STRUCTURAL MONITORING OF PRESTRESSED CONCRETE CONTAINMENTS OF NUCLEAR POWER PLANTS FOR AGEING MANAGEMENT

A. Simon[1], A.Courtois[2]
[1]EDF(Electricité de France, DTG, 21 avenue de l'Europe, Grenoble, FRANCE-38000
[2]EDF(Electricité de France, DTG, 12 Rue Saint Sidoine, Lyon, FRANCE-69003
E-mail of corresponding author: alexandre-gilles.simon@edf.fr

ABSTRACT

Extending the operating life of nuclear power plants implies to monitor the civil engineering structures ageing. Structural monitoring of the prestressed concrete containment is one of the main components of the EDF's strategy to justify that safety requirements will be reached until the end of operating life. Containment structures are instrumented to check their behaviour during construction (especially tendon tensioning), during periodical pressure tests and for prestressing losses monitoring. Nonetheless current instrumentation was designed for 30-40 years of operation. Operating life extension up to 60-80 years requires then developments for an appropriate and sustainable structural monitoring system for reliable long term surveillance.

This paper will present our approach that leads to the definition of an Optimum Surveillance System (OSS). This concept defines the required sensors and measurements that are necessary to ensure efficient surveillance of the pressure concrete containment with an operating life of 60 years.

This Optimum Surveillance System includes on one hand the sensors which deliver global displacement and which can be replaced (such as pendulum) and, on other hand, the sensors dedicated to local phenomena, initially embedded in concrete (such as strain meters) and thus inaccessible. An equivalent system is then required to maintain the OSS in case of failure of an embedded sensor. For that purpose EDF has developed new devices.

This paper will also deepen the specific work made about how to acquire and validate measurements of deformation in the concrete. This work is structured around two principal themes:

- Reinstatement of vibrating wire strain meters owing to innovative electrical excitation approach combined with appropriate signal processing techniques.
- Development and installation of an accurate surface extensometer when embedded strain meters were out of order.

A two-step approach was adopted for the validation of the surface extensometer's behaviour for long term monitoring deformation:

- Step 1: laboratory experiments.
- Step 2: installation on prestressed concrete containment and comparison with embedded strain meters.

The positive results led to the successful validation of surface extensometer for both decennial pressure testing and long term monitoring. The uncertainty associated to surface extensometer is coherent with creep rate measured on containment building and is about a few microstrains per year.

The two proposed developments ensure capturing all the necessary information for suitable monitoring of the long term behaviour of prestressed concrete containment.

INTRODUCTION

In the current fleet operated by EDF in France, containments of the Pressurised Water Reactors (PWR) are made of prestressed, reinforced concrete. Prestressing is used to balance the forces which the containment would be subjected in the event of internal or external hazard.

In addition to the leak tests, the design of containments requires a strength test to be carried out. This test aims to confirm the good mechanical behaviour of the containment when submitted to a pressure equivalent or greater than design pressure (see the requirements of codes, such as RCC-G part 3 in France or ASME section III, division 2, chapter CC6000 in the USA). This acceptance test requires the measurement of structure mechanical response using a wide range of instruments (displacement, deformation and temperature sensors).

Additionally to this design requirements, prestressing must be monitored regularly to ensure that it remains sufficient and effective throughout its operating life. Many phenomena, such as concrete creep or cable corrosion, may significantly reduce its efficiency. The choice of grouting prestressed tendons has advantages in terms of prevention of the reinforcements corrosion. Furthermore, in the event of a strand failure, the bonds between the tendon and the grout enable part of post-tensioning to continue to be transmitted to the structure. On the other hand, this option prohibits future inspection or maintenance operations, which are possible in the case of prestressed tendon injected with grease. Therefore, this specificity led to the setting up of a monitoring system. It consists of periodic tests (every 10 years) at accident pressure and monitoring the behaviour of the containment throughout its life.

In practice, long-term monitoring is mainly carried out by sensors used for the acceptance test. Today, after 20 to 30 years of operation certain sensors have failed. Furthermore, a life extension strategy requires operators to review the durability of containment monitoring systems. It therefore appeared important to define Optimum Surveillance System (OSS) in order to prove that the prestressing level of the containment continues to fulfil the safety requirements. Among sensors constituting the OSS, some are originally embedded in the concrete of the structure, and as such cannot be replaced with the same models. This article will describe two major improvements in this domain:

- The reinstatement of certain embedded sensors initially declared to be unserviceable
- Installing alternative instrumentation capable of measuring the same physical variables as the embedded sensors. Validation of this alternative instrumentation and detailed quantification of the corresponding uncertainties will then be described.

Thanks to the efforts made in the definition and durability of the OSS system, it should be possible to monitor and assess the mechanical behaviour of the containment over several decades.

DEFINITION OF THE OPTIMUM SURVEILLANCE SYSTEM (OSS)

The 58 PWR of the EDF nuclear generating fleet are classified according to their type of containment (Fig. 1) (third barrier between radioactivity and environment):

- The 900MW power plants (34 units): the third barrier consists of a prestressed concrete single wall containment with an internal liner plate (metal sealing lining)
- The 1300 and 1450 MW power plants (24 units): the third barrier consists of two containments (one inside the other: the outer reinforced concrete containment and the internal prestressed concrete containment.

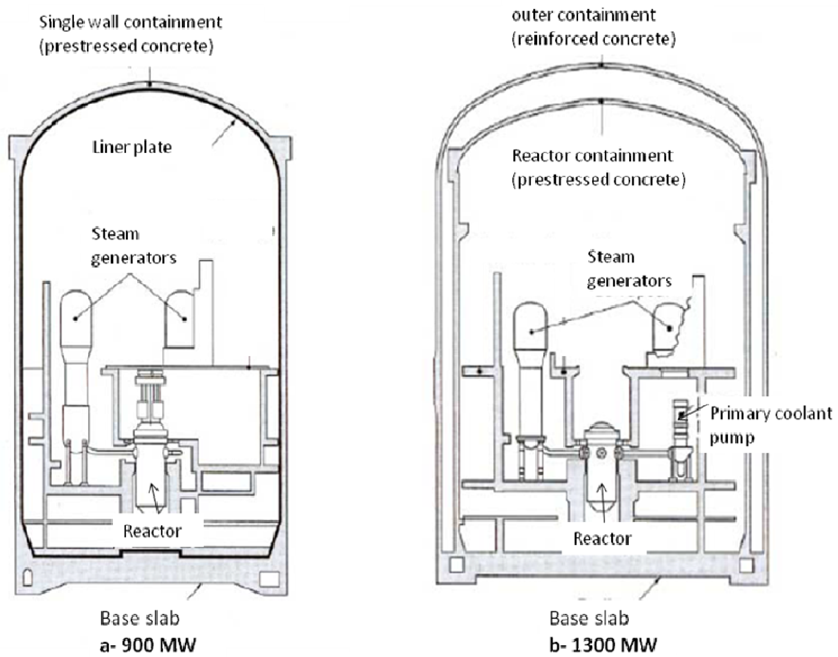

Fig.1: Representation of the two types of containment of the fleet of PWRs

The containment monitoring system was originally used for two purposes. First, to check design hypotheses during construction and second, to regularly assess structure behaviour during containment test. This monitoring system provides three types of measurements:

- Measurement of displacement (plumb lines, Invar wires, survey markers)
- Measurement of the structure local deformation (strain meters embedded in the concrete structure)
- Measurement of variations in stress of certain prestressing cables (dynamometers)

The number of these different measuring instruments varies according to the considered containment. As prototypes, the first containments were equipped with extensive instrumentation to validate the concrete composition formula. The need to monitor prestressing throughout the life of the structure led EDF define a suited instrumentation dedicated to the long term monitoring of the containment (OSS). The sensors and physical variables used in the OSS system are given in table 1:

Table 1: Composition of the OSS

Physical variables	Original monitoring instruments	Part of the OSS	Replaceable nature of the equipment
Displacement (mm)	Survey markers	YES	YES
Displacement (mm)	Hydraulic levelling pots	NO	Not applicable
Prestressing (Mpa)	Dynamometers	NO	Not applicable
Displacement (mm)	Plumb lines and Invar wires	YES	YES
Strain (µm/m)	**Vibratory strain meters embedded in the concrete**	**YES**	**NO**
Temperature (K)	Thermocouples	YES	YES

Strain measurement in the concrete is crucial regarding long run monitoring because it is the only means which cannot be replaced, in the event of failure. This study describes progresses in:

- Extracting the best information from embedded strain meters
- Developing and qualifying an alternative deformation measuring instrument.

STRUCTURE STRAIN MEASUREMENT

Principle of the strain measurement by vibrating wire strain meter

Strain in concrete is measured by sensors using vibrating wire technology. This sensor is made up of a steel wire sensing element enclosed into a protective body. The sensor is embedded in the concrete during construction. When the concrete is compressed, the two ends of the sensor come together and the wire slackens; similarly, when the concrete comes under traction, the ends move away and the wire is stretched. A simple equation links the tension of the wire and its frequency of mechanical vibration. By measuring the vibration frequency, the deformation of the concrete can be assessed. Figure 2 gives an illustration of a vibrating wire strain meter.

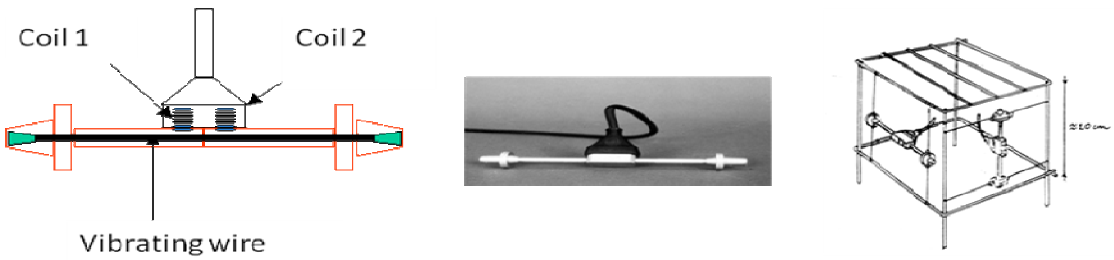

Fig.2: Sketch of a vibrating wire strain meter for the measurement of deformation inside concrete

The wire is set into transverse motion by exciting it with a short pulse of current passed through the two electromagnetic coils positioned near the center of the wire. Since the wire is made of ferromagnetic steel, it is sensitive to the magnetic field and starts vibrating at its natural frequency. The wire vibration induces a magnetic field which is detected by the coils and the frequency of which can be measured remotely. This ingenious system will measure the electrical frequency of the returned signal which is the same as the frequency of mechanical vibration of the wire. This physical principle is very old, since the first types were used on dams in about 1930. It was also used on EDF's first generation power plant (Gas-Cooled Reactor), as early as 1956. The current PWR of the EDF fleet are equipped with large numbers of these vibratory strain meters.

Reinstatement of vibrating strain meters

Although vibrating wire strain meters are very robust [1], they may suffer from a certain number of failures after many years. Indeed, in the event of off limit strains, the wire stretches beyond its normal operating range and abnormal behaviour may appear. Two faults were clearly identified. First when the stretched wire comes into contact with one of the coils. In this case, the natural frequency of vibration of the wire is disturbed and we often measure twice the frequency. Second, this overstretching may cause the oscillation of the wire to be highly reduced and then the monitoring time slot does not allow for the measurement of frequency with the conventional signal processing techniques. Other problems may also occur, such as short-circuits in the coils or demagnetisation of the wire. This problem is common to all operators who use sensors with vibrating wire technology [2].

The first portable electronic frequency meters date back to the mid 1980s and the technology for the measurement of frequency used at that time only allows for measurements if the signal to noise ratio was high. This eliminated certain responses from sensors which were perfectly valid and coherent. Indeed, by using modern signal processing techniques, such as Fourier transform, the use of a high band-pass filter or the reduction of the excitation voltage, it was possible to recover certain strain meters which had been declared unserviceable. The complete methodology which was used to recover vibrating wire strain meters is explained in details in [3]. The method described is used on vibrating wire pressure cells, but it covers all sensors using vibrating wire technology, naturally including vibrating wire strain meters.

Figure 2 illustrates a typical case where the new protocol for interrogating vibrating wire strain meters is used to recover a sensor. By reducing the time-lag just after the voltage pulse and by using a high band-pass filter to eliminate the noise (which is very loud just after the pulse), it was possible to take a repeated and reproducible measurement of frequency. The analysis of the corresponding deformation value was validated by comparison with vibrating wire strain meters in the same zone and in the same direction of measurement. Similarly, any problems owing to the second harmonic due to the wire which knocks against the electromagnets were solved by reducing the excitation voltage.

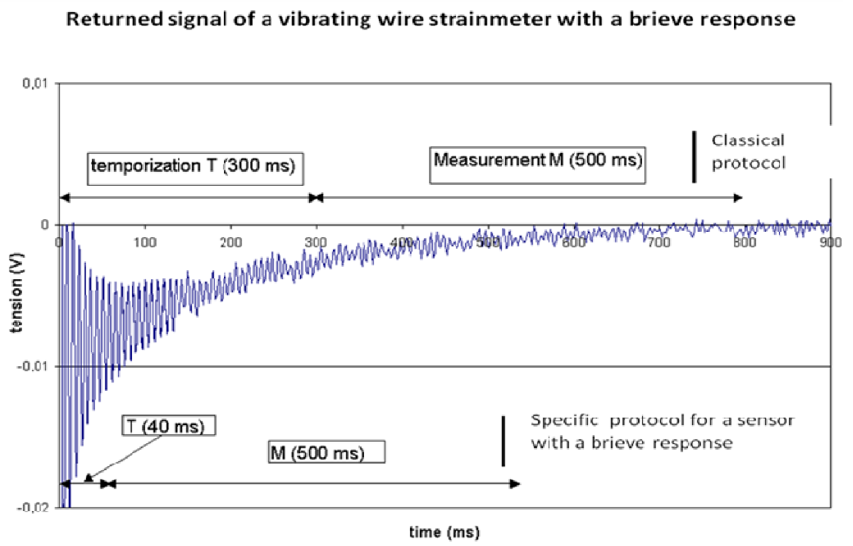

Fig.3: electrical signal from a vibrating wire strain meter with a short response. In this case, the new excitation and signal processing protocol is used to recover the measurement

Finally, the use of this new method of interrogating sensors has enabled to recover between 10 and 30 % of all sensors declared to be defective. The application of this methodology (non intrusive) from the outside would appear to be very useful, since sensors in embedded concrete are inaccessible and cannot be replaced by a similar one. Nevertheless, and to meet the requirements of the OSS system, the mere recovery of vibrating wire strain meters by this method was not always sufficient. We therefore had to innovate and qualify an alternative system for measuring deformation in the concrete: the surface strain meter. This development and its qualification are described in the next paragraph.

Development of a surface strain meter

Principle of the qualification

The surface strain meter developed must be capable of measuring very slight levels of deformation since the lowest creep rates are less than 5 µm/m/year. The measuring instrument was first developed in the laboratory to guarantee its metrology performances; it was then installed on a containment for validation and comparison with strain meters embedded in concrete in the same area and measuring in the same axis. Validation must show that the surface strain meter measures the same deformation as the embedded strain meter, to the nearest uncertainty. Qualification of the surface strain meter on site focused on checking the following 3 points (Fig 4):

- Rate of creep: the rate measured by the surface and embedded devices must be identical for strain meters in the same part of the containment and in the same direction of measurement.
- During the ten-year containment tests, the amplitudes and rates of deformation measured must be identical between embedded devices and those in the facing
- There must be no hysteresis in the deformation value after the containment test

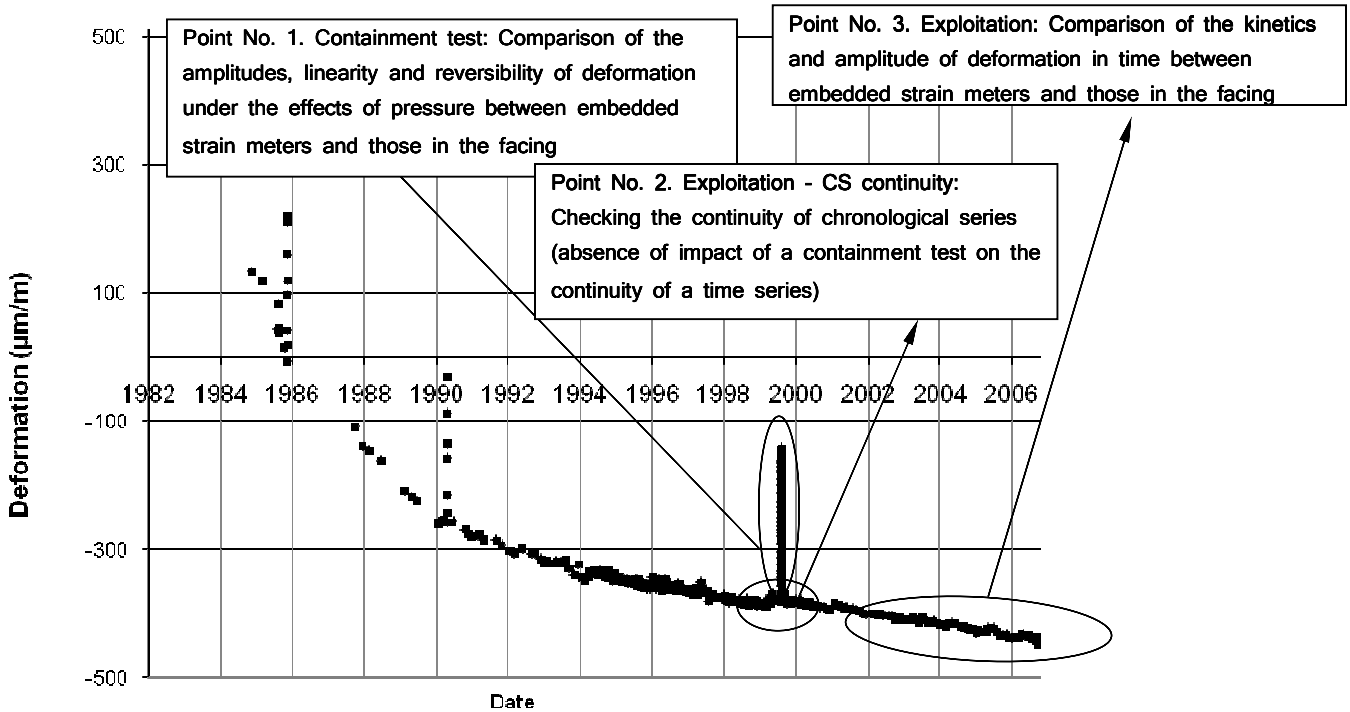

Fig.4: presentation of the different points to be checked to qualify an alternative system for the measurement of deformation

Presentation of the measuring instrument

The surface strain meter is made up of an 1m length Invar bar. Invar is an alloy, of which the coefficient of thermal expansion is very low (approximately 10^{-6} K^{-1}). One end of the bar is secured to an embedded rod in the concrete whilst the other end of the bar slides inside in a rod, which is also embedded in the concrete. The measurement of the displacement between the end of the Invar bar and the embedded rod (sliding part) is used to determine the deformation by dividing the length of displacement by the length of integration (distance between the two embedded rods). A photograph of the device is shown below:

Fig.5: Surface strain meter installed on site. The displacement sensor is installed on the left hand end of the 1 m Invar bar.

Displacement is measured using an LVDT (linear variable-differential transformer) sensor, its accuracy has been checked in a metrology laboratory. Manual measurement in parallel is also possible, without removing the LVDT sensor, thanks to a micrometer which is placed on specific stops. This manual measurement is particularly useful for the periodic metrology inspection of the instrumentation to check that there is no drift of the sensor.

The embedded rods are anchored in the concrete at a depth of 300 mm. This depth imposes special precautions in the positioning of the bore to avoid any risk of breaking the passive reinforcement or prestressing cables.

Uncertainty of measurement

The uncertainty of measurement was determined precisely by laboratory testing and by a comparison with the measurements of the embedded strain meters in terms of drift of the integrating circuit in relation to the anchoring. Table 2 below sets out the nature of the different sources of uncertainty and their relative weights.

Table 2: Uncertainty of measurement of the surface strain meter

Source of uncertainty	**Relative weight (%)**
Drift of the integrating circuit in relation to the anchoring	36.2
Drift of the strain meter in relation to temperature	25.2
Acquisition card of the telemetry system	15.1
Drift of the LVDT in time	9.1
Uncertainty on the measurement of temperature	4.7
Uncertainty of calibration	4.7
Bias error	2.5
Hysteresis error of the sensor	2.1
Repeatability	0.4

Finally, by cumulating the different sources of error, we obtain an overall (with two standard deviations) uncertainty of measurement equals to **12.3 µm/m**. This uncertainty is sufficient to detect any change in behaviour of the structure early enough and for an efficient monitoring of the structure in the long term.

Results of qualification

Qualification on an industrial site consisted in the following:

- Paralleling the measurements of embedded and surface detectors for several years
- Comparing these measurements for a one-off event: the ten-year containment test.

Figure 6 shows 4 years of comparative tangential deformation measurements in the lower third of the cylindrical part of the containment.

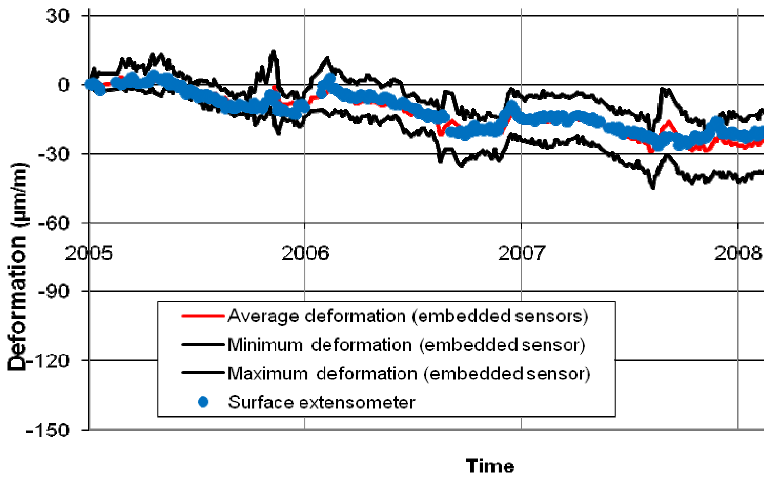

Fig.6: Tangential measurement of deformation (surface and embedded device), lower third of the cylindrical part of the containment, outside (minimum, maximum and average values of the group of embedded strain meters)

The analysis of these data shows that the surface strain meter follows the average curve given by the embedded sensors perfectly. The group embedded sensors has inherent variability, since they are not all on the same location, such that the thermal and environmental conditions may change slightly, which explains the variability (minimum, maximum and average) of the group of embedded strain meters.

The performance of the surface strain meters was also checked during a containment test for which the deformations measured are considerable. Figure 7, which shows the deformations according to the level of pressurisation of the containment, demonstrates the absence of hysteresis of the sensor and its ability to monitor linear and reversible deformations during the test. The surface measurements made are also similar to those obtained using the embedded device. It is therefore possible to determine Young's modulus and Poisson's ratio thanks to the surface strain meter

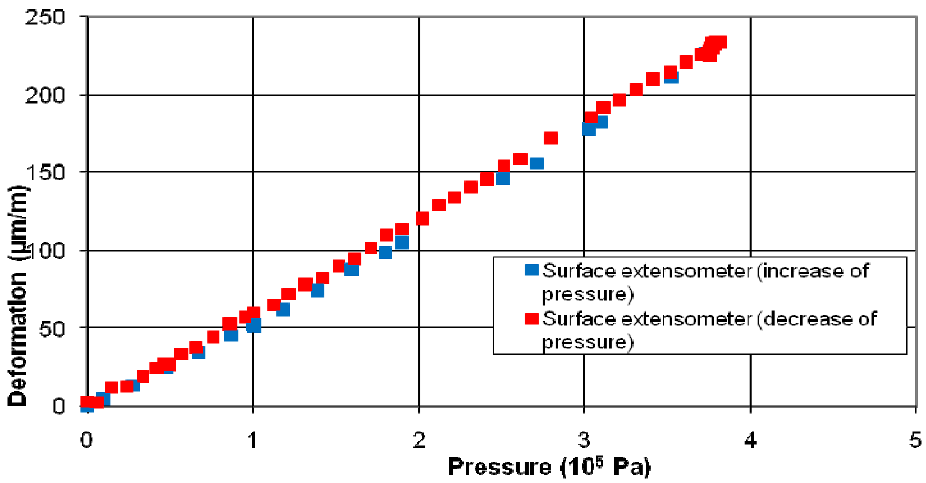

Fig.7: Measurement of deformation during a containment test (graph showing deformation versus pressure inside the containment)

After several years of validation on a containment and thanks to the comparison of the measurements with the original embedded device, the surface strain meter was qualified for the long term monitoring of deformation of the containment. It may therefore replace vibrating wire sensors, if necessary. This device is to be deployed on all containments of the EDF fleet with a lifetime objective of 60 years.

CONCLUSION

The monitoring system of nuclear containments was conceived to check the initial design hypothesis. This system also ensures that prestressing remains compatible throughout reactor containment lifetime. An Optimum Surveillance System (OSS) which guarantees satisfactory monitoring of the containment behaviour was defined by EDF. The OSS sensors have to be made permanent.

The principles and methods described in this article allow long-term containment surveillance, provided that the following points are respected:

- Continuous monitoring of OSS data for early detection of sensor failures. In this context the use of innovative methods for sensor data collection and analysis is of special interest, in particular for long-term monitoring
- Replace, if necessary, all defective OSS sensors, as early as possible
- In case sensors cannot be replaced (strain meters embedded in concrete), plan an early installation of surface strain meters as an alternative means of measuring deformation

In accordance with these principles and precautions, the long-term monitoring of the mechanical behaviour of the containment will be guaranteed and the operator will achieve better control over the ageing of the containment.

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