CONSEQUENCES OF LEAKING FUEL ROD FAILURE DURING RIA TRANSIENTS

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ABSTRACT

This paper presents a methodology developed by EDF for the evaluation of the consequences of the presence of leaking fuel rods during RIA transients in PWR conditions. During such transients, the postulated failure of leaking fuel rods generates pressure waves that can impact the adjacent structures and core vessel walls. The generation of these pressure waves and their potential mechanical effect has been evaluated by means of fluid and structure dynamics calculations using EUROPLEXUS[1] fast transient dynamics software, with bounding input data and assumptions. The calculations show that the impact of the pressure waves does not impair the core coolability in the neighborhood of the leaking fuel and the integrity of the 2nd containment barrier.

1. Background and purpose

The fuel rod cladding is the first containment barrier for the fissile material. In France, with a fleet of 58 PWRs in operation, up to 2644752 fuel rods can be simultaneously irradiated. So it is not surprising that among them, several rods may lose their tightness during normal operation. The most frequent cause of this loss of tightness is debris fretting, as is illustrated on figure 1 below.

As a consequence, the ingress of water in the rod free volume can induce cladding embrittlement by secondary hydriding, which can take place far from the primary defect (i. e. up to 2-3 metres below or above it). In such conditions, the occurrence of a RIA power transient due to a rod ejection accident (REA) induces specific physical phenomena with potentially deleterious consequences regarding reactor safety.

EDF has analyzed these phenomena in order to assess bounding assumptions and input data for their simulation and evaluate the potential consequences on the adjacent structures (fuel rods and guide tubes) and the core vessel wall.

Figure 1: example of a fuel rod with a through-wall defect due to debris fretting

[1] Co-owned by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) and the Joint Research Centre of the European Commission (EC/JRC)

2. The physical phenomena involved

As was already mentioned, the fuel rod loss of tightness during reactor operation is followed by water ingress in its free volumes. In PWR conditions, the water is in subcooled liquid state at hot zero power (HZP) and vaporized at hot full power (HFP).

The application of an REA transient can induce two phenomena:

- First, the potential burst of the over-pressurized cladding leads to the generation and propagation of an acoustic pressure wave in the core. According to Tanzawa & Fujishiro [1], the inner pressure at failure in a waterlogged and sealed rod can reach very high values, i. e. up to ~ 1000 bars. In the case of a fuel rod filled with steam (HFP), the maximum rod overpressure is expected to be much smaller.
- Then, fuel particles can be ejected and have a violent thermal interaction with the coolant, which induces local vaporization and volume expansion around the fuel particles. A part of the thermal energy transferred to the coolant is converted into mechanical energy, in the form of a pressure wave that also propagates through the core. This phase is commonly designated as Fuel-Coolant Interaction (FCI).

The next section is dedicated to the assessment of bounding assumptions and input data to be introduced in the simulations performed to evaluate the consequences of an REA transient.

3. Assessment of bounding assumptions and input data

3.1 Bounding cases

The bounding REA transients have been determined for the different fuel rod designs and the related core managements operated on the French NPP fleet. The most penalizing transients are obtained for MOX fuel, operated according to the “MOX Parity” core management, and irradiated at low burnups (i. e. < 33 GWd/tM, F/A average), for both HZP and HFP initial conditions. The characteristics of these transients are gathered in Table 1 below.

Initial condition	Initial enthalpy (cal/g)	Enthalpy rise (cal/g)	Available enthalpy (cal/g)
HZP	17	106	106
HFP	77	77	137

Table 1: main characteristics of the bounding REA transients

N.B.: the available enthalpy is the energy that can be transferred from the fuel to the coolant, i. e. the difference between the maximum fuel enthalpy and the final enthalpy at coolant temperature (~ 17 cal/g).

3.2 Input data for the simulation of the acoustic pressure waves

For RIA transients occurring in HFP conditions where the rod is initially filled with water steam at 155 bars, the maximum inner pressure is obtained by SCANAIR [2] calculations, considering that the rod is intact. The maximum rod overpressure is 22 bars.

For RIA transients occurring in HZP conditions where the rod is initially filled with liquid sub-cooled water at 155 bars, the rod overpressure at failure, which is expected to be much higher due to the low compressibility of liquid water, is determined as follows:

i) The first steps of the transients are simulated with SCANAIR in order to obtain the evolutions of the gap and clad temperatures with time;

ii) By analyzing the PROMETRA mechanical test database [3], the evolution of the cladding material ultimate tensile stress (UTS) with temperature is obtained (figure 2);

iii) The evolution of the gap pressure is incrementally determined: at each time step, the pressure increment ΔP(t) is deduced from the gap temperature increment ΔT(t) according to the following equation:

$$\Delta P(t) = \left(\frac{\partial P}{\partial T}\right)_V .\Delta T(t) \qquad (1)$$

where $\left(\frac{\partial P}{\partial T}\right)_V$ is the water compressibility factor at constant volume. This factor is deduced from the water tables and its values in PWR conditions is fairly constant at 11.8 bar/K.

iv) The evolution of the equivalent stress in the cladding is deduced from that of the rod inner overpressure:

$$\sigma_{VM}(t) = \alpha.(P(t) - P_{ext}).\frac{D_{ext} - e}{2e} \qquad (2)$$

where P_{ext} is the core pressure (155 bars), D_{ext} and *e* are the cladding outer diameter and wall thickness, respectively, and α is a coefficient introduced to transpose the mechanical uniaxial tensile tests to the loading condition (biaxial stress) of the over-pressurized cladding.

v) Clad failure is postulated when the equivalent stress due to rod overpressure exceeds the cladding material UTS at the same time.

Bounding conditions at failure can be determined from the different cases examined, giving an overpressure of ~ 1000 bars (consistent with what was observed in [1]) and a gap temperature of ~ 400°C.

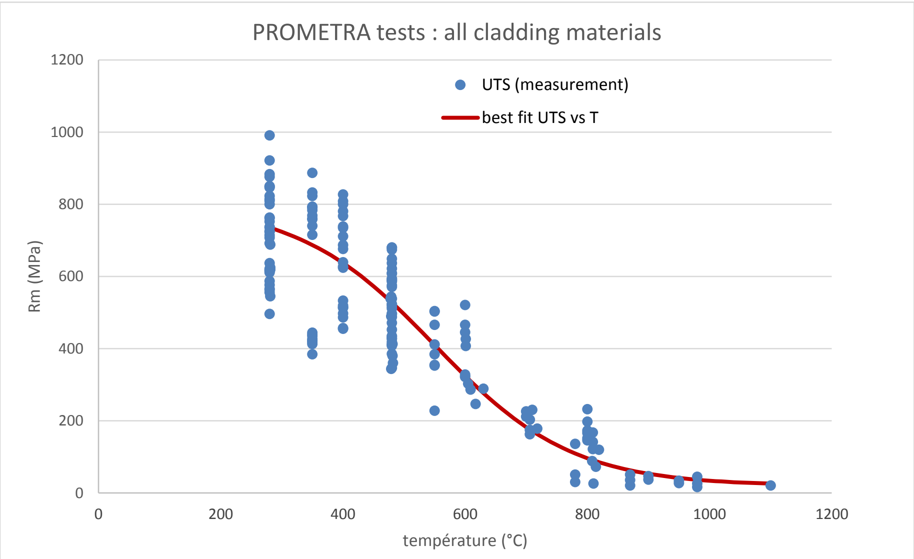

Figure 2: evolution of cladding material UTS with temperature, deduced from PROMETRA tests

3.3 Input data for the simulation of the pressure wave due to FCI

The characteristics (amplitude, shape and duration) of the pressure wave generated by FCI strongly depend on the heat transfer amount and kinetics, which also depend on the size of the ejected fuel particles and the available thermal energy (see Table 1 above). These parameters are assessed in the next subsections.

3.3.1 Fuel particle size

On the basis of several experiments, JAEA deduced an inverse relationship between the mechanical energy conversion ratio and the average diameter of the ejected fuel particles (between 20 and 250 µm, cf. figure 3). A way to maximize the pressure wave characteristics is to consider the smallest possible particle size, i. e. the fuel grain size.

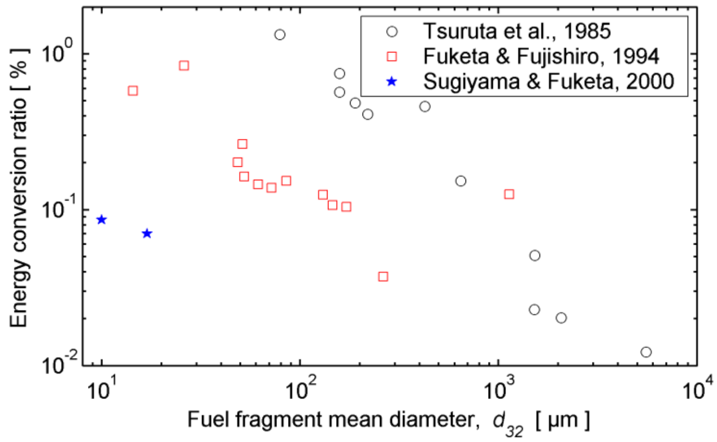

Figure 3: relationship between fuel particle and mechanical energy conversion ratio, deduced from various experiments conducted by JAEA

In MOX fuel, the high burnup structure (HBS), characterized by a very small grain diameter (~ 0.2 µm) and high porosity is present in the Pu-clusters, even at low burnup, and in the pellet volume comprised between mid-radius and periphery, i. e. 75% of the overall pellet volume. Since the Pu-clusters represent 15% of the whole volume in fresh pellets, the relative HBS volume is 11.25% of the total pellet volume. In the remaining volume, the average grain diameter is that of uranium dioxide, i. e. ~ 10 µm.

3.3.2 Available energy

The amount of the energy transferred from the fuel particles to the coolant is determined for both HZP and HFP cases and both particle sizes, on the basis of the radial thermal profiles at maximum enthalpies and location of the different zones. The values are gathered in Table 2 below.

Initial condition	**Normal zone**		**Restructured zone**	
	Volumic proportion (%)	Available energy (cal//g)	Volumic proportion (%)	Available energy (cal//g)
HZP	88.75	105.9	11.25	108.6
HFP	88.75	138.7	11.25	124.1

Table 2: available energy for both cases and both grain sizes

3.3.3 Amount of fuel loss

The relative fuel loss after clad failure is conservatively assumed to be 100%, consistently with what was observed in [1] with waterlogged fuel rods, or in some NSRR full-scale tests with rod failure.

3.3.4 Energy transfer kinetics

The energy transfer kinetics depend on the first order on the particle size (see § 3.3.1 above) and the fuel material thermal properties.

Let us consider a spherical fuel particle, of diameter D, at an initial temperature T_0 and which is embedded in a fluid at temperature $T_f < T_0$ at time t = 0. The energy balance between the particle and the fluid leads to the following differential equation:

$$\rho C_p \frac{\pi D^3}{6} . \frac{dT}{dt} = -H \pi D^2 .(T(t) - T_f) \qquad (3)$$

whose analytical solution is:

$$\frac{T(t) - T_f}{T_0 - T_f} = \exp(-\frac{t}{\tau}) \qquad (4)$$

where τ is the heat transfer characteristic time defined by:

$$\tau = \frac{\rho C_p D}{6H} \qquad (5)$$

with the following notations:

- ρ = fuel density (kg/m^3);
- C_p = fuel material specific heat (J/kg/K);
- H = heat transfer coefficient between the fuel particle and the fuel (W/m^2).

A well-established value for ρC_p is 3.10^6 J/K/m^3. The value of H is deduced from dedicated experiments performed by JAEA (figure 4 [4]). A realistic (best-estimate) value for H is ~ 10^5 W/m^2 and an upper-bound value is around 5.10^5 W/m^2.

With these bounding assumptions, we obtain the values for the characteristic heat transfer time: 10 ms and 0.2 ms for particle sizes of 10 µm and 0.2 µm, respectively.

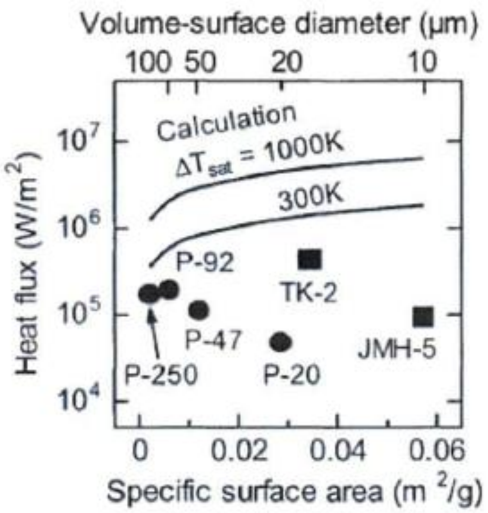

Figure 4: evaluation of heat transfer coefficient between ejected fuel particles and coolant [4]

3.3.5 Heat transfer transient

Gathering the hypotheses introduced above, the postulated energy transfer transient is defined as a two-step transient, illustrated on Figure 5 below.

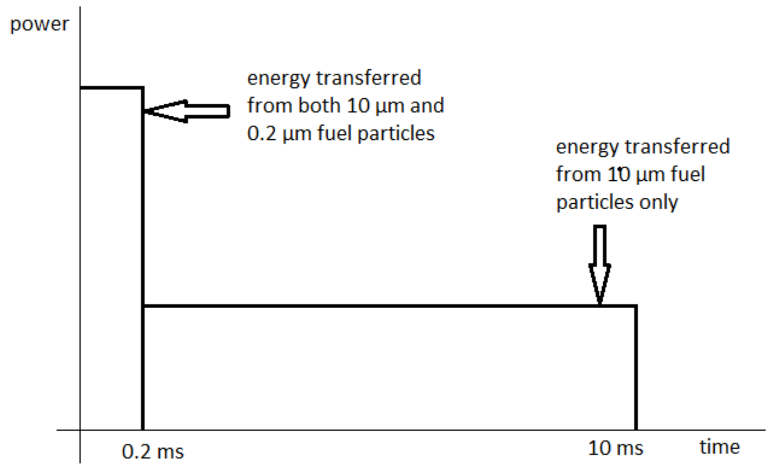

Figure 5: schematic of the two-step energy transfer transient from the fuel particles to the coolant

4. Transient simulation and results

4.1 Simulation tools

The acoustic and FCI pressure waves generation in the coolant fluid in the vicinity of the failed fuel rods following the RIA transients, and their combined mechanical effects on the surrounding structures, are simulated separately using the EUROPLEXUS fast transient dynamics software. Explicit time scheme resolutions based on finite volume and finite element formulations are respectively used for fluid and structure calculations.

4.2 Calculation schemes

Two different calculation schemes are used in the present study:

- A 2D-plane scheme (see figure 6 below) to study the pressure waves generation and propagation through a PWR fuel assembly, and evaluate the time-dependent force applied on the surrounding structures (fuel rods and guide tubes);
- A 2D-axisymmetric scheme to study the pressure wave propagation in open field conditions towards the core vessel wall.

In both schemes, concentric volumes representing the fuel stack, the local free volume and the thermal interaction volume (a volume equivalent to the pellet volume) are modelled. At failure time, the cladding is assumed to “disappear” and pressure wave generation and propagation in all directions can take place.

4.3 Cases examined

Consistently with § 3.1, three cases have been examined:

- RIA transient occurring at HZP with a linear free volume of 25 mm^2 (fresh fuel rod);
- RIA transient occurring at HZP with a linear free volume of 10 mm^2 (irradiated fuel rod with closed gap);
- RIA transient occurring at HFP with a linear free volume of 10 mm^2.

4.4 Consequences on adjacent fuel rods

4.4.1 Pressure wave propagation through a fuel assembly

The propagation of pressure waves (both acoustic and resulting from FCI) through a fuel assembly has been simulated considering that the leaking rod is in the middle of a PWR 17x17 fuel assembly. Figures 6 and 7 illustrate the different geometries used and the obtained time-history of the linear force applied on an adjacent fuel rod. It is notably observed that the first (and largest) oscillations, due to multiple reflections of the pressure wave in the fuel rod bundle, are insensitive to the number of surrounding rod rows that is considered.

Figure 6 : geometries of the fuel rod bundles with 4, 5 and 7 rod rows around the leaking fuel rod (1/8 of the rod bundle is represented; an "absorbing" boundary condition is set on the right side of the meshing)

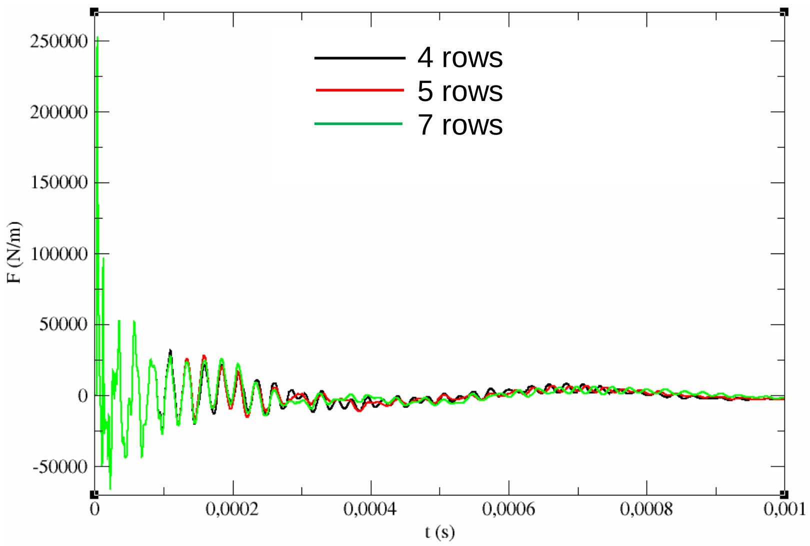

Figure 7: time-history of the linear force applied on an adjacent fuel rod, resulting from the impact of the pressure wave

4.4.2 Mechanical behavior of the adjacent rods

The force time-history has been used to determine the mechanical response of an adjacent fuel rod to the impact of the pressure wave. In this study, we consider a portion of an adjacent fuel rod comprised between two consecutive grids (length = 53 cm). This portion is modelled as a beam, whose mechanical characteristics (linear mass and moment of inertia) take into account the presence of fuel pellets in the rod.

The cladding material is assumed to be elastic, with a Young's modulus ranging from 40 to 80 GPa (corresponding to temperatures from ~300 to ~1000°C). For the most bounding case, the maximum kinetic and strain linear energies are less than 1.13 and 0.24 J/m, respectively. The strain energy is well below the linear strain energy at failure deduced from 3-point bending tests performed on rod portions with pellets at room temperature; this energy has been estimated at ~ 32.5 J/m.

The results obtained are consistent with the expected behaviour, considering the very high-frequency oscillations of the mechanical loading compared to the dynamical characteristics of the adjacent fuel rod (first natural bending frequencies lower than 100 Hz). This explains that only a very small part of the mechanical energy is actually converted into strain energy.

With such a result, the integrity of the adjacent fuel rods is not impaired by the impact of the pressure wave propagating from a leaking fuel rod after its failure due to an RIA transient.

4.5 Consequences on the core vessel

4.5.1 Methodology

The methodology adopted to evaluate the core vessel behavior is as follows:

- The EUROPLEXUS 2D-axisymmetric calculations in open field geometry provide the pressure time-history in the vicinity of a failed rod;
- The pressure wave generated by the failure of several rods, conservatively assumed to be perfectly superposed and synchronized, propagates towards the vessel wall according to a propagation law applicable in an open field (the wave amplitude is proportional to $1/\sqrt{x}$, with x = distance of propagation);
- The dynamic loading applied on the vessel wall is multiplied by 2 in order to take the wave reflection into account;
- On the basis of this loading, the risks of vessel failure by both plastic instability and fast fracture are evaluated.

4.5.2 Input data and preliminary results

An analysis of the operating experience regarding the presence of leaking fuel rods in the French NPP fleet shows that:

- Less than 5 rods are simultaneously leaking in a single core;
- Less than 2 rods are simultaneously leaking in a single fuel assembly.

Moreover, the EUROPLEXUS calculations show that the amplitude of a pressure wave that propagates through a fuel assembly (with the meshing shown on Figure 6) decreases very rapidly. As a consequence, only rods located at the very periphery of the core have to be considered, i. e. 2 rods facing the vessel wall and assumed to be superposed.

With such hypotheses, the maximum amplitude of the dynamic pressure wave that impacts the vessel wall (assumed to be at a distance of 40 cm from the failed rods) is 211 bars. The loading exhibits a very sharp transient, as is shown on Figure 8.

It should be noted that in a reactor, the core is tightly surrounded by the baffle, which does not constitute the 2nd containment barrier by itself. In such conditions, the pressure wave applied to the baffle would be much higher than 211 bars, but, according to [1], only a very small part (i. e. ca. 1%) of the pressure wave amplitude can propagate beyond the baffle towards the core vessel wall. As a consequence, the present analysis, which does not consider the presence of the baffle, is very conservative.

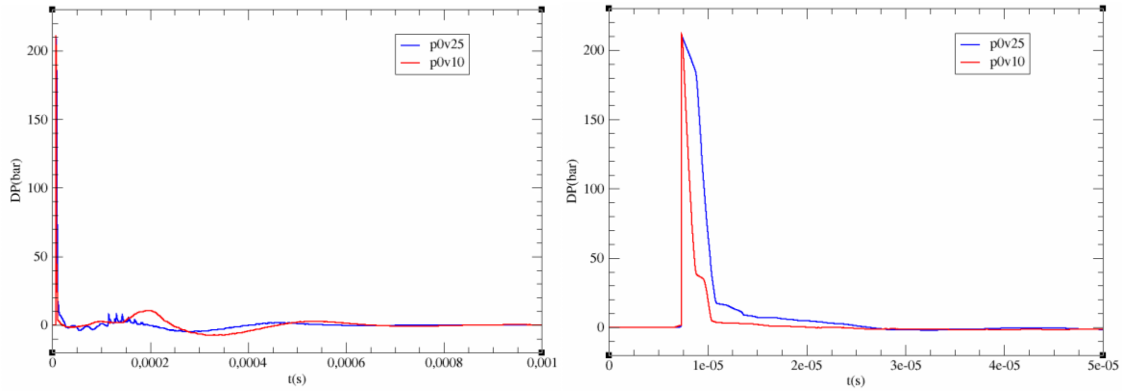

Figure 8: dynamic pressure loading of the core vessel wall resulting from the failure of 2 leaking fuel rods (right: zoom on the first instants of the loading)

4.5.3 Core vessel behaviour

With this loading, the dynamic response of the core vessel cylindrical body has been calculated with EUROPLEXUS. Figure 9 shows the 2-D meshing of the vessel body with its boundary conditions. Figure 10 shows the mechanical response of the impact of the pressure transients with two different loading (on a single point and uniformly on the vessel inner wall) and at two different instants.

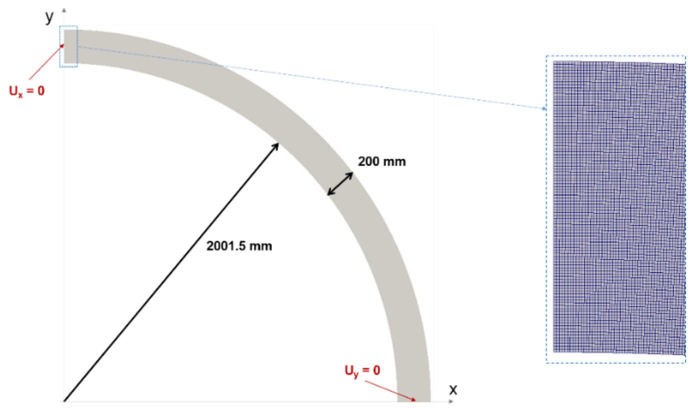

Figure 9: meshing of the cylindrical body of the core vessel with its boundary conditions

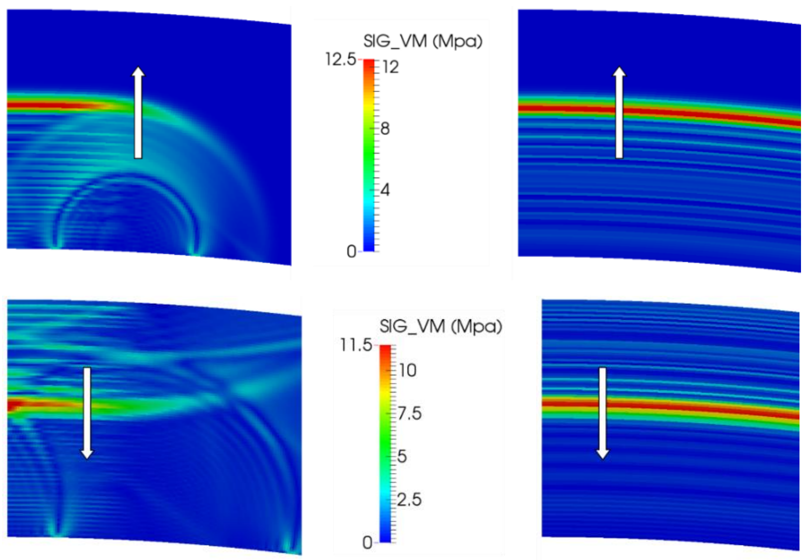

Figure10: dynamic loading of the core vessel wall; left: with a loading on a single point, bottom: with a uniform loading on the inner wall; the arrows indicate the direction of propagation of the Von Mises stress waves

The highest stress in the vessel wall roughly corresponds to a static overpressure of 15 bars. This is well below the pressure limit that could impair the integrity of the core vessel by both plastic instability and fast fracture.

5. Conclusions and perspectives

EDF has analyzed the consequences of the presence of leaking fuel rods during RIA transients, regarding the behavior of the adjacent structures (other fuel rods and guide tubes) and the integrity of the core vessel.

Two phenomena caused by the ingress of water in the rod free volume and which can impair the geometry of the adjacent structures and the integrity of the vessel have to be considered: the acoustic pressure wave generated by the burst of the leaking fuel rod (with a very high amplitude when liquid water is present in the rod) and a second pressure wave resulting from the ejection of fuel particles and thermal interaction with the coolant.

First, some bounding assumptions and input data have been determined in order to evaluate the characteristics of the pressure waves that emerge and propagate from a leaking fuel rod. Then, the mechanical consequences of these pressure waves on the adjacent structure and vessel wall have been evaluated by the means of EUROPLEXUS calculations. The maximum bending linear energy of an adjacent fuel rod impacted by the pressure waves is less than 0.24 J/m. The maximum equivalent static overpressure in the core vessel wall resulting from the impact of the propagating pressure waves is 15 bars. In such conditions, the geometry of the adjacent structures is not degraded and the integrity of the core vessel is not impaired. The safety requirements applicable to accident situations (i.e. maintaining a coolable geometry of the core and the integrity of the 2nd containment barrier) are thus not violated.

References:

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