Permanent Deformation of PWR Fuel Grid Spacers In Case of Severe "Over Design" Earthquake.

J-P.Fabry[1], E.Viallet[2], A.Decauwers[1], M.Hesius[1] and C.de Limelette[1]

1) Belgonucleaire - Avenue Ariane, 4 – B 1200 BRUSSELS - BELGIUM
2) Electricité de France/SEPTEN - 12 Avenue Dutriévoz - 69628 VILLEURBANNE CEDEX - FRANCE

ABSTRACT

In case of Design Basis Accident, a PWR fuel assembly has to guaranty essential safety requirements (fuel rod cooling and control rod drop). As a consequence, the spacer grids of the assemblies are usually designed to prevent any residual deformation. Consequently, seismic analyses of PWR cores are performed assuming that the behavior of this grid remains elastic.

The aim of this paper is to show that the consequences of a severe "over design" earthquake on the geometry of the core might be very limited, even if some assembly grid spacers experienced buckling for a short period of time.

In a first phase, a study is carried on using a reference set of severe earthquake spectra and assuming that the grids remain elastic. The results show overestimated but brief load peaks on some grids, largely in excess of the buckling threshold.

In a second phase, the same calculations are performed again, taking into account buckling and plastic deformations. Despite the severity of the spectra, the calculated permanent deformations of the grids remain small in comparison with their size. It is worth mentioning that these slightly deformed grids are located against or near the core baffle (low neutron flux and no control rod).

It can thus be concluded that PWR fuel assembly spacer grids can withstand a severe "over design" earthquake without impact on Safety.

These seismic simulations were performed using the CLASH computer program, in use since the late seventies. In this application, it simulates the behavior of a row of PWR fuel bundles, considering it as a set of vertical embedded beams. The program calculates the beam deformations, according to an explicit time history method. The shocks between grids and against the core baffle are modeled with gap elements. To obtain average results with acceptable statistical accuracy, each typical CLASH simulation is repeated ten times, with a different accelerogram generated randomly from the same spectrum (program THGE).

In the second phase of the study, the gap elements between bundles are supposed to remain elastic, as long as the load remains below the buckling threshold. Beyond that point, the maximum load a gap element can transmit drops sharply and remains constant. Further elastic unloading and loading of buckled gaps are calculated assuming reduced stiffness. Such over-elastic behavior can be deduced from scale-one grid crush tests.

This paper describes the used methodology and typical results from a series of 270 simulations.

INTRODUCTION

The major concern of the PWR fuel designers, with regard to the occurrence of an earthquake, is to make sure that the control rods can be properly inserted into the reactor core, to shut it down safely [1]. A second concern is to maintain the cooling of all rods inside the core at a safe level. Current practice is to consider that these objectives are reached if the grid spacers of the fuel assemblies can withstand the earthquake, without showing residual deformation. In other words, no spacer grid may experience buckling or loads in excess of its elastic limit. This paper aims at evaluating how conservative this approach is, by showing the minor consequences of severe "over design" earthquakes on Safety.

MODELS AND COMPUTER PROGRAMS.

The Time History Method

Due to the importance of the gaps and of the shocks that occur between the assemblies during an earthquake, the classical Response Spectrum Method for linear systems does not apply. The so-called time-history method is used instead. It simulates the evolution of the shape of the assemblies, step by step, under the action of the time varying ground acceleration due to the earthquake. When grid spacers hit against each other or against the reactor baffle, the forces that develop are computed according to a force-displacement diagrams that is usually determined experimentally. These forces are then applied on the assemblies, as would external loads. This detailed approach requires a significant amount of computing time. Calculation time steps of 100 µs or less have to be used, to be much smaller than the duration of the shocks between assemblies.

The Generation of the Accelerograms with THGE

The time varying ground acceleration diagram that prevails at the reactor core level – the so-called accelerogram – depends of course on the site and on the reactor building. Relevant accelerograms are seldom available from measurements, due to the low probability of getting records of such phenomena. Artificial accelerograms are generated randomly from response spectra that have been established by well-specified methods. A well-known software called THGE [2] has generated these used in this study. The frequency content of each artificial accelerogram is checked versus the given input response spectrum. Fig. 1 shows a typical comparison of a generated accelerogram versus its target spectrum. THGE is, in a sense, the inverse function of the process used to establish a response spectrum, using natural accelerograms.

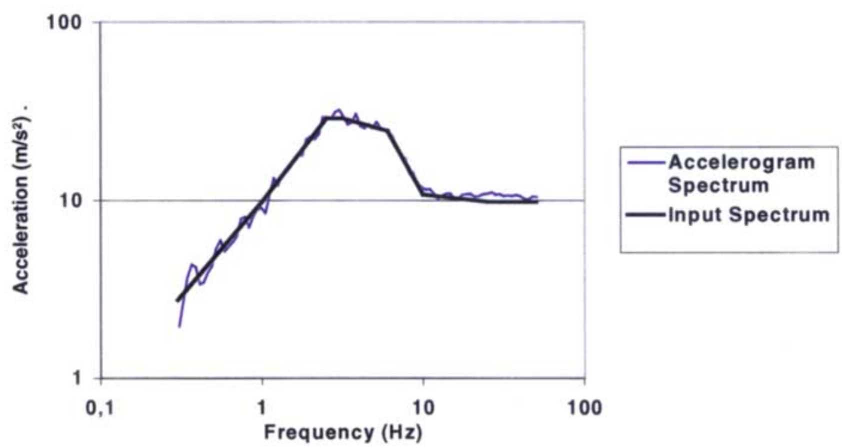

Fig. 1 Comparison of an Artificial Accelerogram with its Target Input Spectrum

The intensity of the accelerations must conform to a given standard pattern : it first develops linearly and then stabilizes; it finally ends with an exponential decrease (fig. 2). As the generation of the accelerograms is random, large fluctuations can be observed on the results of the simulations.

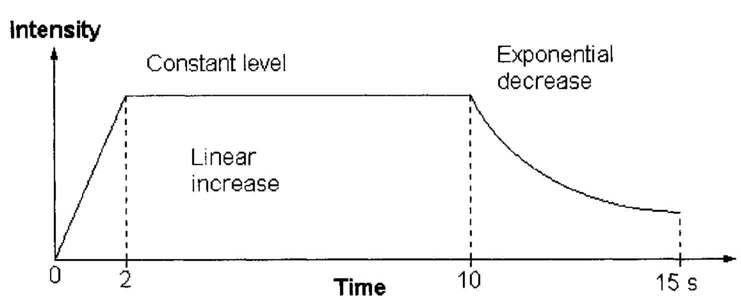

Fig. 2 Typical Earthquake Intensity versus Time

To draw reliable conclusions about the sensitivity of the results versus a given parameter, many computer runs must be performed with various accelerograms, derived from the same response spectrum. For this study, all computer runs have been repeated 10 times, by just varying the accelerogram.

The Non-linear Transient Behavior of a Row of Fuel Assemblies.

This method takes advantage of the fact that fuel assemblies in a Western PWR are square. This means that if an assembly moves along a direction parallel to one of its sides (let us called it the X direction) it only pushes neighbor assemblies from a single row. The same is valid for a row parallel to axis Y (perpendicular to X). The recommended practice is to combine the results of both X and Y earthquake simulations of the longer rows, to evaluate the maximum global effect on the structure. It can be easily demonstrated that shorter rows show lower stresses and strains.

For the purpose of this study, one row of assemblies is modeled as a series of vertical beams, fully embedded at both ends. The embedding corresponds to the plugging of the assemblies inside the reactor support plates.

Each grid spacer is modeled as a spring that links either two assemblies or one assembly with the reactor baffle. These springs are so-called gap elements. They can only transmit contact forces. If they are compressed below their buckling threshold, the springs behave elastically (stiffness equals K1, in fig.3). Beyond this point, the stiffness of the spring gets negative (K2). Then, despite its length reduces, the compression force it transmits also reduces. For large deformations, the compression force stabilizes at level F2, at least as long as the spring length decreases further. Once the peak of the shock is over and the assemblies tend to separate, the unloading occurs with a positive stiffness K3, which is usually deduced from grid crush tests. This "post-buckling stiffness" is lower than K1, as the grid structure is then significantly deformed. This reduced stiffness will prevail in case of further shocks.

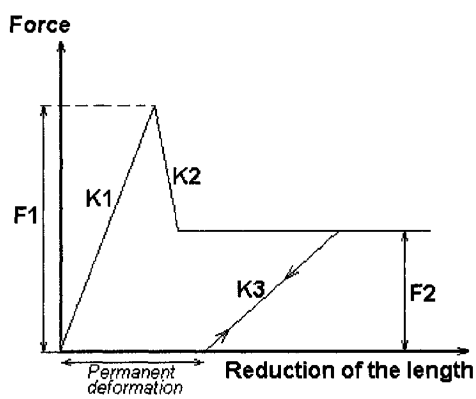

Fig. 3 Force – Length Diagram of the Springs

The Force-Length diagram of each modeled spring is updated by the computer program, as it changes as soon as the buckling load is exceeded. This makes it possible to model the progressive enlargement of the gaps and its effect on the intensity of further impacts.

The computer program used to perform this study is CLASH 3.01. It has been developed by BELGONUCLEAIRE, starting in the late 70's [3]. This newest version has been validated according to ISO 9001 procedures, which required careful comparisons of CLASH results with these from other computer codes and with specially developed non-linear verification cases. CLASH has also been used for many other applications, such as seismic evaluation of Fast Breeder Reactor cores; verification of the stability of fuel racks in pools and evaluation of the basket loading during transport casks drop tests [4]. It can model the fuel rods and the skeleton of the assemblies separately. The possible non-linear behavior of the grid dimples is then modeled. This option is unused in this study [5]. It might be useful however, to best evaluate the possible local damages on the rods.

Reference Simulation of the Elastic Behavior of the Assemblies.

This is the conventional approach for the mechanical design of the fuel. This part of the study is used as a reference solution, around which the sensitivity of the results to buckling and permanent deformation will be assessed. In this instance, the earthquake intensity is tuned to be in a range that would normally buckle some grid spacers. These reference elastic calculations are made assuming a constant elastic stiffness, whatever the level of the deformations is.

A first series of 10 calculations has been run, using a set of 10 accelerograms derived from the same response spectrum. The maximum impact forces at the grid spacers - recorded during each of these runs - have been averaged. The obtained mean value exceeded the buckling threshold by 15%. This set of accelerograms was thus identified by δ=1.15. This coefficient is deemed to characterize the severity of the set versus the assembly design.

Similarly, two other sets of 10 accelerograms have been tested to yield earthquake severity coefficients δ=1.72 and δ=1.95, respectively. The latter set thus induced impact forces almost twice as large as the buckling strength. Such high calculated impact forces could be reached only because the grid spacers were not supposed to buckle. Buckling would actually behave as a force limiter.

In this analysis, the elastic stiffness of the grid, K1, was set equal to 30 MN/m. For purpose of evaluation of δ, F1 has been taken equal to 15 kN (rounded value).

This first elastic study finally provides with three sets of 10 accelerograms, characterized by three dimensionless severity coefficients. These are convenient parameters to present the results derived from the rest of this study. In this way, the extrapolation to other similar assembly designs and earthquakes is made possible, by just evaluating the severity coefficient δ, using standard elastic methods.

Reference simulation of the plastic behavior of the assemblies.

The aim of this study is to get a first idea of what could occur if the buckling threshold of the grids were overshot. The three sets of ten runs performed using the above mentioned accelerograms have been repeated but, this time, a grid type has been modeled, taking into account buckling and permanent deformation. The stiffnesses and thresholds, according to the nomenclature of fig. 3, are the following :

K1 = 30 MN/m ; F1 = 15 kN
K2 = - 40 MN/m ; F2 = 5 kN
K3 = 10 MN/m

Sensitivity Analysis versus the Data defining the Plastic Behavior of the Assemblies.

The sensitivity versus the final plastic level (F2) has been assessed by varying it from 3 to 7 kN, around the already available reference value (5 kN). The sensitivity versus the negative buckling stiffness (K2) has been assessed by increasing it strongly above the reference value (Reference : K2 = - 40 MN/m; additional runs made using K2 = -100 MN/m and -200 MN/m). The sensitivity versus the post buckling stiffness (K3) has been assessed by varying this parameter as follows : K3 = 3.5, 7 and 15 MN/m (in addition to the already available run with K3 = 10 MN/m). Table 1 below summarizes a total of 27 data sets, to be run 10 times with a different accelerogram.

Table 1 : Summary of the Runs :

	Severity Coefficient	Elastic Stiffness	Buckling Force	Post Buckling Force	Buckling Stiffness	Post Buckling Stiffness
Symbol	δ	K1	F1	F2	K2	K3
Units	None	MN/m	kN	kN	MN/m	MN/m
Ref. Elastic Runs	1.15/1.72/1.95	**30**	-	-	-	-
Ref. Plastic Runs	1.15/1.72/1.95	**30**	**15**	**5**	**-40**	**10**
Sensitivity to F2	1.15/1.72/1.95	30	15	**3 / 7**	-40	10
Sensitivity to K2	1.15/1.72/1.95	30	15	5	**-100 / -200**	10
Sensitivity to K3	1.15/1.72/1.95	30	15	5	-40	**3.5 / 7 / 15**

Results from the Reference Elastic Study

The elastic study, like any CLASH run, provides the user with a large number of tables and graphs. An animation of 1500 frames helps to figure out the behavior of the row of assemblies during the earthquake. Fig. 5 shows a typical picture available during the animation. It shows the already applied accelerogram at a given time from the beginning of the earthquake and some instantaneous maximums. A star indicates the impact locations, together with the corresponding impact force and colliding velocity. The grid levels, as referred to below, are numbered on the right side of the picture and the assembly numbering is displayed at the bottom line.

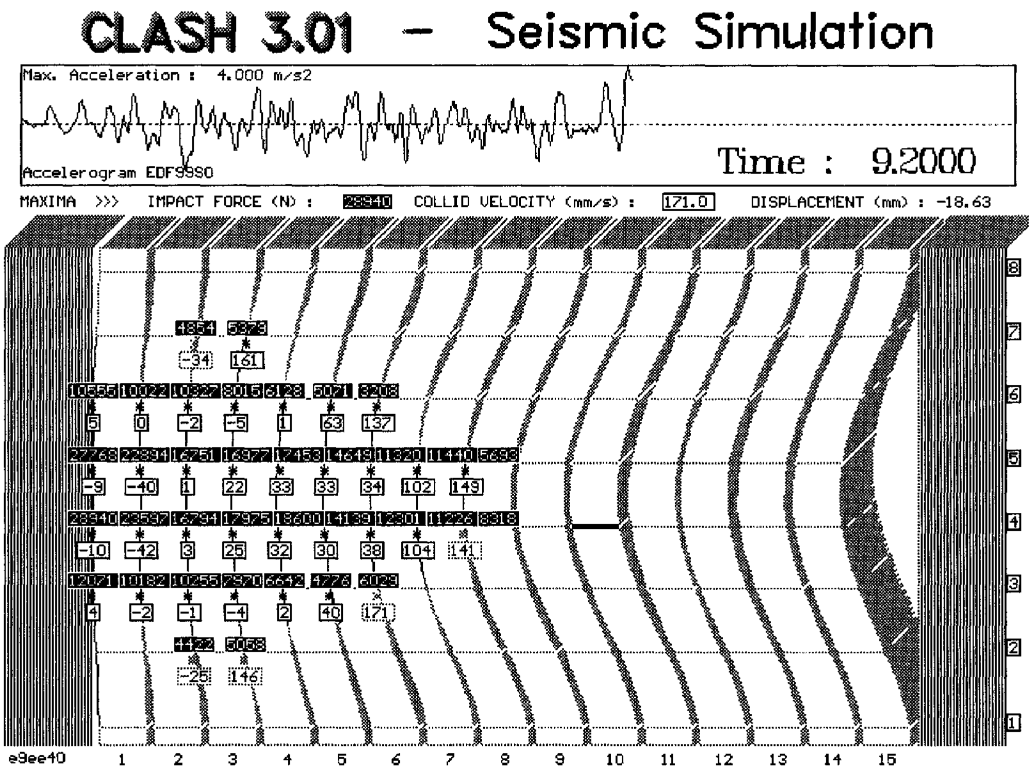

Fig. 5 Typical picture from the standard Animation of the Results

As explained above, the major purpose of this study is to determine the severity coefficient δ, associated with the set of accelerograms. The fundamental frequency of the assembly is 2.5 Hz, which was the target value. Fig. 6 gives the sensitivity of δ versus the Zero Period Acceleration of the normalized spectra. It is interesting to note that this coefficient does not increase linearly with the acceleration.

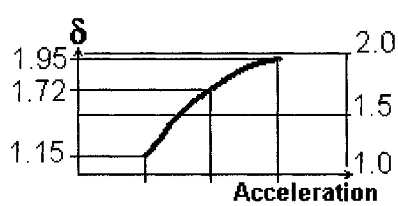

Fig. 6 Sensitivity of δ versus the Seismic Acceleration

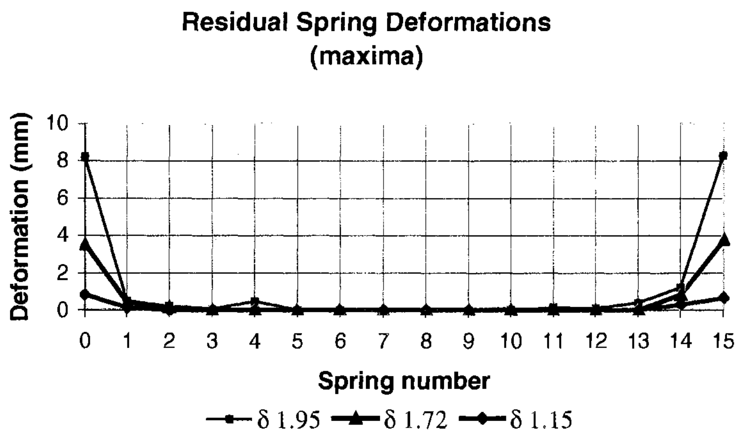

Fig.7 Average Spring Deformation at Mid Core Level vs Position in the Row.

Results from the Reference Plastic Study

Fig. 7 shows spring deformations at mid core level, as recorded from the basic plastic calculations. The results were obtained from three sets of 10 simulations. They have been averaged, to make the comparison more legible. Each dot actually corresponds to the average of 20 values : 10 from grid level 4, and 10 others from grid level 5, which are on symmetrical positions.

Spring 0 and 15 represent respectively the possible contact of assembly 1 and 15 against the reactor baffle. Spring number n, actually represents the right side of assembly n that hits the left side of assembly n+1.

It first appears that left and right ends of the row give symmetrical results, as expected. The impacts with the reactor baffle show the largest residual deformations. Even the largest deformation (8mm) is small in comparison with the width of an assembly (typically 215 mm). It must be noted however that the severity coefficient has an exponential effect on the results.

Again due to symmetry, the deformations at grid levels 3 and 6 should be the same, as they are equally distant from the mid level of the core. The average values recorded at 4 locations (levels 3 and 6, at left and right ends) in 10 jobs are equivalent and give a rather stable average value, which can be correlated with the δ of the accelerogram set. Fig. 8 presents a plot of the so obtained aggregate values. Each dot on the curve is, this time, the average of 40 calculated deformations. So, the deformations recorded at grid levels 3 and 6 appear to be much smaller than these recorded near the mid core level. Fig. 6 showing the typical bended shape of the fuel assembly helps understand why.

It must be pointed out that, where an elastic simulation indicates impact loads in excess of buckling by 95%, the larger deformation given by the plastic model is only 8 mm. The actual maximum force is just higher than the buckling strength F1. The small excess is due to the damping. It is also worth mentioning that significant grid deformations mostly occur against the reactor baffle, i.e. where heat production is low – due to lower neutron flux - and where no control rods must cross the assemblies. Grid spacer buckling has thus virtually no impact on Safety related issues.

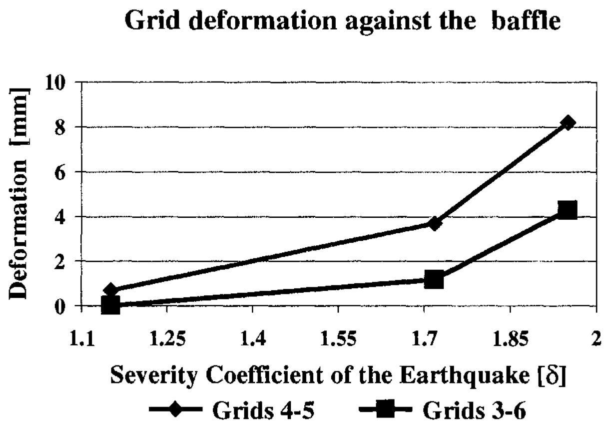

Fig.8 Average Deformation vs the Severity Coefficient.

Sensitivity to the Post Buckling Strength (F2).

It is clear that the higher the plastic force F2, the smaller the deformation (Table 2).

For an increase from 5 to 7 kN, the maximum deformation – which occurs against the baffle – reduces by 0.3 to 3.5 mm, depending on δ. Conversely, for a decrease of F2 from 5 to 3 kN, the maximum deformation increases by 0.5 to 4.4 mm. A careful experimental evaluation of the post buckling strength seems thus important.

Table 2. Maximum Residual Deformation vs F2 and the Severity Coefficient (mm)

Post Buckling Strength	Severity Coefficient $\delta = 1.15$	Severity Coefficient $\delta = 1.72$	Severity Coefficient $\delta = 1.95$
F2 = 3 kN	1.2	5.7	12.6
F2 = 5 kN	**0.7**	**3.7**	**8.2**
F2 = 7 kN	0.4	2.3	4.7

Sensitivity to the Negative Buckling Stiffness (K2)

As shown on table 3., even important increases of this parameter have nearly no effect on the maximum residual deformations.

Table 3. Maximum Residual Deformation vs K2 and the Severity Coefficient (mm)

Negative Buckling Stiffness	Severity Coefficient $\delta = 1.15$	Severity Coefficient $\delta = 1.72$	Severity Coefficient $\delta = 1.95$
K2 = -40 MN/m	**0.7**	**3.7**	**8.2**
K2 = -100 MN/m	0.8	3.7	8.6
K2 = -200 MN/m	0.8	4.1	8.4

Sensitivity to the Post Buckling Stiffness (K3)

It appears on table 4. that if this stiffness increases, the residual deformations are somewhat larger. In other words, shocks between more rigid assemblies induce slightly larger damages. For instance with a 50% increase on K3, the maximum residual deformation increases by less than 1 mm (with $\delta = 1.95$).

Table 4. Maximum Residual Deformation vs K3 and the Severity Coefficient (mm)

Negative Buckling Stiffness	Severity Coefficient $\delta = 1.15$	Severity Coefficient $\delta = 1.72$	Severity Coefficient $\delta = 1.95$
K3 = 3.5 MN/m	0.4	2.8	6.4
K3 = 7.0 MN/m	0.6	3.2	7.4
K3 = 10.0 MN/m	**0.7**	**3.7**	**8.2**
K3 = 15.0 MN/m	0.9	4.3	8.7

SUMMARY AND CONCLUSIONS

This study shows that a severe "over design" earthquake would not significantly damage the assemblies. The largest recorded residual deformations amount to half an inch, when using the most unfavorable set of data. This is small in comparison with the width of an assembly.

The study also shows that these deformations are very local. They occur against the reactor baffle, i.e. where the neutron flux is low and where no control rods have to be inserted. The consequences on safety issues are virtually negligible.

A sensitivity analysis shows that, besides the buckling strength, which is usually well known, the most significant parameter that requires investigation is the post buckling strength (F2, on fig. 3).

The limits of the dimensionless severity coefficient, as a way of extrapolating these results to other designs and other sites, might be evaluated further.

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