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Original Article

Mechanical robustness of AREVA NP's GAIA fuel design under seismic and LOCA excitations

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ABSTRACT

Recent events in the nuclear industry have resulted in a movement towards increased seismic and LOCA excitations and requirements that challenge current fuel designs. AREVA NP's GAIA fuel design introduces unique and robust characteristics to resist the effects of seismic and LOCA excitations.

For demanding seismic and LOCA scenarios, fuel assembly spacer grids can undergo plastic deformations. These plastic deformations must not prohibit the complete insertion of the control rod assemblies and the cooling of the fuel rods after the accident. The specific structure of the GAIA spacer grid produces a unique and stable compressive deformation mode which maintains the regular array of the fuel rods and guide tubes. The stability of the spacer grid allows it to absorb a significant amount of energy without a loss of load-carrying capacity.

The GAIA-specific grid behavior is in contrast to the typical spacer grid, which is characterized by a buckling instability. The increased mechanical robustness of the GAIA spacer grid is advantageous in meeting the increased seismic and LOCA loadings and the associated safety requirements. The unique GAIA spacer grid behavior will be incorporated into AREVA NP's licensed methodologies to take full benefit of the increased mechanical robustness.

1. Introduction

Recent events in the nuclear industry have resulted in a move toward increased seismic and LOCA excitations and requirements. Reevaluation of the seismic risk at nuclear power plants has been requested by various safety authorities with the goal of evaluating a plant's resistance to design basis and beyond design-basis accidents. The increased excitations present a challenge to current fuel designs to maintain sufficient margins to spacer grid crushing as well as component stresses. For demanding seismic and LOCA scenarios, the assembly spacer grids can undergo plastic deformation if the impact forces exceed the strength of the spacer grid. These grid deformations must not prohibit the complete insertion of the control rods and the cooling of the fuel rods after the accident. AREVA NP's GAIA fuel assembly and, specifically, the GAIA spacer grid have the potential to meet the demands of the increased seismic and LOCA requirements.

2. GAIA fuel assembly design

AREVA NP's new GAIA fuel assembly design for pressurized water reactors (PWR) has been in operation as lead fuel assemblies in Europe since 2012 [1] and in the United States since 2015. The GAIA fuel assembly has been designed to maximize the product performance in the following domains:

- rod-to-grid fretting resistance, thanks to use of 8 soft line contacts per cell and a low fluid-structure interaction obtained via streamlined components like the GRIP bottom nozzle;
- critical heat flux with optimized mixing features on grids and optional intermediate mixers;
- and fuel assembly bow resistance, thanks to the use of reinforced guide tubes made with the Q12[i] creep resistance alloy, each welded in 8 points to the spacer grids.

The GAIA assembly also introduces a new robustness to resist the effects of seismic and LOCA excitations by means of the GAIA spacer grid. The GAIA spacer grid design is distinguished by the fuel rod support spring hulls which are inserted and welded at the strip

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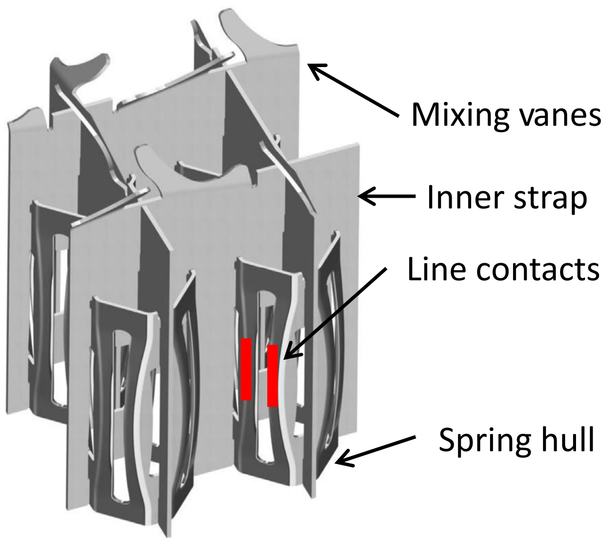

Fig. 1. Detail of the GAIA spacer grid rod support and spring hull.

intersection (see Fig. 1). The inclusion of the spring hull provides a resistance to the localized buckling and bending of the grid strips at the intersections, which is the typical failure mode of the classical spacer grid.

2.1. Spacer grid behavior in compression

The specific structure of the GAIA spacer grid produces a unique and stable compressive deformation mode. The compressive deformation is distributed uniformly over the entire grid, thus maintaining the regular array of the fuel rods and guide tubes. By contrast, the classical spacer grid exhibits a pronounced shearing deformation in the postbuckling state which distorts the fuel rod and guide tube array. A comparison of the compressive deformation modes for the classical spacer grid and the GAIA spacer grid is provided in Fig. 2. Both spacer grids have experienced approximately 2 mm of permanent deformation in the loading direction.

The stability of the GAIA spacer grid under compressive loads allows it to absorb a significant amount of energy without a loss of load-carrying capacity. The response of the GAIA spacer grid to dynamic impacts of increasing kinetic energy is plotted in Fig. 3 for beginning-of-life (BOL) conditions and in Fig. 4 for simulated end-of-life (EOL) conditions. The response of the classical spacer

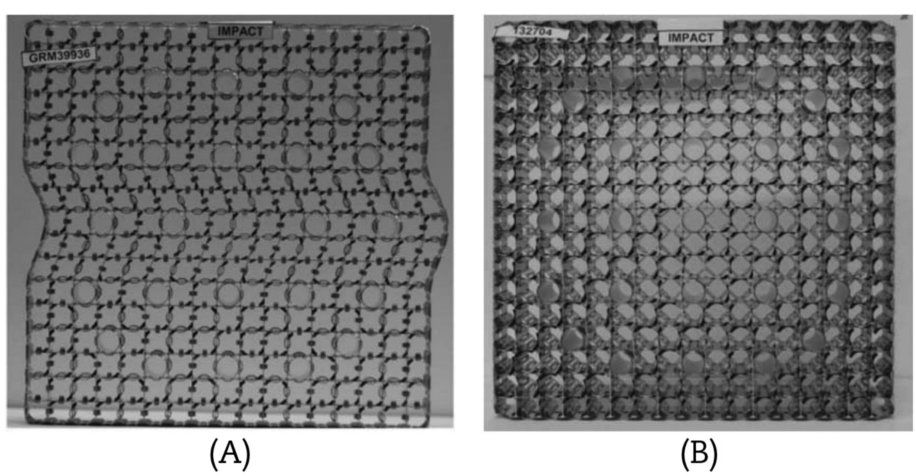

Fig. 2. Comparison of failure modes. (A) Classical spacer grid. (B) GAIA spacer grid.

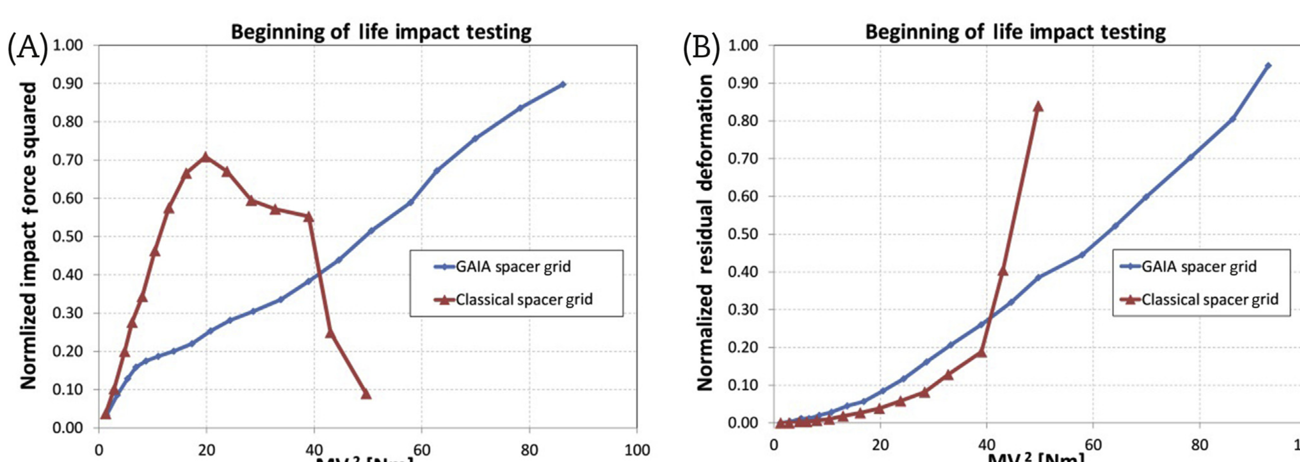

Fig. 3. Beginning-of-life conditions. (A) Impact force squared. (B) Residual deformation versus impacting kinetic energy.

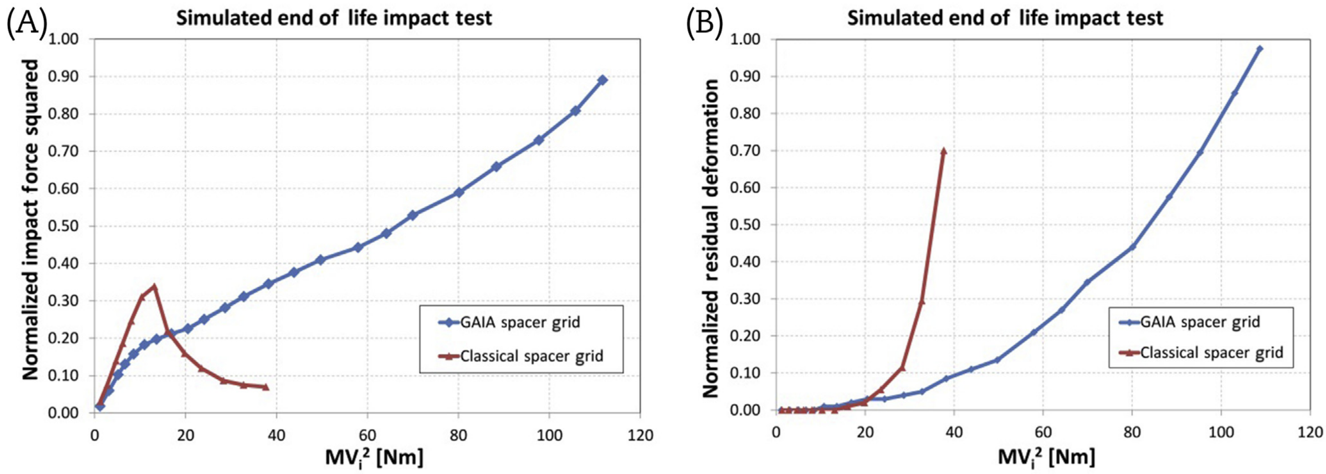

Fig. 4. Simulated end-of-life conditions. (A) Impact force squared. (B) Residual deformation versus impacting kinetic energy.

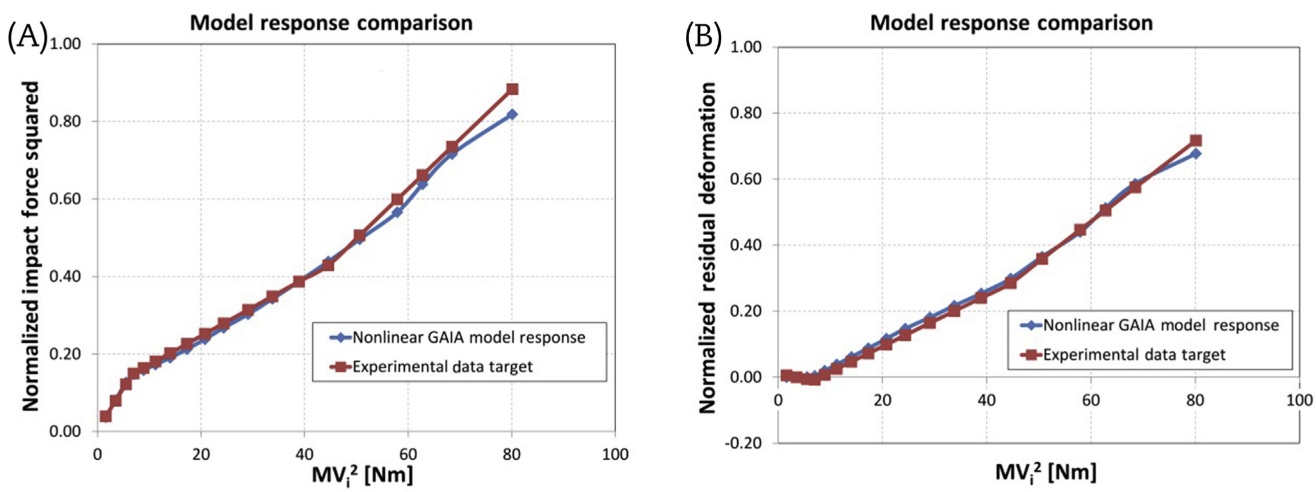

Fig. 5. Comparison of impact element model and test data. (A) Impact force. (B) Residual deformation as a function of the impacting kinetic energy.

grid up to and beyond the buckling strength is also shown for comparison.

The notion of spacer grid strength must evolve when comparing the response of the classical grid and the GAIA grid to focus more on toughness and energy absorption. The nonlinear response of the GAIA spacer grid, coupled with the uniform compressive deformation, requires a new modeling technique and a new methodology to take full benefit of the increased mechanical robustness.

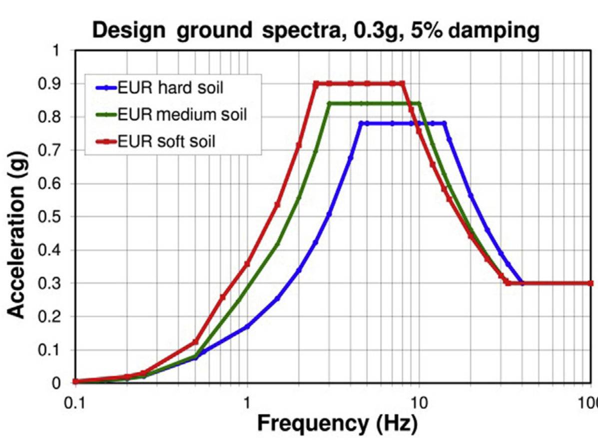

Fig. 6. European Utility Requirements seismic ground response spectra.

3. Modeling the spacer grid behavior

The current methodology for analyzing the effects of seismic and LOCA excitations is to assume that the spacer grid behaves as a linear viscoelastic spring. As seen in Figs. 3 and 4, this assumption is valid for the classical grid, up to the buckling strength, based on the measured response from dynamic impact tests. For the GAIA spacer grid, the assumption of linearity can be verified by considering only the initial elastic stiffness. However, the GAIA spacer grid exhibits a clear nonlinear response over the range of tested impact energies. A new methodology for analyzing seismic and LOCA excitations has been developed to specifically address the nonlinear behavior of the GAIA spacer grid. As part of this new methodology, a nonlinear impact element was developed to capture the important physical behaviors of the GAIA grid. This element represents both the load-deflection behavior as well as the energy dissipation behavior of

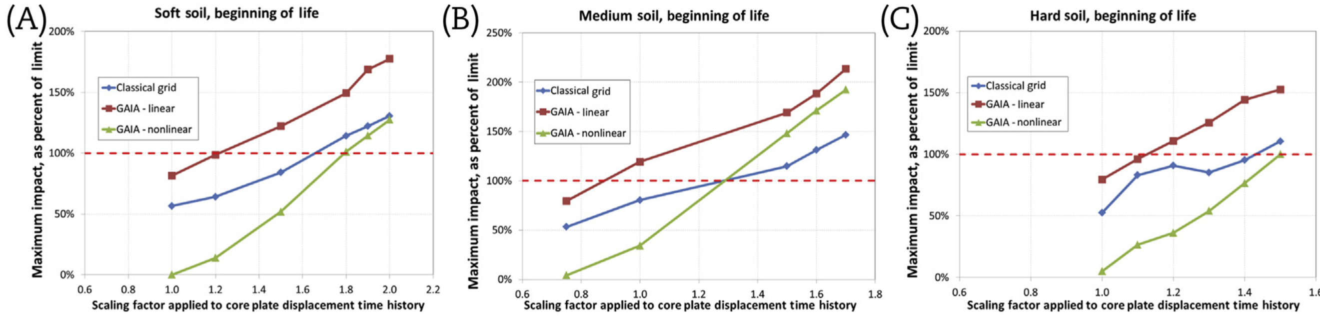

Fig. 7. Maximum impacts from seismic excitation. (A) Soft soil, beginning-of-life. (B) Medium soil, beginning-of-life. (C) Hard soil, beginning-of-life.

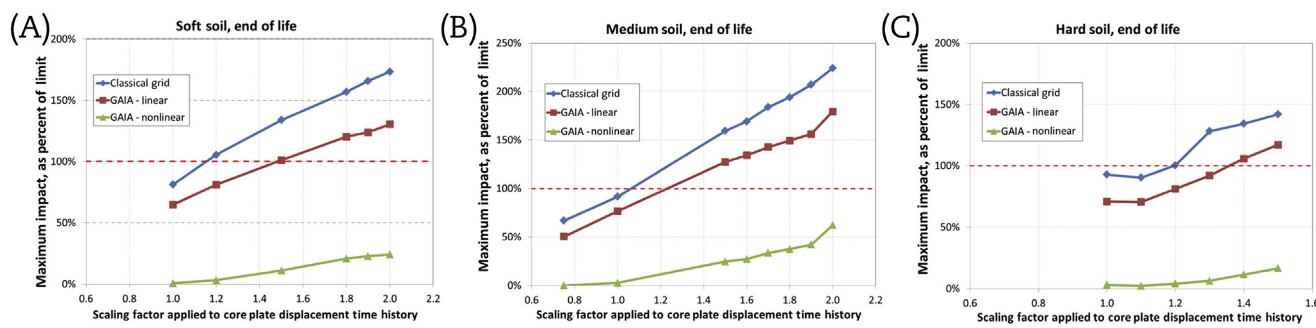

Fig. 8. Maximum impacts from seismic excitation. (A) Soft soil, end-of-life. (B) Medium soil, end-of-life. (C) Hard soil, end-of-life.

Table 1
Maximum impacts from LOCA excitation, as percent of limit.

Grid model	Beginning of life	End of life
Classical grid	21%	30%
GAIA—linear	33%	24%
GAIA—nonlinear	0%	0%

the grid when subjected to dynamic impacts. Energy dissipation through viscous forces, friction forces, and plastic deformation are all present in the nonlinear impact element.

Constitutive equations describing the load-deflection behavior and the different energy dissipation mechanisms are imbedded in the nonlinear impact element. The coefficients to these equations are input parameters set by the user to reproduce the test data from the standard dynamic impact test protocol. A benchmarking analysis is performed with the impact element where an impacting mass and the series of impact velocities from the experiment are input into the model to simulate the dynamic impact test. During the benchmarking analysis, the input parameters are adjusted so that the impact element output matches the experimental data. Two of the primary outputs, the square of the impact force and the residual deformation, are compared to the test data target in Fig. 5. As shown in Fig. 5, the nonlinear impact element is capable of reproducing the measured dynamic response of the GAIA spacer grid.

4. Definition of limiting deformation

The basic regulatory requirements for the fuel assembly design in seismic and LOCA conditions are control rod insertability, maintaining a coolable geometry, and preventing fuel rod fragmentation. In the case of the classical spacer grid, the regulatory requirements are assumed to be satisfied if the predicted grid impact load remains below the grid strength. The assumption is valid because the spacer grid usually experiences negligible deformation at the maximum impact load.

In the new methodology developed for the GAIA spacer grid, the regulatory requirements are met by applying a deformation limit. Control rod insertion is confirmed by characterization of the guide tube array for increasing levels of deformation. The characterization is performed with a functional gauge to ensure compatibility with the control rod assembly, thus negating the need to perform full-scale control rod drop testing. This characterization retains a significant amount of conservatism based on the flexibility of the control rod assembly rodlets and the friction needed to arrest the insertion of the control rod assembly.

Satisfying the coolable geometry requirements is aided by the fact that the GAIA spacer grid deforms uniformly in the loading direction with negligible shear deformation (see Fig. 2). By maintaining a nearly square flow area rather than a rhomboidal flow area, the reduction in flow area is minimized, thus limiting the post-LOCA consequences of a reduced flow area. The fuel rod fragmentation requirement is respected by performing the fuel rod cladding stress evaluation per normal practices. The additional compression of the grid spring due to grid deformation does not produce excessive stresses in the cladding.

5. Margin study

A study was performed to demonstrate the benefits to be gained from the implementation of a nonlinear grid element to represent the GAIA spacer grid. Three spacer grid models are used in the study:

1. Classical spacer grid.
2. Linear GAIA spacer grid— limited to the linear elastic range.
3. GAIA spacer grid—nonlinear model

In the study, seismic and LOCA excitations are applied to a reactor core of 14FT GAIA fuel assemblies. Both BOL and EOL calculations are performed with corresponding parameters for the fuel assembly and spacer grid models. Although three spacer grid models are considered, the same fuel assembly model is unchanged between the three grid models. All row configurations are included in the study.

5.1. Seismic excitations

The seismic excitations are derived from the European Utility Requirements (2001) [2] standard free field response spectra. The soft, medium, and hard soil free field response spectra are considered in this study and have been scaled to a 0.30 g peak ground acceleration as shown in Fig. 6. The free field spectra have each been combined with three soil profiles to calculate the basemat response. Finally, the basemat response is applied to the reactor building model to arrive at the response at the core plate locations. The excitations at the core plate locations are applied to each fuel assembly row model.

The initial set of seismic excitations corresponding to a 0.30 g peak ground acceleration is defined as having a scaling factor of 1.0, i.e. the nominal case. The excitations at the core plates are then scaled to increase the spacer grid impact forces until the design margin for the grid is zero.

5.2. LOCA excitations

Only one LOCA excitation is applied to the fuel assembly row models, and no scaling of the excitation is performed.

5.3. Margin study results

The results of the margin study are presented as the maximum impact for each seismic or LOCA excitation as a function of the design limit. For the classical grid and the linear GAIA grid, the limits are defined as strength. For the nonlinear GAIA grid, the limit is defined as a deformation. If the maximum calculated impact exceeds 100%, then it is concluded that the impact load exceeds the strength or deformation limit of the grid. The results for the seismic excitations are presented in Figs. 7 and 8 for the BOL and EOL conditions, respectively, as a function of the soil type and the scaling factor applied to the excitations.

In general, the classical grid and the linear GAIA grid produce higher impact forces, as a percentage of the limit, than the nonlinear GAIA grid. The larger margin to the design limit for the nonlinear GAIA grid is consistent with the fact that the GAIA spacer grid can absorb a significant amount of kinetic energy before reaching the limiting deformation. Using the BOL medium soil nominal case (scaling factor if 1.0) as an example, the maximum impact force experienced by the classical grid is 80% of the strength limit, whereas the maximum deformation experienced by the nonlinear GAIA grid is only 34% of the deformation limit. The benefit of the nonlinear GAIA grid model is especially significant for the EOL conditions. The buckling strength of the classical grid will decrease because of spring relaxation. However, the GAIA spacer grid design does not lose strength when the springs are relaxed because of its specific geometry.

In the case of LOCA excitations, the loads for the three grid models are less than their respective limits (see Table 1). The nonlinear GAIA grid model does not produce any residual deformation since the impact forces are below the elastic limit of the grid model.

6. Conclusions

The robustness of AREVA NP's new GAIA fuel assembly design in seismic and LOCA accident scenarios has been demonstrated through a new methodology which takes advantage of the unique design of the GAIA spacer grid. As part of the new methodology, the GAIA spacer grid is described with a nonlinear element that can model the energy absorption and dissipation to correctly predict the residual deformation of the spacer grid. By implementing this nonlinear modeling approach, significant gains in margins and best in class performance are achieved in seismic and LOCA accidents. AREVA NP plans to license this new methodology to take benefit from the specific GAIA spacer grid behavior and to satisfy the needs for increasing accident and safety requirements. As part of the licensing effort, a dedicated topical report will be submitted to the U.S. Nuclear Regulatory Commission (NRC) in 2018.

Conflict of interest

All authors are employees of AREVA NP and affiliates.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.01.001.

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[2] European Utilities, European Utility Requirements for LWR Nuclear Power Plants, 2001.

[i] Q12 is a trademark of AREVA NP or its Affiliates in the USA or other countries.