce overall core seismic motion and thus, to allow scram to be guaranteed during earthquake: the clearance between this ring and the core is small but not zero for handling reasons /12/.

## 3. Seismic safety and operational requirements

Two reference earthquakes are defined for PEC /1/: the earthquake TSS ("Terremoto di Sicuro Spegnimento"), corresponding to the American SSE and characterized by a maximum ground acceleration of 0.3 g in the horizontal directions, and the earthquake ½TSS. ½TSS represents the normally acceptable earthquake, taking into account economical aspects. For this earthquake, damages may be accepted only on components which can be inspected and easily repaired. PEC has to withstand five ½TSS (for components remaining in the reactor during its whole life) and one TSS.

With regard to the core, the safety philosophy implies that the following requirements have to be satisfied for the horizontal earthquake component, up to TSS :

- the rapid automatic insertion (during and after the earthquake) of a number of control rods sufficient to shut down the reactor has to be guaranteed ;
- deformations or ruptures of core elements, which may hinder the element cooling, have to be avoided ;
- fuel element compaction has to be limited, in order to reduce neutronic-seismic interaction to an acceptable level.

Furthermore, the core elements should not be damaged by any earthquake less than ½TSS, or at least, their replacement should be guaranteed.

It is therefore evident that, in order to demonstrate that the above mentioned requirements are satisfied, it is necessary to calculate correctly, for both TSS and ½TSS, the seismic motion time-histories of the core elements at various axial levels (beside that of the core diagrid), to determine the consequences of such displacements in terms of strains at the element feet, response of the shutdown system and core volume variations, and to evaluate element shroud deformations due to element impacts. These studies have to be performed in both the case of presence of the test channel, and that of replacement of the test channel by a group of 7 elements; furthermore, both initial and end-of-life distorted core geometries have to be analysed.

## 4. The computer program CORALIE

The PEC core seismic analysis is particularly complicated due to clearances between adjacent elements and between the external elements and the core-restraint ring, allowing shocks to occur among these. Moreover, strong fluid-structure interaction effects are present, due to the small distances among elements and between the core and the neutronic shields. Finally, the dynamic behaviour of each single element is also non-linear, due to internal mobile parts and presence of clearance in the feet.

Thus, a numerical technique for the dynamic core non-linear analysis has been developed and implemented in the computer program CORALIE /4,7/. This work has been carried out in collaboration with CEA, due to the fact that a numerical tool was also needed for the Superphenix-1 core seismic analysis. In CORALIE the shocks are simulated by systems of springs and dampers, the action of which starts as soon as local contacts occur, and the fluid effects can be described by an increase of viscous damping and (after the recent improvements of CEA) the introduction of a complete added mass matrix.

The features of CORALIE have been described in the mentioned references /4,7/; however, it appears important to discuss, in the next paragraphs, some limitations of the program and some problems in its application.

## 5. Core excitation

To analyse the fast reactor core seismic response it is necessary, in general, to calculate core diagrid acceleration time-histories for both reference earthquakes. Furthermore, in the case of PEC the analysis of the core configuration containing the test channel requires that also the plug acceleration time-histories are determined. (According to ref. /20/, due to PEC high vessel wall stiffness, we assume that the relative motions among the plug, restraint-ring and diagrid are negligible in the reference system fixed to the diagrid itself).

The evaluation of the mentioned time-histories is performed by NIRA with linear calculations of the whole reactor block. More precisely, as described in /5/, to take into account the strong effects of the vessel-core seismic interaction characterizing PEC, they are obtained through iteration of the NIRA linear calculations and those, non-linear, performed by ENEA for the single core with CORALIE : this implies the definition of an equivalent linear core model, obtained at each iteration step linearizing the CORALIE response. It is worth noting that in the case of PEC the final linear core model features appear to depend on the excitation level (TSS or ½TSS), core configuration (presence or absence of the test channel) and assumptions made with regard to fluid effects (see ref. /12/).

Up to now reference has been made to only one (artificial) time-history at the level of the vessel supporting structure, for each of the two reference earthquakes. However, we intend to investigate the "shape" effect of the excitation on the core response (some studies have been initiated). Furthermore, we also intend to investigate the effects of the uncertainties related to the linear core model, i.e. both those depending on definition modalities of the models and those affecting the CORALIE response which is linearized to obtain such models (§ 13).

## 6. Analysed core configurations

The CORALIE analysis can be carried out only assuming that the core response is negligible in the direction normal to the excitation. This assumption was introduced according to the results of experiments carried out by CEA for a large core configuration, which had shown that the maximum displacements of the elements of a central row (i.e. those located on a core diameter) are very similar in the case of excitation of the whole core and that of excitation of the single central row /4,7/. Furthermore the data measured in the CEA experiments with excitation of the whole core have been shown to be in excellent agreement with the numerical results calculated for the single central row, in the case of two earthquake directions, normal to each other (i.e. that normal to hexcan flats and that normal to hexcan corners) /4,7/. Finally, the core response has been found to be very similar for the two excitation directions.

Thus, the PEC core design calculations are normally carried out on the two single central rows of core elements corresponding to the the two previously cited earthquake directions /12/. Anyway, calculations are also performed for other single rows of elements, in order to check the conservatism of the central row calculations and to obtain information on the control-rod guide-elements, which are not present in central rows /12/. Furthermore, some calculations have been performed with preliminary data and in the case that the test channel is replaced by a group of seven elements, for core configurations of up to nine rows: these have confirmed (within the limits of validity of the assumption of negligible transverse response) that the single central row approach is adequate for the core geometry analysed in that study /15/.

In spite of the above mentioned justifications, however, the single row analysis certainly introduces some uncertainties; furthermore it makes it difficult to simulate correctly the fluid coupling among elements through a complete added mass matrix (§ 8), and for PEC, the presence of the test channel (in this case parametric runs and calculations with three element rows are in progress). Finally, the single row approach makes it impossible to use CORALIE for the evaluation of reactivity insertion due to an earthquake in a realistic (i.e. not too conservative) way.

## 7. Number of modes

The computer code CORALIE makes use of modal analysis. Only the first two modes are usually assumed for the PEC core elements, because the natural frequency values corresponding to the third mode are largely outside the frequency range characterizing seismic excitations. The validity of this procedure has been confirmed by the results of runs performed with up to six modes for each element /12/. Anyway, we intend to perform further checks, by use of an option of CORALIE which allows a quasi-static correction of the computed response to be applied for taking into account the effects of the shock-induced excitation of the neglected modes (the method of correcting the shock stiffness, applied in previous studies to account for these effects /5/, has been found to lead to uncorrect results for the PEC restrained core, especially with regard to the maximum shock forces, see § 11).

## 8. Fluid effects

Up to now, due to lack of more precise information specific for the PEC geometry, the sodium effects have been taken into account by an increase of element linear mass and damping coefficients measured in air /12/.

More precisely, the linear mass is increased by 56% in order to reduce maximum core response frequency to 80% of the value corresponding to absence of sodium effects, thus averaging the available experimental data obtained for other core geometries /7,8/. This assumption has been found to lead for PEC (also taking into account vessel-core interaction) to conservative results with respect to those obtained by neglecting all added mass effects /12/. More accurate methods, capable to evaluate the single terms of the added mass matrix /16/, have not been applied, because these neglect the fluid motions in the vertical direction, which should be of the same order of magnitute as the horizontal ones . Furthermore, the use of a complete added mass matrix (beside the difficulty of a correct measurement) would imply the necessity of expensive 3D calculations of the whole core (which are not possible with CORALIE), because the coupling effects among each core element and the surrounding element rings do not vanish with increasing distance from the element /16/ and because it does not appear reasonable to try to define some kind of equivalent coupling coefficients applicable to the single row analysis. Finally, for a correct analysis of the PEC core with fluid-coupling effects, also those related to the vessel and internal shields should be taken into account (see the dimensions of the core and internal shield in § 2).

Moreover, with regard to damping, we have assumed that the fluid applies an additive correction to the fractions of critical damping with respect to the values in air, $\Delta\eta = 4\%$ : this is in agreement with the results of the fluid-structure interaction measurements performed by Belgonucléaire / 1/. It should be noted, however, that these data are certainly conservative, because our recent tests performed in water with single prototype mock-ups and couples of the PEC core elements show that the presence of fluid inside elements and in the interspace between feet and cans leads already to an increase of damping $\Delta\eta$ of about 2÷3% /14/ (in the tests of Belgonucléaire the core elements were simulated by solid blocks).

Finally, it is worth citing that we have started experiments for a correct evaluation of the fluid-structure interaction effects in the PEC core, which will allow to check the adequacy of the cited assumptions in the final calculations /14/. In these tests core configurations of up to 19 (at least) elements are analysed, the first purpose being to determine the global effect of fluid on displacements, frequency response and damping, both related to internal core phenomena and (possibly) interaction with the vessel.

## 9. Element vibrational parameters

The natural frequencies and the associated vibrational parameters of the PEC core assemblies are calculated by means of the finite-element method. Double-contact restraints are assumed at element feet. Beside the linear mass corrections mentioned in § 8, corrections are also applied to the theoretical stiffness (especially in the feet, to account for foot-can clearance effects) : these are estimated on the basis of the results of the dynamic experiments carried out on prototype mock-ups of the PEC core elements in air and water (see refs./6,12,14/). We note that we refer to isostatic models of the single assemblies, instead of trying to simulate with CORALIE the non-linear effects of the clearance in the foot, because of the too many uncertainties which affect (in our opinion) the parameters characterizing the non-linear restraints. It is obvious, however, that our method does not allow the strains at the element feet to be correctly calculated with CORALIE. Anyway, to determine these, specific experiments are performed on the basis of the computed maximum displacements /17/: the measured values are certainly more correct than those which could by computed through any CORALIE calculation with the assumption of one-dimensional stress and strain fields made in the code.

Up to now, according to a first set of experimental results /6,12/, natural frequency values independent of excitation level have been assumed in the design calculations. However, the most recent measured data, referring to excitation levels up to TSS, indicate the necessity of making use, in the final calculations, of different values for TSS and ½TSS (especially for the elements with large clearance in the foot); furthermore, an uncertainty range has to be associated to such values /14/.

With regard to the test channel, an equivalent beam, defined by NIRA through a detailed analysis, is used in the CORALIE calculations: this beam is supported at both diagrid and plug.

## 10. Damping values

Constant values of the fractions of critical damping, $\eta^* = 5\%$, have been assumed up to now for all elements and all modes, for both TSS and ½TSS. These correspond to the assumption of $\eta = 1\%$ in air and as mentioned, $\Delta\eta = 4\%$ due to sodium effects ( § 8). However, similar to $\Delta\eta$, the experimental tests performed on prototype core element mock-ups have shown that the assumed $\eta$ values in air are normally conservative, especially for the elements with large foot-can clearance /14/. Thus, for the final PEC core calculations, less conservative $\eta^*$ values will be used. These will be different for the different elements and for the two reference earthquakes : in fact, damping values appear to decrease with increasing excitation up to TSS /14/.

## 11. Shock parameters

The shock spring constants are obtained by means of 3D static calculations estimating shroud deformations and from the results of experiments /17/. Due to the small gaps among core elements at the two pad levels, the assumption of two opposite equally loaded hexcan flats is usually taken to determine these parameters : in fact, this assumption leads certainly to conservative element displacements for the PEC restrained core. However, while the conservatism related to absolute displacements is acceptable for a correct structural and functional verification of the core elements and shutdown system, that characterizing core volume variations is not acceptable, due to non-negligible effects of shroud deformations on these variations: thus for reactivity insertion evaluations, higher shock stiffness values are assumed in the CORALIE runs, which take into account the contact map evaluated statically at the time of maximum core compaction /18/.

With regard to the effects of the shock-induced excitation of the high-order modes, neglected in the CORALIE modal analysis, the method of accounting for these by correcting shock stiffness /4,5/ is not adopted any more for PEC, after the recent considerable reduction of gap values among elements. In fact, such correction applies only to the case that the shocks are not simultaneous (by the way, this is implicitly excluded by the assumption made for assessing the shock spring values). Furthermore, as mentioned in § 7, calculations carried out with up to 6 modes have shown that such correction leads to rather uncorrect results : this is especially true for the shock forces, which would be underestimated for fuel elements /12/.

Finally, the shock damping values are calculated from the shock spring constants with the method of ref. /7/ (based on energy balance considerations), assuming a restitution coefficient of 55% and measured shock durations /19/ : it is worth citing that the validity of the method is now being checked through a re-analysis of the measured data, because the shock damping values have a considerable effect on the maximum shock forces in the PEC case /19/.

## 12. Integration time-step values

Various parametric studies have been carried out to assess the correct integration time step value, $\Delta t$. These have shown that a rather small value, $\Delta t = 0.4$ ms, is necessary for the PEC core geometry to obtain an adequate response in terms of displacements and core volume variations and an even lower value, $\Delta t = 0.1 \div 0.2$ ms to determine maximum shock forces correctly. Thus, in the actual PEC core calculations, $\Delta t = 0.1$ ms is assumed.

## 13. Notes on the linear core models

The features of the linear core models adopted for PEC have been described in /5/. It is worth noting that, for estrapolating the CORALIE results from the single central row of elements to the whole core, it is now assumed that the average motion of each type of elements and impact forces acting on the restraint ring are equal in all rows. The effect of other possible assumptions are being investigated; if necessary, appropriate uncertainty parameters will be associated to core excitation in the final calculations. Furthermore, the study of the effects of the uncertainties related to core element data (i.e. frequencies, damping,etc.) is also in progress, together with some work on vessel-core coupling due to sodium effects /15,20/.

## 14. Use of the results

The results of the numerical and experimental studies of the PEC core have been applied :
(a) to the structural and functional verification of the shutdown system ;
(b) to the structural and functional verification of the single elements (feet and shrouds) ;
(c) to the numerical studies performed for evaluating reactivity insertion in an earthquake.

With regard to items (a) and (b) specific papers are presented to this Conference /13,17/, while the first results concerning item (c) have been discussed in ref. /18/. We only note, on neutronic-seismic interaction, that a static approach has been used for TSS, making reference to dynamic analysis only for the evaluation of average hexcan deformations to be applied in the static calculations; on the contrary, a dynamic approach is used for the case of ½TSS.

## References

/1/ CICOGNANI,G., MARTELLI,A., "Key Issues in European Reactor Seismic Design", IAE Intl. Symposium on LMFBR Development, Tokyo, Japan, 1984, Paper V-1; ENEA Rep. RT/VEL in the press.
/2/ MARTELLI,A., NERI,P., SCANDOLA,G., MARESCA,G., CASTOLDI,A., LABANTI,M., "Some Aspects of the PEC Fast Reactor Aseismic Design Analysis", Energia Nucleare, in the press.
/3/ MARTELLI,A., et al., "Some Key Issues of the PEC Fast Reactor Aseismic Design Analysis", Intl. Topical Meeting on Fast Reactor Safety, Knoxville, U.S.A., 1985.
/4/ MARTELLI,A., GAUVAIN,J., BERNARD,A., "Non-Linear Dynamic and Seismic Analysis of Fast Reactor Cores. 1- Theoretical Model", SMiRT-6, Paris, France, 1981, Paper K9/1.
/5/ MARTELLI,A., CHIOCCHIO,S., MARESCA,G., "Vessel-Core Seismic Interaction for a Fast Reactor", SMiRT-7, Chicago, U.S.A., 1983, Paper F7/6.
/6/ BONACINA,G., et al., "Dynamic and Seismic Behaviour of PEC Reactor Core Elements: Comparison between Computed and Measured Results", SMiRT-7, Chicago, U.S.A., 1983, Paper F7/2.
/7/ GANTENBEIN,F., GAUVAIN,J., BERNARD,A., VAN DORSSELAIRE,J.P., "Seismic Behaviour of a Fast Reactor Core. Application to Superphenix 1", SMiRT-7, Chicago, U.S.A., 1983, Paper F7/1*.
/8/ SASAKI,Y., MUTO,T., "Experimental Studies on Seismic Vibration Phenomena of FBR Core Components", SMiRT-7, Chicago, U.S.A., 1983, Paper F7/3.
/9/ MADELL,J.T., MORAN,T.J., ASH,J.E., McLENNAN,G.A., FULFORD,P.J., "Core Restraint Analysis of a Large Heterogeneous Free-Flowering Core Design", SMiRT-7, Chicago, U.S.A., 1983, E2/2.
/10/ MORAN,T.J., "Seismic Analysis of a Free-Flowering LMFBR Core", SMiRT-7, Chicago, U.S.A. , 1983, Paper E6/2.
/11/ PREUMONT,A., RAYMACKERS,A., PARENT,J., DELCON,M., "Fluid Coupling Effects in LMFBR Core Seismic Analysis", SMiRT-7, Chicago, U.S.A., 1983, Paper E6/7.
/12/ CECCHINI,F., DI FRANCESCA,R., MARTELLI,A., MELLONI,R., MURATORI,P.G., MARESCA,G., "Feed-Backs on PEC Fast Reactor Core Design due to Seismic Conditions", this Conference (EK2/6).
/13/ CASTOLDI,A., et al., "Experimental Demonstration of PEC Fast Reactor Scramability in an Earthquake", Paper presented to this Conference (EK2/7).
/14/ BONACINA,G., et al., "Dynamic and Seismic Response in Air and Water of Prototypic Models of PEC Fast Reactor Core Elements", Paper presented to this Conference (EK2/5).
/15/ MARTELLI,A., FORNI,M., AMENDOLA,A., LUCIA,A.C., MARESCA,G., "Uncertainty Evaluation of Fast Reactor Core Seismic Response", SMiRT-7, Chicago, U.S.A., 1983, Paper M3/6.
/16/ PREUMONT,A., PARENT,J., "Experimental Determination of Fluid-Coupling Coefficients in an Array of Hexagonal Prisms", Specialty Conference on Structural Engineering in Nuclear Facilities, Raleigh, U.S.A., 1984.
/17/ NERI,P., et al., "Experimental Tests for Structural and Functional Verification of PEC Fast Reactor Core Elements with Seismic Loadings", presented to this Conference (EK2/8).
/18/ ARTIOLI,C., CECCHINI,F., CORTICELLI,P., DI FRANCESCA R., FORNI,M., MARTELLI,A., McLOUGHLIN, J., MURATORI,P.G., "Evaluation of the Neutronic-Seismic Interaction Effects in the PEC Fast Reactor Core Analysis", Intl. Topical Meeting on Fast Reactor Safety, Knoxville , U.S.A., 1985.
/19/ BONACINA,G., CASTOLDI,A., ZOLA,M., MARTELLI,A., SARTORI,C., VINCENZI,D., "Response to Impacts of Fast Reactor Core Elements during Seismic Excitation", this Conference (EK2/4).
/20/ DESCLEVES,P., MARCHAND PASQUIER,B., MARTELLI,A., MARESCA,G., "Comparison between a Beam and a Shell Model for the Seismic Analysis of a Reactor Vessel", this Conference (K9/11).