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EPR – TESTS PERFORMED TO CONFIRM THE MECHANICAL AND HYDRAULIC DESIGN OF THE VESSEL INTERNALS

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ABSTRACT

The EPR is an Evolutionary high-Power Reactor which is based on the best French and German experience of the past twenty years in plant design construction and operation. In the present detailed engineering phase of the plant under construction in Finland (Okiluoto 3) and in France (Flamanville 3), some actions were led in order to improve the knowledge of the hydraulic behavior of the innovative Reactor Pressure Vessel internals (RPV). The RPV internals are mainly derived from former French N4 or German Konvoi with some evolutions to take into account the operating experience. Design and validation of the internals were performed within AREVA's engineering teams, which develop state of the art methods in the field of thermohydraulic testing. The experimental validation program was closely followed by EDF. Moreover, an EDF R&D project, whose results are not addressed here, was held to consolidate the RPV internals conception. The aim of the paper is to present the hydraulic tests performed on mock-ups to characterize the hydraulic behavior of the innovative EPR Reactor Pressure Vessel internals, and to present the role of these tests in the global conception process of the EPR RPV internals (CFD code qualification, design validation, database…).

Three different mock-ups are presented to illustrate these tests:

- JULIETTE for the reactor pressure vessel lower internals,
- ROMEO for the reactor pressure vessel upper internals,
- MAGALY for the design of the skeleton-type control rod guide assembly.

I. INTRODUCTION

The EPR is an Evolutionary high-Power Reactor under construction in Finland and France which benefit of the best French and German experience of the past twenty years in plant design construction and operation. In the detailed engineering phase, some actions were led in order to improve the knowledge of the hydraulic behavior of the innovative Reactor Pressure Vessel internals (RPV).

Design and validation of the internals were performed within AREVA's engineering teams, which develop state of the art methods in the field of thermohydraulic testing. The experimental validation program was closely followed by EDF. Moreover, an EDF R&D project, whose results are not addressed here, was held to consolidate the RPV internals conception.

The aim of this paper is to illustrate main technical developments performed in support to the EPR nuclear power plant. It is divided into three main parts:

- the first one presents the new design of the EPR,
- the second part illustrates the complementary approach of experiments and numerical simulation in the fields of plant design and safety justification,
- the third part presents three test programs performed to confirm the hydraulic and mechanical design of the EPR vessel internals.

II. NEW DESIGN ON A PROVEN FOUNDATION

The EPR Reactor Pressure Vessel (RPV) internals are designed in order to achieve the maximum benefit from the accumulated experience in designing and operating the Pressurized Water Reactor (PWR) units in service.

II.1 Lower Plenum

To improve the intrinsic safety of the reactor, the in-core instrumentation penetration of the EPR have been removed from RPV-bottom and implemented on the RPV-head in order to avoid pipe connections to the lower part of the RPV. Furthermore, the secondary core support is now ensured by eight radial keys. As a consequence the EPR lower plenum could be empty of structures.

In a lower plenum with no internal structure, large vortices may appear, with negative consequences, such as high disturbance in the core inlet flow and high increase of the RPV pressure loss. As a consequence, a specific Flow Distribution Device (FDD), developed by FRAMATOME-ANP, is fixed below the lower core plate by means of vertical columns to avoid flow vortex inside the lower plenum and to homogenize the flow distribution at core inlet.

II.2 The Heavy Reflector

In order to improve the fuel management (decrease of neutron leakage), to reduce Reactor Pressure Vessel fluence and to avoid barrel-baffle bolting check and replacement (increase of plants operability), the heavy reflector is a mechanical structure surrounding and restraining the core which replaces the bolted or welded baffle assembly presently existing respectively on French and German reactors. The reflector is located inside the core barrel, without contact with the barrel, and lays on the lower support plate of the internals. Its interior shape matches the core shape, while its outer shape is cylindrical. It is composed of twelve forged slabs, made of austenitic stainless steel without welding, positioned together with keys and attached to lower support plate by tie rods. The slabs are perforated to allow the passage of cooling water to remove heat generated by gamma power.

The reflector is hydraulically designed with the target to ensure a sufficient cooling of the slabs without inducing a high core by-pass flowrate. Cooling is provided by the core peripheral flow, the by-pass through the holes of the reflector, the local by-pass flow around tie-rods and keys, and the by-pass flow in the annular gap between reflector and core barrel. The cooling ducts and water gaps are subjected to the pressure difference between the bottom and the top of the core. The bottom slab contains a pressure and flow distribution chamber which feeds the ducts and the annular space between reflector and core barrel.

II.3 Upper Plenum and Control Rod Guide Assembly (CRGA)

In the upper plenum, located above reactor core, the reactor coolant flows out of the upper core plate vertically, then is distributed through the CRGA columns and the in-core instrumentation guide tubes and finally flows out horizontally into the four hot legs. The EPR upper plenum presents several innovations which affect flow downstream the core exit:

- increase of the number of Rod Cluster Control Assembly (RCCA) guide tubes and changes in their design (ex: cylindrical support columns)
- modification of flow paths between the tops of fuel assemblies and the upper plenum through openings in the upper core plate and at the bottom of the CRGA columns
- reorganization of the upper plenum (location of outlet nozzles, coolant passages through the upper core plate)
- installation of Aeroball structures and other instrumentation in the space under the reactor vessel closure head and in the upper plenum

The EPR CRGA design has been adapted from the Konvoi design to a 17x17 fuel assembly geometry.

III. DESIGN METHODOLOGIES EVOLUTION

III.1 Former Methodologies Reminder

The thermal-hydraulic design of the first PWR's was mainly based on experimental approach, with a large series of test on the main equipments (RPV plenums, control rod guide tubes…) to check their performances.

Mock-up and tests series were used to master the thermal hydraulic behavior of the RPV, to evaluate best-estimate loads applied on the structure and more globally to achieve a better design. At this moment, no computer code was able to model accurately such a complex RPV structure and flows, mainly because of the variety of encountered conditions and combined physical phenomena:

In normal operation:

- Jet impact,
- Flow reversal,
- Vortex,
- Piping swirl effect,
- Cross flows.

And in accidental conditions:

- Buoyancy effect,
- Jet mixing (injection device),
- Thermal coupling on RPV wall.

For all, the only solution was to experiment each phenomenon independently in order to provide elements needed to justify the design (separate tests) and to verify on global tests.

III.2 New Design Methodologies Process

Since some years, Computational Fluid Dynamics (CFD) computer codes are able to model the complex structures (on a three dimensional numerical model) and to solve the complex physical aspects, in the same time.

Nevertheless, experiments always play their role: for such complex structures; flows and physical phenomena. Comparison to experiment is essential to qualify the numerical codes because 3D combined thermal-hydraulic effects are not easy to simulate.

Thus, the first step of the new methodologies process is the computer code qualification thanks to the experimental results and the numerical approach takes place only after.

The validation of the EPR is based on both experiments and hydraulic calculations, handled in a complementary approach: The CFD simulations could help us at the beginning to define the suitable position of the instrumentation on the mock-up. The tests provide qualification results and validation results if the similitude laws are respected between the mock-up and the reactor for the non-dimensional numbers which govern the physical phenomena.

Once the code is qualified, the CFD simulations allow us to:

- test a large number of configuration and then to limit the number of tests on the mock-up.
- perform simulations at reactor scale with real reactor operating conditions for the design and safety justification of the reactors.

IV. REACTOR PRESSURE VESSEL INTERNALS VALIDATION

This section presents a part of the work performed to validate the design of main equipments of the reactor: the Reactor Pressure Vessel (RPV) internal structures.

The preliminary design of RPV internals, performed during the EPR Basic Design phase, was mainly based on analytical studies and tests with a preliminary geometry. It concluded that, for some aspects, it would be necessary to perform validation tests in order to confirm the final hydraulic and mechanical design of internals.

IV.1 Hydraulic Validation of the Lower Internals

The final hydraulic validation test of the lower internals has been performed on the JULIETTE mock-up located in AREVA NP Le Creusot Technical Center.

IV.1.1 Description of the mock-up (figure 1)

The JULIETTE mock-up represents at scale 1/5 the EPR vessel with the four inlet reactor coolant lines equipped with blades inducing a flow rotation (to simulate the flow rotation induced by the reactor coolant pumps), annulus, lower plenum, FDD, core support plate, core head loss simulation and axisymmetrical outlet. The head loss coefficient of the mock-up's bottom core support plate (including the flow rate measuring instrument) is set to a value higher than its equivalent on the reactor in order to take into account the effect of the core on flow distribution through the bottom core support structure.

The mock-up is fed by a pump which can flow until 500 l/s at ambient temperature; this flow rate can be then distributed between one, two, three or four of the cold legs (CL) (but could not exceed 125 l/s per CL).

Figure 1 : the JULIETTE loop

IV.1.2 Objectives of the JULIETTE hydraulic tests

The aims of the JULIETTE hydraulic tests are:

- to confirm the head loss coefficients of the main discontinuities encountered by the flow: RPV inlet nozzles and lower plenum,
- to confirm the performances of the FDD (figure 2) in the lower plenum of the RPV: mixing and flow distribution at core inlet,
- to provide data for quantification of the EPR geometry on vessel dilution phenomena (water plugs),
- to generate data required to verify the numerical RPV flow simulations: measuring flow velocity maps and temperature distributions in the cold legs, annulus and lower plenum

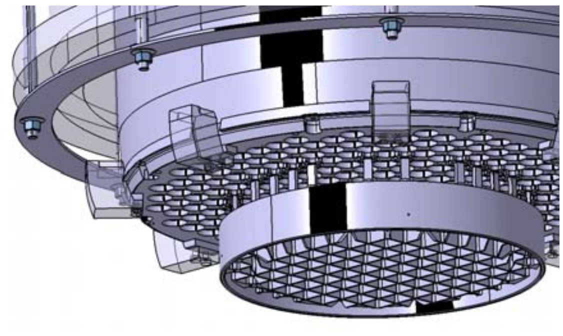

Figure 2 : the JULIETTE mock-up - FDD

The instrumentation and data acquisition allow measuring static pressure at more than 70 different positions: in the cold legs, at different level of the annulus, in the downcomer, under the core support plate and at the outlet of the mock-up.

For the first time, the flow distribution and the hydraulic load are measured at each fuel element position through 241 venturi (figure 3) with a really good precision despite the disturbance of the upstream flow. The accuracy of the venturi has been verified in a single channel loop even with disturbed upstream flow configurations. Moreover, the measure at each fuel element position allows verifying measurement coherence and accuracy by mass balance on the mock-up.

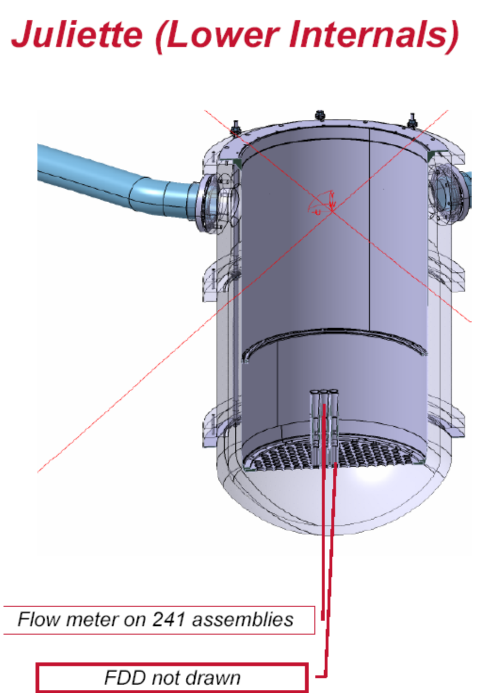

Figure 3 : the JULIETTE mock-up – Venturi instrumentation

The velocity field is measured within the lower plenum using Laser Doppler Velocimetry and Particle Image Velocimetry methods.

For steady states, the temperature distribution and mixing flow at core inlet are measured at each fuel element position thanks to a new technology: the ICP AES (Inductive Coupling Plasma Atomic Emission Spectrometry) which allows determining precisely the concentration of a tracer element even for very low concentration.

To measure vessel dilution phenomena during transient, the mock-up is instrumented with more than 80 thermocouples at the bottom of the down comer and at the core inlet.

IV.1.3 Main test results

Inside the RPV lower plenum, a part of the flow is directly deviated to the inlet of the core support plate by the outside of the FDD. The other part flows towards the bottom of the lower plenum, where flows coming from all 4 loops join and mix, and then flows up to the core support plate through the FDD. Finally, at core inlet, overflows are mainly located in the center of the core, while underflows are located in the border. To limit this tendency and to have a more flat flow distribution at core inlet, we realized a differential drilling for the core support: the strategy for the differential drilling was to decrease the head loss coefficient of the holes located at core periphery.

The FDD and the differential drilling optimized on the mock-up guarantee a maximum overflow at core inlet which is compatible with fuel assembly design, even in penalizing conditions (unbalanced loop-flows, swirl in cold legs). Moreover, in the same conditions, it guarantees that the minimum flow rate feeding any fuel assembly is acceptable and prevents too large feeding differences between neighbor fuel assemblies from occurring which limits cross flows at the bottom of the assemblies (see figures 4, 5 & 6).

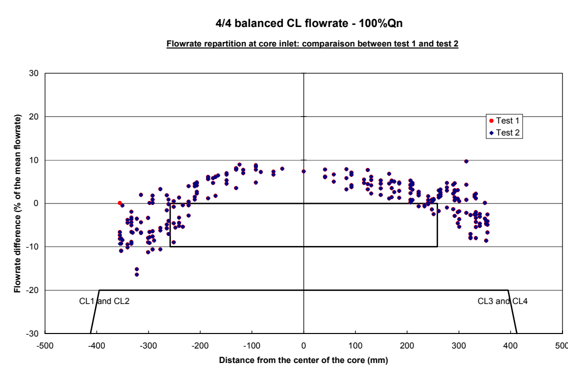

Figure 4 : JULIETTE mock-up – Flow rate distribution

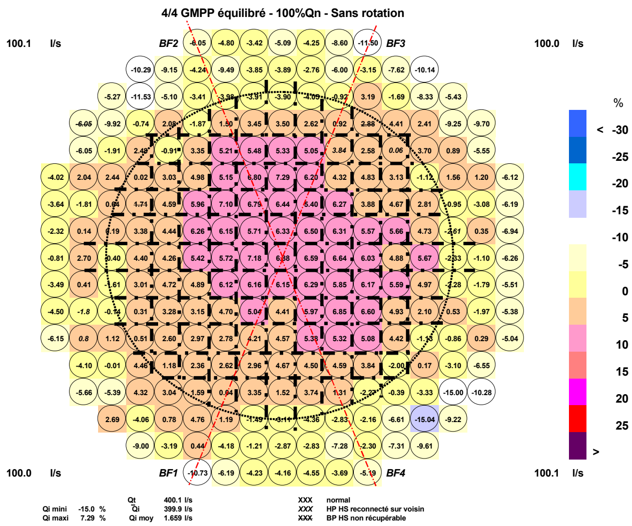

Figure 5 : JULIETTE mock-up – Flow rate distribution at core entrance

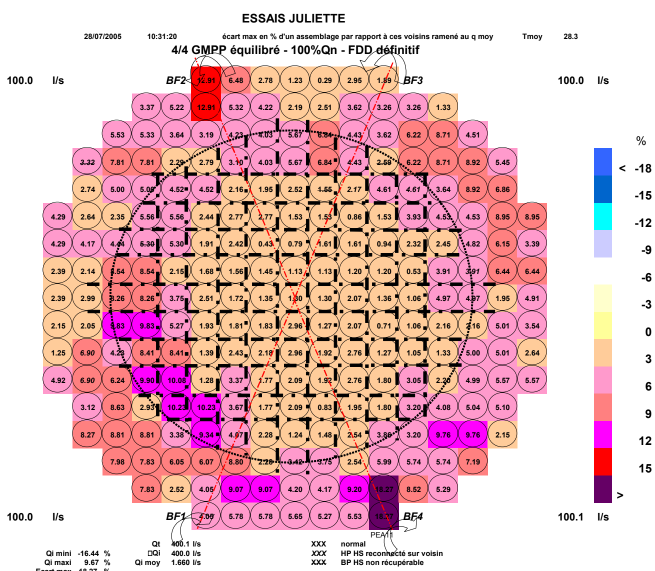

Figure 6 : JULIETTE mock-up – Flow rate difference between neighbours

Finally the overall flow distribution generated by the optimized FDD and differential drilling of the core support plate is flat enough not to create any flow heterogeneity in the core which could damage fuel assembly. The flow distribution at core inlet obtained on the EPR is better than the one obtained on previous French N4.

As the FDD prevents vortices from appearing, the pressure loss in the RPV lower plenum has been greatly decreased compared to the case where the lower plenum was empty.

The pressure loss is also lower compared to the value obtained on previous French reactor plant (N4 or 1300MWe) .This has a positive impact on the required head of Reactor Coolant Pump, on its cost and on global plant efficiency.

IV.2 Hydraulic Validation of the Upper Internals

The final validation test of the upper internals has been performed on the ROMEO mock-up also located at Le Creusot Technical Center.

IV.2.1 Description of the mock-up (figures 7 & 8)

It consists in a 1/5 scale mock-up complementary to the JULIETTE one, representative of the upper core plate with simplified holes geometry and calibrated head losses, the upper plenum with all its columns (normal and Control Rod Guide Assembly columns), the four RPV outlets and hot legs. The head loss coefficient of the mock-up's upper core plate (including the flow rate measuring instrument) is set to a value higher than its equivalent on the reactor in order to take into account the upstream effect of the core on flow distribution through the upper core plate. The mock-up is fed by a pump which can flow until 500l/s at ambient temperature

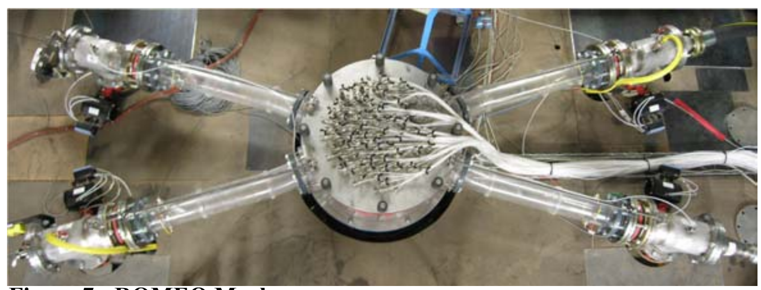

Figure 7 : ROMEO Mock-up

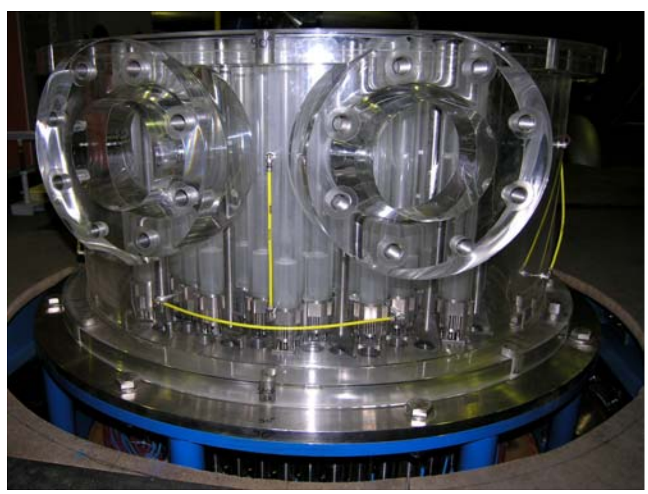

Figure 8 : ROMEO upper plenum

IV.2.2 Objectives of the ROMEO hydraulic tests

The aims of the ROMEO hydraulic tests are to determine:

- the flow rate map of upper plenum inlet: the purpose is to determine the effect of the upper plenum on flow distribution through the various openings in the UCP, at each fuel assembly exit.
- the pressure field in the plenum at the level of the upper support plate and in the CRGA,
- the head loss coefficients of the upper plenum and of the hot leg nozzle
- hydraulic loads on the CRGA columns,
- velocity maps, the temperature heterogeneousness and the temperature map stability in hot legs,
- fluid mixing in the upper plenum.

The test results concerning temperature heterogeneousness and fluid mixing in the upper plenum will allow qualifying the CFD simulations that should be performed in order to:

- justify the adequacy of the number and the position of the hot leg temperature measurement devices (see figure 9 which describes the methodology applied to take into account the impact of the hot leg streaming on the hot leg temperature measurement uncertainty)
- to determine the upper plenum mixing coefficients matrix

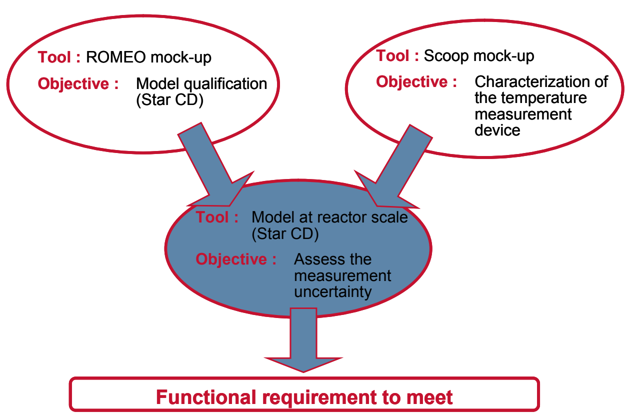

Figure 9 : Hot leg streaming methodology

The instrumentation and data acquisition allow measuring static pressure at more than 120 different positions: in the hot legs, under the upper support plate, in the CRGA columns, and on the upper plenum barrel. For the first time, the flow distribution is measured at each upper plenum flow channel through 241 sensors and also the relative hydraulic head between the 241 flow channels.

This flow distribution (see figure 10) allow meeting the functional requirements on maximal local overflow, maximal local underflow and flow difference between neighbours.

	A	B	C	D	E	F	G	H	J	K	L	M	N	P	R	S	T
17						4,0	1,3	0,1	3,0	-1,5	1,6	4,7					
16				6,7	-0,1	0,7	-5,6	-3,1	-9,9	-3,9	-6,1	-0,8	-1,4	5,8			
15			12,4	-3,3	-0,3	-7,7	-0,6	-4,1	-1,6	-5,9	-1,9	-7,4	-1,7	-4,4	11,9		
14		13,0	-0,2	1,9	-8,2	-3,6	-4,7	-2,2	-2,5	-3,4	-5,5	-2,5	-7,5	-0,4	-1,6	14,4	
13	HL2	9,2	4,8	-5,3	-1,0	-5,5	-0,8	-5,3	-1,3	-5,1	-1,2	-5,5	-1,6	-5,2	4,3	8,7	HL3
12	14,5	8,7	-0,3	1,6	-4,1	-2,1	-4,8	-1,3	-5,7	-2,4	-5,3	-2,2	-4,1	0,8	-1,7	9,6	13,7
11	12,3	3,0	5,5	-0,5	2,0	-4,4	-0,9	-5,6	-3,8	-5,9	-1,8	-5,6	1,7	-1,2	4,4	3,2	13,9
10	8,8	7,4	0,8	0,8	-2,4	-0,7	-5,7	-1,9	-6,6	-1,2	-5,2	-0,8	-3,0	1,6	0,2	5,5	7,9
9	12,2	-1,3	4,8	1,1	2,6	-4,7	-4,5	-5,9	-2,3	-5,3	-3,3	-4,4	2,2	2,3	4,1	-1,2	13,1
8	8,2	6,2	1,3	2,6	-2,5	-0,8	-5,9	-2,6	-6,2	-2,7	-5,7	-0,4	-2,4	2,0	0,8	6,8	9,0
7	13,8	3,4	4,9	-1,5	1,9	-4,8	-1,7	-7,0	-4,8	-5,6	-1,8	-4,0	1,8	0,2	4,7	2,4	12,9
6	14,3	9,1	-2,3	1,0	-3,3	-2,5	-5,6	-2,3	-6,9	-1,6	-5,3	-2,5	-4,2	1,4	-0,4	10,3	13,8
5	HL1	8,7	3,5	-5,3	-0,2	-3,8	-1,2	-5,5	-1,3	-4,7	-0,6	-5,2	-1,7	-6,1	4,6	11,2	HL4
4		13,9	-1,0	0,5	-7,0	-2,3	-5,9	-3,0	-2,8	-3,5	-4,3	-3,8	-7,7	0,3	-0,5	14,2	
3			12,5	-3,5	-1,2	-7,1	-2,3	-4,7	-1,0	-6,6	-2,1	-8,0	-0,9	-3,4	13,5		
2				5,2	-0,7	0,7	-5,4	-3,1	-10,2	-4,1	-6,1	-0,3	-0,3	5,3			
1						5,7	3,2	-1,1	1,7	1,7	1,1	3,4					

Figure 10 : Core outlet flow distribution

The velocity fields (figure 11) are measured within the hot legs using Laser Doppler Velocimetry and Particle Image Velocimetry methods.

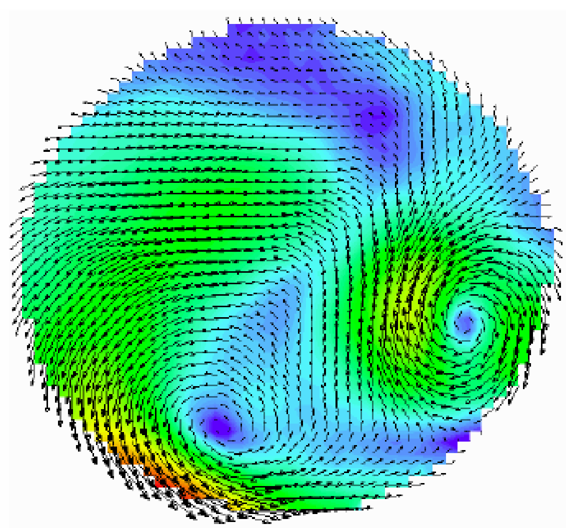

Figure 11 : Hot leg transverse velocity field

The temperature heterogeneousness will be measure in 161 points of a section (figure 12) and for different sections of a hot leg with thermocouples.

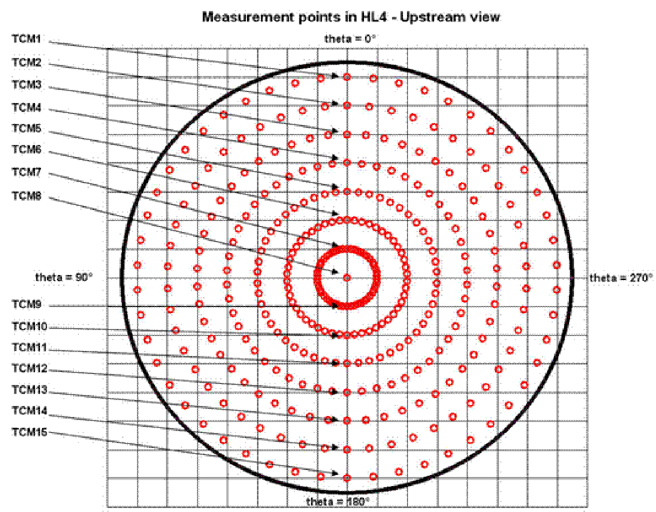

Figure 12 : temperature measurement in a cross section of the hot leg

Concerning the fluid mixing tests, we measure simultaneously in four hot legs the mean tracers concentration in each leg.

IV.3 Control Rod Guide Assembly and Rod Cluster Control Assembly Validation

The aim of MAGALY tests is to optimize and validate the EPR CRGA (Control Rod Guide Assembly) parts design, with respect to hydraulic (head loss, drag force and contact force measurements), and vibratory aspects (RCCA rod, CRGA and drive rod). The facility is located at AREVA Le Creusot Technical Center.

IV.3.1 Description of the MAGALY mock-up and its instrumentation

The MAGALY mock-up (figure 13) is a scale 1:1 hydraulic facility operating in water at a temperature of 40°C. The mock-up represents the full scale reactor control line, including a real EPR innovative CRGA. The MAGALY test loop is representative of the EPR drive line from the top of the fuel assembly to the drive shaft housing. The figure 14 describes the bottom part of the CRGA.

The test facility includes a main water circulation loop with a total volumetric flow rate up to 1200 m^3/h.

Figure 13 : MAGALY loop

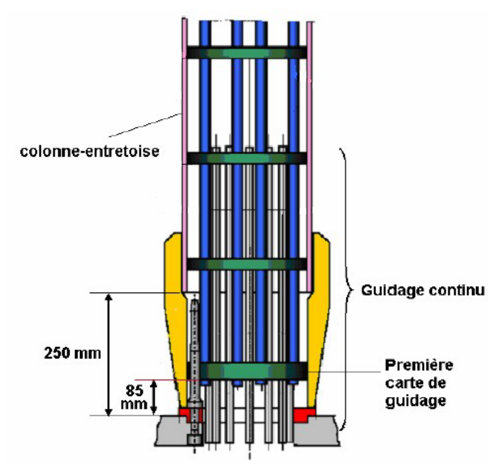

Figure 14 :EPR CRGA bottom part

Instrumentation

The instrumentation of the MAGALY bench allows different kinds of measurements.

- The RCCA control rods vibrations are measured by the mean of eddy-current sensors in two orthogonal directions at several levels of the CRGA. The data recorded thanks to these sensors are the vibration amplitude, the control rod trajectories and the force and frequency of the impact of the rod on its antagonist (C-tube, guide plate, FA guide tube).

- The pressure difference exerted on both sides of the control rod in the continuous guidance creates a normal hydraulic force that presses the control rod along the C-tube slot and that induces friction force which can be likened to an individual rod drag force. The measurement of the pressure difference is done thanks to an instrumented rod that allows measuring the pressure along the continuous guidance.
- The overall RCCA drag force (total friction force that goes against RCCA axial motions) is measured by raising/lowering the RCCA axially and measuring the corresponding restraint force under flow. The difference of the two measurements allows determining the drag force.
- The head losses measurements are performed on differents level of the control line.

Flow rate simulations in the facility

As mentioned above, the aim of the MAGALY tests is to study the behaviour of the CRGA to be used on the EPR in regard to the hydraulic (overall drag force and contact forces in C-tubes) and vibratory (CRGA and control rod vibrations) standpoints.. All flow paths that can have an influence on these measurements are simulated.

The flow paths are represented on figure 15 and are the followings:

- Q1: axial flow exiting the fuel assembly (guide tubes excluded);
- Q2: axial flow coming from the guide tubes of the fuel assembly;
- Q3: transverse flow under the UCP, simulating a flowrate coming from a neighbouring fuel assembly;
- Q4: flow coming from or going to the upper dome;
- Q5: crossflow in the upper plenum. This flow is simulated in the case of the installation of some particular deflectors (see below);
- QS1, QS2, QS3 and QS5 are flowrates going through the four outlets of the bench.

All the previously mentioned flowrates cover EPR configuration both in term of flowrate and kinetic energy.

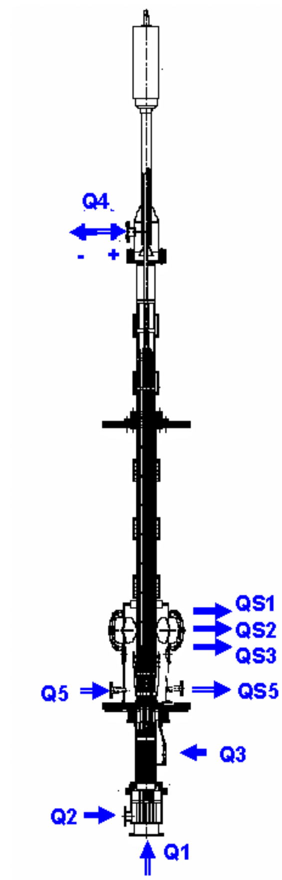

Figure 15 : MAGALY flow rates

Hydraulic representation of particular positions of CRGA in the upper plenum

The hydraulic environment at the bottom of the CRGA depends on its position in the upper plenum. To simulate the hydraulic at the bottom of the CRGA and to better understand the impacts of the geometrical restriction and the crossflow in the upper plenum on the hydraulic behaviour EPR CRGA, deflectors of restriction have been designed. Four different deflectors are used to represent some of the most penalizing situations encountered in a PWR upper plenum:

- no deflector of restriction
- deflector of maximum restriction: this case corresponds to a CRGA in central position, surrounded by four neighbouring CRGAs and four circular holes in the UCP. In this case, the flow exiting the UCP is strongly forced upwards. This situation can constitute an extreme case (very closed plenum) in regard with the drag forces and will be compared to the case where no deflector of restriction is installed (corresponding, on the contrary, to a very opened plenum);

- deflector of maximum crossflow: this deflector corresponds to a CRGA subjected to a significant crossflow;
- deflector deviation: this deflector simulates the case of an edge CRGA, located near a RPV outlet nozzle. In this case, the flow coming from the FA is almost totally deflected.

IV3.2 Test program organization

The MAGALY hydraulic test campaign is divided in two main phases. The first phase of the MAGALY tests is dedicated to the optimisation of the CRGA and to the definition of the final design of the bottom part of the CRGA. Different geometrical parameters are studied:

- Altitude of the first guide plate of the continuous guidance
- Opening height between the UCP and the lower end of the support column.
- Presence/absence of holes in the split tubes of the continuous guidance.

The goal of the optimisation process is to choice the best geometrical configuration of the EPR CRGA leading to the lowest RCCA overall drag force and rod vibrations in various hydraulic conditions. At the end of the first phase, an optimised geometry of the lower part of the CRGA is defined.

The second phase aims to obtain a fine characterisation of the hydraulic and vibratory EPR CRGA behaviours with a more complete instrumentation than in the former phase. More particularly, the validation test phase evaluates:

- Pressure drop at the bottom of the CRGA
- RMS vibrations and impact loads of the control rods
- Overall RCCA drag force
- Evolution of the profile of the pressure difference exerted on both sides of the control rods.

The second phase of MAGALY tests aims at validating the optimised geometry from control rod vibrations and RCCA overall drag forces standpoints. The EPR CRGA design must respect hydraulic and vibratory behavior requirements established on the basis of prior MAGALY tests and feedback experience in reactor. Indeed, the EPR CRGA drag force must not exceed drag forces measured on previous design CRGA MAGALY tests and the control rod vibrations have to be moderate, ideally lower from ones of the “1300 type” CRGA.

The second phase of MAGALY tests also aims at collecting input data for other validation tests:

- Impact loads at the level of guide plate and normal forces in the split tube of the CRGA are recorded and are to be used as input data for wear-induced degradation tests.
- Vibratory amplitudes and natural frequencies of the CRGA under flowrate modal analysis are also studied and will be used as an input data for fatigue vibratory tests.

IV3.3 Main tests results

The presentation of the result emphasizes the drag force studies. Indeed, the vibrations of the control rods exhibit low amplitudes of vibration at all levels where measurements have been performed. They do not exceed amplitudes of vibrations of control rods in case of “1300 type” CRGA, which is considered as a maximal value not to exceed regarding wear phenomena. The MAGALY test results show that the EPR rod vibrations are acceptable compared to the former EDF PWR and should lead to a better wear resistance of the CRGA and of the control rods.

Impact of the CRGA bottom part design

Several geometries of the lower part of the CRGA have been studied: different opening heights of the support-column and different altitudes of the first guide plate in regard to the reference design. Finally, it appears that drilling of holes in the continuous guidance and modifying the altitude of the first guide plate leads to lower overall drag forces than the reference design. The figure 16 compares the overall drag force between different geometrical configurations and different flow rates.

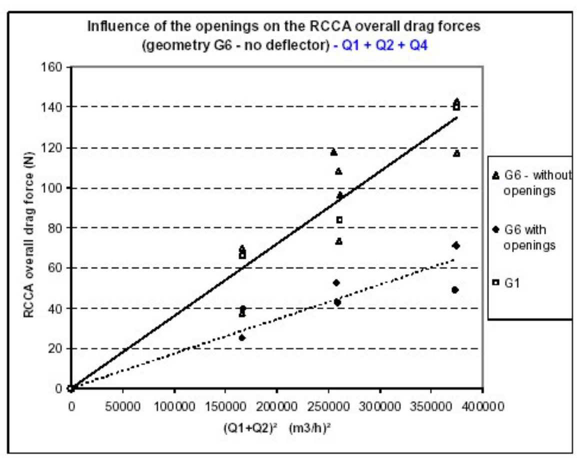

Figure 16 :EPR CRGA optimization – Drag force

As seen before, openings in the continuous guidance allow lowering the drag force. Indeed, the drag coefficient is directly linked to the evolution of the difference of pressure on both sides of the control rods. Machining holes at the level of the split tubes of the CRGA allows balancing the pressure on both sides of the control rods and so limiting the RCCA overall drag force (cf. figure 19). The first step of openings is drilled just above the first guide plate, and the second one is machined just above the second guide plate. The presence of openings leads to a large decrease of the pressure difference above the first guide plate and so to a decrease of the rod drag force.

Impact of the hydraulic conditions

The impact of the different deflectors and flowpaths on the hydraulic behaviour of the drive line was studied. The figure 17 presents the evolution of the drag force with the flowrate value for different hydraulic configurations (deflectors of restriction). The impact of the flowrate value is more important than the impact of the deflector geometry. Moreover, the less penalizing situation is without deflector, close to the situation with deflector of deviation. The most penalizing situations are with deflector of maximum restriction or maximum crossflow. Nevertheless for given values of Q1 to Q3 and Q4 (if any), the maximal difference between the less and the most penalizing situation is quite low.

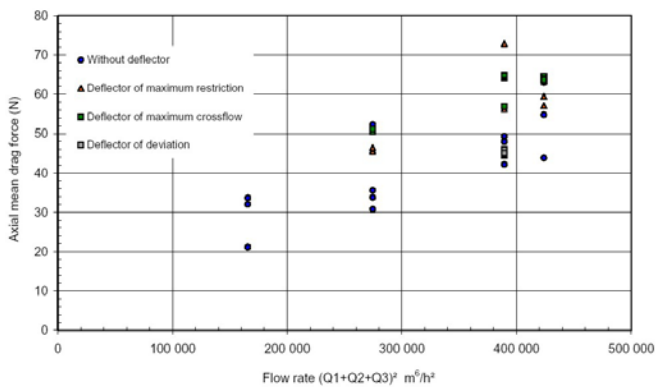

Figure 17 :EPR CRGA validation – Drag force

The figure 17 shows that the drag forces evolution with $(Q1+Q2)^2$ is linear. Indeed, the increase of Q1 + Q2 induces an increase of the maximal normal force measured over a height of 100 mm. It can be observed on Figure 19 the presence of a peak at the entrance of the C-tube: the more important Q1+Q2 is, the higher the peak.

The figure 17 also shows that the effect of the transverse flow rate Q3 on the RCCA overall drag force can be likened to an overflow of the axial flow rate. Figure 18 shows the impact of the transverse flow rate Q3 on the pressure difference in the continuous guidance and so on the overall drag force. Indeed, the peak at the entrance of the C-tube is more important than in cases of Q1 + Q2 only: the flow Q3 forces rods against the split of the C-tube and its effect can be assimilated as an overflow.

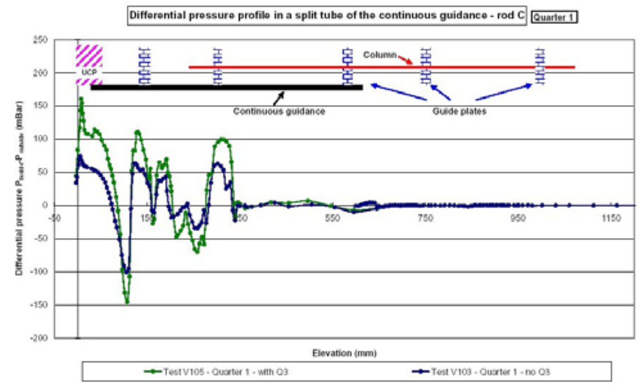

Figure 18 :EPR CRGA validation – Individual drag force

The Q4 flow rate (flow coming from or going to the upper dome) induces very slight effects on RCCA global drag force (figure 19)

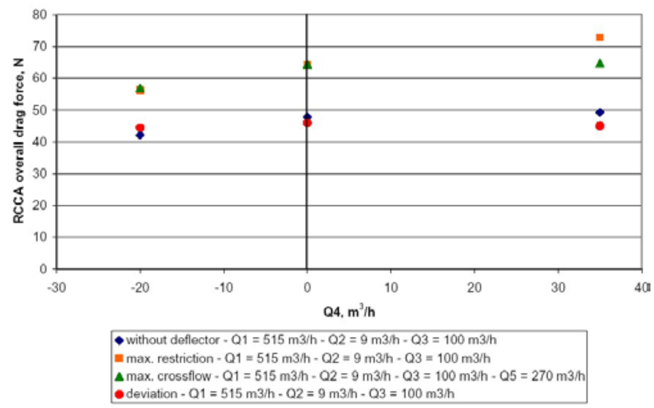

Figure 19 :EPR CRGA validation – Impact of Q4 on the drag force

Comparison to previous MAGALY tests

The figure 20 compares the RCCA overall drag forces in the case of the EPR with what has been obtained in MAGALY former CRGA tests. The EPR RCCA drag forces appear to be the lowest. From overall drag force point of view, the comparison validates the EPR CRGA design.

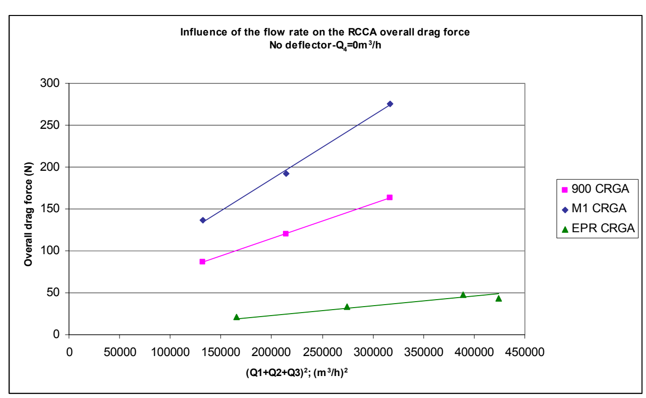

Figure 20 :EPR CRGA validation –Overall drag force

Conclusion:

From control rod vibrations and RCCA overall drag forces points of view, MAGALY tests demonstrate that the EPR CRGA design is fully satisfactory. RCCA overall drag forces are lower than the values previously obtained for various geometry of CRGA and satisfy requirements. Control rods exhibit low amplitudes of vibration at all levels where measurements have been performed. The MAGALY test results show that the EPR rod vibrations are acceptable compared to the former EDF PWR and should lead to a better wear resistance of the CRGA and of the control rods. This point needs to be confirmed by wear tests.

On the other hand, the data needed for other EPR CRGA validation tests (not addressed here) have been gathered. The vibration impact loads and frequency are input data for wear-induced vibrations test. The normal force induced by the pressure difference on both sides on the control rods are input data for wear-induced translation test and the skeleton vibrations are input data for CRGA fatigue tests.

The EPR MAGALY tests campaign is thus a central element of the validation process of the EPR CRGA.

IV. CONCLUSIONS

The design of the EPR, an evolutionary reactor which keeps the best of French and German experience in water reactor design and construction, has benefited from large R&D programs in Hydraulics based for the first time on a new complementary approach: experimental tests on mock-up and hydraulic calculations thanks to the evolution of CFD codes. The design evolutions led to increase the plant safety, operability and life time.

The complete and accurate instrumentation of the mock-ups and the wide scope of the tests, allied to 3D calculations, have provided a unique and comprehensive set of material validating and demonstrating the soundness of the EPR design features.