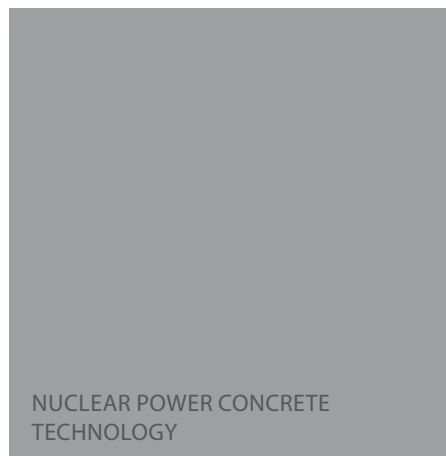
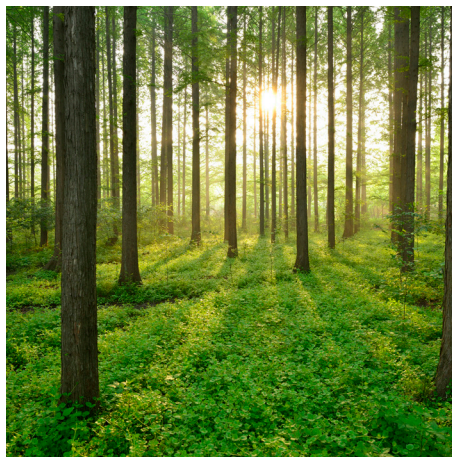
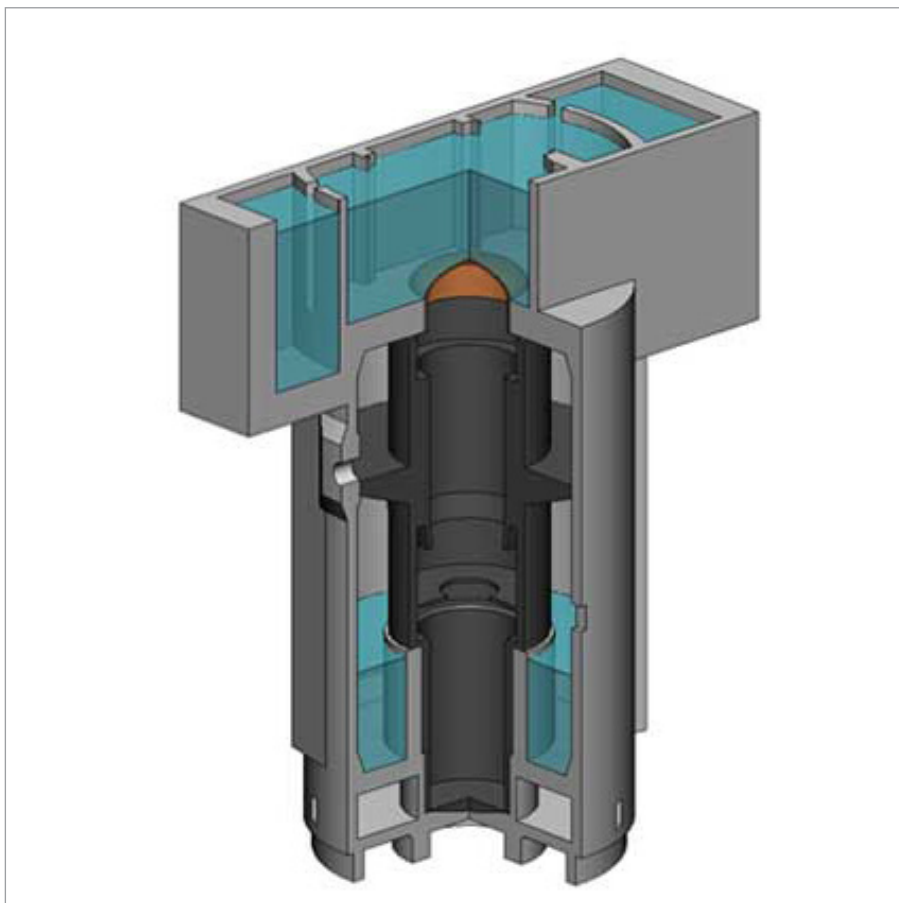
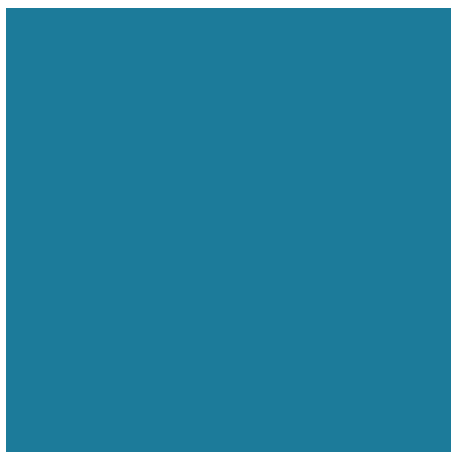


INSTRUMENTATION OF NUCLEAR CONCRETE CONTAINMENT BUILDINGS

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NUCLEAR POWER CONCRETE
TECHNOLOGY



Instrumentation of nuclear concrete containment buildings

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Foreword

The Energiforsk Nuclear Power Concrete Program aims to increase the knowledge of aspects affecting safety, maintenance and development of concrete structures in the Nordic nuclear power plants. A part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

Precise and accurate instrumentation and monitoring of containments can provide valuable insights for continued maintenance as well as future development. This report summarizes different types of instruments that can be applicable, based on what is used today in the nuclear business as well as in other businesses.

The study was carried out by Richard Malm and Leonard Sandström, Sweco Sverige AB. The study was financed by the Energiforsk Nuclear Power Concrete Program, which in its turn is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, SSM and SKB.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

The containment building is the outermost barrier in the defence-in-depth principle used by nuclear power plants. The Nordic nuclear containment buildings are made using pre-stressed concrete with an embedded steel lining. Instrumentation and monitoring are an important part in ensuring the continued performance of the structure.

The monitoring of the containment can provide insight into the behaviour of the structure both during short term events such as pressure tests as well as during normal operation to see how the behaviour changes over time.

This report summarizes different instruments that are used to monitor containment buildings, as well as instruments from other civil structures that could be applicable. The instruments are divided into either detectors or support instrumentation. Detectors are used to detect if a potential failure mode is being initialized. Support instrumentation is used to gather information needed to evaluate the structure. Detectors may for example measure the deformations over a large area of the structure (global sensors). Support instrumentation includes measuring temperatures as well as air pressure.

The report includes suggestions on which sensors to include in the instrumentation of a containment building. It also touches upon what to consider when designing a measurement system to handle, store and process measurement data from the sensors.

Keywords

Containment, concrete, pre-stressed tendons, monitoring, instrumentation, alarm, alert, detectors, strain gauge, pendulum, measurement system, extensometer

Inneslutning, betong, spännarmering, övervakning, instrumentering, alarm, varning, detektorer, töjningsgivare, pendel, mätsystem, extensometer

Sammanfattning

Reaktorinneslutningen är den yttersta barriären i kärnkraftverkens djupförsvar. De nordiska inneslutningarna är byggda med förspänd betong och en ingjuten tätplåt. Instrumentering och övervakning är en viktig del för att säkerställa byggnadens fortsatta prestanda.

Att övervaka inneslutningen kan ge insikt i hur beteendet hos byggnaden ändras över tid. Det möjliggör att tidigt upptäcka degraderingar i byggnaden och fungerar som ett komplement till rutinmässiga inspektioner.

Denna rapport summerar olika instrumentering som används för att övervaka inneslutningar eller som används i andra liknande anläggningar.

Instrumenteringen delas upp i detektorer och stödinstrumentering. Detektorer används för att upptäcka initiering av en potentiell felmod. Stödinstrumenteringen används för att samla information nödvändig för att kunna utvärdera konstruktionens prestanda. Detektorer kan till exempel mäta deformationer över ett stort område på konstruktionen (globala sensorer). Stödinstrumentering inkluderar mätning av temperaturer och lufttryck vilket ger en bild av det förväntade svaret från konstruktionen.

Förslag ges på vilka sensorer som bör inkluderas i instrumenteringen av en inneslutning. Det ges även förslag på vad som bör beaktas vid dimensioneringen av det mätsystem som ska hantera, lagra och processera mätdatan från sensorerna.

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1 Introduction

In a Nuclear Power Plant (NPP), several barriers are installed to prevent that the society and environment is affected in case of an incident. The concrete containment building is one such barrier that encloses the reactor and the radioactive materials. The reactor containment building is built as a thick concrete structure which normally is pre-stressed with tendons to prevent cracking. Despite this, it is not the concrete containment that is designed to ensure leak tightness. Instead, it is a steel liner installed at the interior surfaces of the concrete containment building that provides the leak tightness. In Swedish nuclear power plants, the steel liner is protected by an additional layer of concrete which embeds the liner in concrete. An example of a reactor containment building is shown in Figure 1—1.

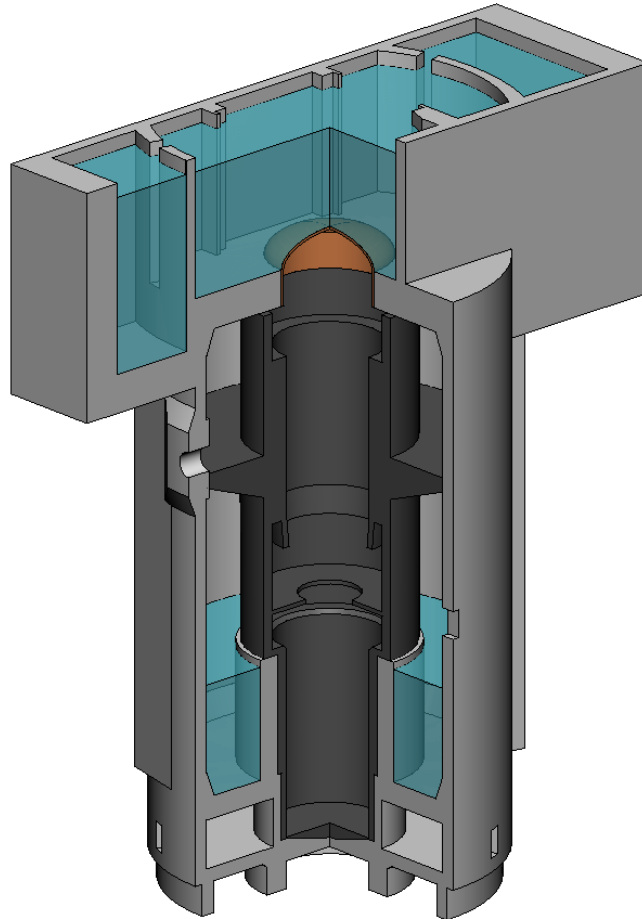


Figure 1—1 Illustration of a boiling water reactor containment building, from Hassanzadeh et al. (2021).

As an important step in the safety assessment of the nuclear power plants, the containment buildings are regularly exposed to pressure tests (leak tightness tests). The purpose of these pressure tests which are performed to monitor the leak tightness of the containment building. These tests can also be used to monitor and assess that its behaviour is as expected. For structures with grouted tendons, this is performed in accordance with US Regulatory Guide 1.90, which provides two methods (Alternative A and B) for assessing the prestressing level of the installed tendons:

- Alternative A) Monitoring the pre-stressing level of the reactor containment by means of instrumentation and pressure tests,
- Alternative B) Monitoring of the deformation of the reactor containment under pressure tests.

This report will focus on how to monitor the normal conditions of these reactor containment buildings as well as during pressure tests. This also includes how monitoring can/could be used to obtain early warnings if the response is out of the expected range.

1.1 PURPOSE OF MONITORING

Monitoring of structures are performed in many fields within civil engineering. Regardless of if monitoring is performed on buildings, bridges, dams, etc. the purpose is to gather information about the current status of the structure and/or the response of the structure during an event. The event can be short-term, such as influence from trains passing on a bridge or long-term such as settlements of building. The different aspects regarding measurements for short and long-term monitoring are described more in detail in Section 1.1.1.

Based on the different types of monitoring, the recordings may be either recorded automatically with a pre-defined time interval or manually using personnel on-site that records the measured values with a reoccurring frequency, see Section 1.1.2.

Depending on the type of sensor used, it can be expected to either capture the local behaviour specific behaviour at a certain point (*Local sensor*) or measure the integrated behaviour of the structure (*Global sensor*). The terminology local and global sensors are discussed more in detail in Section 1.1.3.

It should be noted that monitoring is not only conducted to measure the behaviour of the structure. One other important type of monitoring is also to gather information about loads such as measurements of water pressure between the concrete structure and the rock foundation of concrete dams. The information regarding the measured loads can be used either as input into different types of theoretical models. One application can be that a threshold value is defined for the external load which has been pre-determined based on

the expected variations or required safety of the structure. Sensors that are expected to be able to detect potential failure modes are normally denoted as *Detectors*. Another type of application is that these loads are used as input in a detailed theoretical model with the purpose to mimic the measured response. In this case, the measurement of the loads is a way of reducing uncertainties in the modelling stage which allows for well calibrated models. Sensors that only provide information that later can be used in different models are commonly denoted *Support instrumentation*. Detectors and support instrumentations are described in Section 1.1.4.

1.1.1 Long-term vs short term measurements

Long-term measurements are as described by its denotation, carried out over a long period of time. The type of events that are intended to be captured are not expected to occur rapidly, but are instead related to aspects related changes in material properties caused by degradation or long-term effects from creep, shrinkage, relaxation etc.

In case of monitoring concrete containment buildings, long-term measurements are typically cast into the concrete during construction or installed after structure has hardened.

Short-term measurement is something that occurs for a definite period of time. This can for instance be measurements related to vibrations caused by an earthquake, or measurements during a pressure test. It can also be that instrumentation are mounted and dismounted to measure the response during a short duration for instance during construction work, etc.

In many cases, the type of sensors that are installed for long-term monitoring of the behaviour can also be used for short-term measurements. In automatically recorded systems, it is possible to change the sampling frequency for when the measurements are recorded. With this is possible to have more frequent recordings during the short-term events and more seldom recordings for the long-term events. One example of such an example is monitoring the displacement of a reactor containment building using pendulums which are illustrated in Figure 1—2. There are also systems that measures the response with relatively high frequency and then stores, data such as average and extremes for the desired time interval. This can be a suitable procedure to handle disturbances in the signals etc.

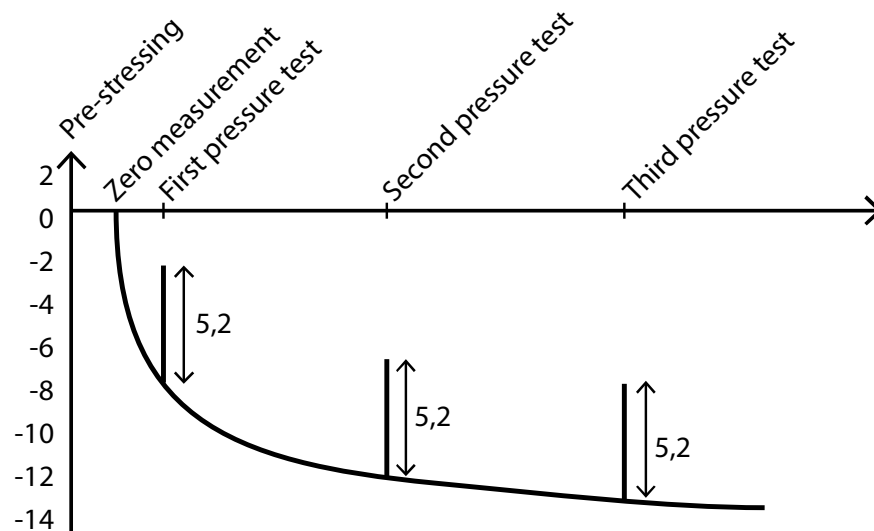


Figure 1—2 Illustration of long-term trend in global displacement of a containment building and the influence from short-term events from pressure tests. From Hassanzadeh et al. (2020)

Not all types of sensors are suitable to use for long-term monitoring, it can for instance be that the sensors are expected to drift over time which will create unreliable results from a long-term perspective. At the same time, not all sensors are suitable for short-term monitoring. Short-term monitoring often requires that the measurements are performed automatically, hence some types of sensors may not be suitable for this. Another aspect is that some sensors may have limitations in how frequent they can sample data. In short-term recordings it is required that the sampling frequency larger than the expected frequency of the measured response. The theoretical limit is the Nyquist frequency where the sampling frequency has to be twice as large as the natural frequency of the response. However, this is insufficient if the response is to be evaluated and typically ten times larger sampling frequency is desired to allow for data processing and evaluation, Malm (2017).

1.1.2 Automatic vs manual recordings

One main difference between automatic and manual recordings is the possibility to use the monitoring program as a tool for finding deviating values and obtain warnings when an unexpected behaviour occurs. One could for instance argue that in case of a very slow

process, where no significant changes may occur over a sufficiently long period of time could be detected with warning values from manual recordings. This may be considered true, however, one has to bear in mind that it is normally not sufficient to have one measurement that deviates in order to detect a potential unexpected behaviour. One recording that is deviating can be treated as a measuring error and hence in worst case scenario a warning is not issued until 2 or more recordings are out of scope. If the recordings occur on monthly basis, this could mean that at least 3 months may have passed before two consecutive recordings are detected that deviates from the expected behaviour. The manual recording is also more demanding from a personnel perspective since it requires man-hours for both collecting data but also for evaluating the data. Manual data logging also has a higher risk of errors caused by human factors.

On-Line Monitoring (OLM) is currently used in many adjacent fields such as long-term monitoring of concrete dams and in bridges, see for instance Bernstone (2006). Automatic recording is a prerequisite for On-Line Monitoring (OLM). On-line monitoring can be described as a framework where it is possible to access and evaluate the result from automatic recordings through a specific program. For dams, such a program can for instance be IntelliDam¹ or OSI-PI², which are two programs used for dam surveillance in Sweden.

In this report the focus is on measurements that can be recorded automatically, since it is only these types of measurements that can effectively be used as warnings. One should note though, that there are many aspects that must be considered when automatic recordings are used. This includes for instance more practical aspects such as not over sampling which would produce large databases. The more important aspects are however, how to treat noise and disturbances that may occur in the recordings. This can for instance be handled by installing filters that removes high frequencies or by using averaging procedures for data with higher frequencies than the sampled data, see Figure 1–3.

¹ <http://www.intellidam.com/>

² <https://www.osisoft.com/pi-system>

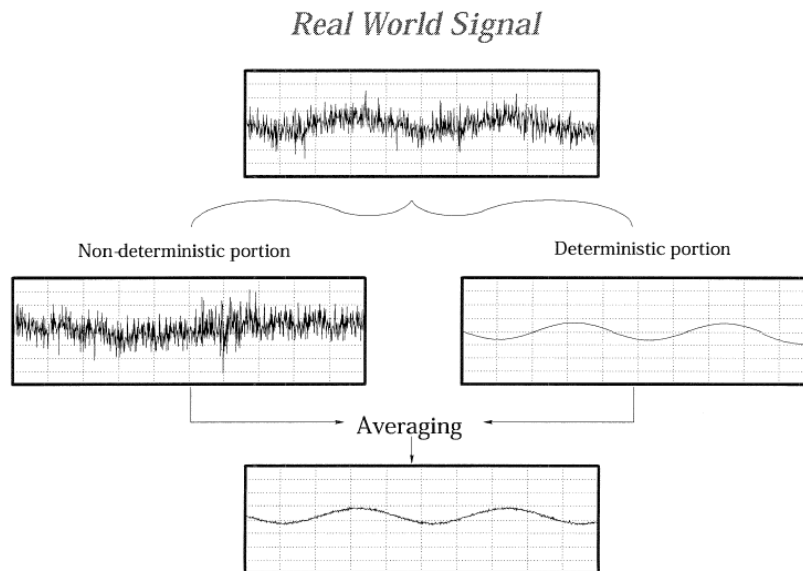


Figure 1—3 Illustration of a signal containing noise and application of an averaging procedure.

1.1.3 Global vs local sensors

Different type of sensors installed on a nuclear containment building may either measure the behaviour in one specific point, along a line or in an area. This measurement may either represent the local behaviour of the structure at the location of the sensor, or the global structural behaviour. Sensors are therefore denoted as either *Global* or *Local* sensors to indicate if the recordings quantify the behaviour on a global or local scale.

Local sensors – measure locally at a specific point or the relative behaviour between two adjacent points. Some examples of local sensors are strain gauges, crack width sensors or joint meters.

Global sensors – still measures the response in a specific point, a line or in an area, but the behaviour represents the integrated response of parts of the structure or the whole structure. An example of a sensor for measuring of global displacements is a hanging pendulum. The displacement in a specific point represents the integrated response of the structure and will also be influence by local effect such as cracking etc.

One important limitation of using local sensors is that the measured behaviour only represents what is occurring at this specific location. The behaviour in an adjacent point may be completely different. For instance, if the strain is measured in concrete, a high value and possibly also sensor failure may occur if a crack crosses the sensor. On the other hand, if the crack occurs near the strain gauge, it will instead show reducing strain as a result of unloading caused by the adjacent crack growth. Another example of this is strain measurements along bonded tendons as shown by Hassanzadeh (2019). In this project, a wire in the tendons was cut while measurements were performed on the same tendon a few meters apart. As was shown by Hassanzadeh (2019), even though a wire was cut through, nothing could be detected with measurements using strain gauges placed four meters away on the same tendon.

Global sensors are commonly used to monitor the structural health of different types of structures and are often connected to alert values. Since global sensors capture the integrated structural behaviour, they are likely to capture changes in behaviour even if they occur from local defects etc. For instance, cracking of a structure results in larger displacements. However, it should be noted that the damage / defect may have to progress longer before it can be noticed on global sensors compared to a case where it is measured locally at the point of interest. It may also be difficult to assess the cause and identify the location of a damage based on global sensors.

1.1.4 Detectors vs support instrumentation

In this report, the different sensors are denoted as either *Detectors* or as *Support instrumentation* in accordance with ICOLD (2018). A description of these definition is as follows:

Detectors – sensors that have the purpose to detect an initiation of a potential failure mode. A failure mode is defined as a situation or condition where the structure or the structural element can no longer fulfil its prescribed function. This definition includes failures due to a wide range of events such as both degradation over time as well as accidental loading of the structure. Different types of sensors can be detectors for different types of failure modes. A detector measures a quantity that can be directly related to the safety of the structure or to any abnormal behaviour. This thereby requires that the sensor is placed in a location where significant changes are expected to be

recorded in a potential failure mode. These types of sensors often measure global behaviour of the structure since global measurements are less likely to miss a global failure regardless of where in the structure the failure is initiated. It can also be local sensors which record the behaviour at known defects / weaknesses etc. Some examples of sensors commonly used as detectors are: displacements in the ground or in the structure (pendulums, extensometers, crack width sensors), leakage of air or water. Sensors used as detectors are commonly given a real time alarm value so that appropriate measures can be taken in case of an alarm.

Support instrumentation – are sensors that are installed with the intention to gather information that constitute important input data for analysis of the structure. This can for instance be to assess long-term changes in the response or recording external parameters such as temperature, relative humidity or deformations (displacement, strains) in parts of the structure that is considered to have a small influence during a potential failure. These types of sensors are typically not defined with real time alarm values.

In case a sensor is defined as a detector and connected to a real time alarm value, then it is important to know the normal expected variation and also how this sensor would react in case of a potential failure mode. In these cases, a contingency plan is required so that suitable measures have been defined in case of a warning or alert value is obtained.

1.1.5 Warning and alert values

Warning and alert values can be defined in different ways depending on the desired level of accuracy. Warning levels are intended to be issued when the behaviour is no longer as expected. Warning levels may be, in its most simple form, be defined as a static value that the recorded signal should not exceed. This is however a rather blunt measure since many parameters varies naturally over the year, due to seasonal temperature variation etc. Hence if a static value is defined, for instance for a certain displacement, then this would imply that different safety factors are incorporated depending on if the event occurs during summer or winter conditions. If significant seasonal variation is expected, warning levels are defined based on the current external variables such as temperature, etc. The threshold for the

warning level can for instance be defined (here written in the order of their expected accuracy, from low to high)

- Based on engineering judgements
- from observations of previous measurements
- finite element models
- data-based models (such as artificial neural networks, etc)

Alert values are intended to be issued when there is a risk of a potential failure. The choice between the ratio of the threshold for the alert cannot be based on previous measurements and thereby not either data-based models. Data-based models cannot be used for extrapolation for conditions that deviates for which it has been defined / calibrated. Hence, in order to develop alert values, models based on physics such as design calculations or finite element analyses form the basis for these assessments. The choice of the threshold value thereby depends on the expected accuracy of the model and the estimated progression of the failure. In case of a brittle failure, typically larger ratio between the threshold value and the expected value at failure will be required. In addition, the expected time available for performing a counter measure to prevent the failure is also of great importance when the alert value is defined.

1.1.6 What we want to monitor vs what we can monitor

When measurements are performed or evaluated it is natural to think that we measure the variations in for instance displacements or strains. However, this is not the case, measurements are performed with electronic sensors where variation in response is detected by the sensor as variation in resistance (unit ohm). The change in electric potential (unit volt) can thereby be determined based on the change in resistance and the electric current (unit ampere). The variation in electric potential can thereafter be translated into the physical parameter of interest based on gauge factor and or calibration factor. It should be noted that these can be temperature dependent and that in those cases compensations for variations in temperature has to be considered. It is thereby important that the gauges are calibrated before installation and that their response is validated through-out the whole measuring period, for instance through repeated calibrations.

In monitoring programs of structures, the aspect that we often are most interested in is the stress in the material. However, the stresses cannot be measured with any existing technique. In order to determine the stress in the material from strains, one has to assume that the behaviour is linear elastic and that the stress can be calculated using Hooks law. However, this is difficult for concrete, considering that the stiffness of concrete varies during hardening and may also have a spatial variation over the structure. There can also be cracks in the concrete which invalidate the assumption of linear elastic materials. Materials such as steel are easier from this perspective since steel has less spatial variation in stiffness and varies with time to a smaller extent³. If a theoretical value for the stiffness of the material can be determined, then the stress can be calculated (using the assumption mentioned above). However, one additional assumption has to be made; which strain level should correspond to zero stresses? During construction of concrete structures, the material undergoes significant change in properties from a flowing material that hardens and obtains a strength and stiffness. During this period, the material is subjected to volume change caused by variation in moisture and temperature. When the concrete is subjected to restraint, then these will start introducing stresses in the material. If the zero-strain level is not determined, it is not possible to calculate the current stress state in the material.

For nuclear containment buildings, the tendons are especially of interest since these enforce a compressive state of stress in the containment building. In Sweden, both applications with tendons that are free to slide inside ducts embedded in the concrete and those tendons that are cement grouted and hence restraint to slide.

1.2 AIM AND GOALS

The aim of this project is to gather information about techniques that are used to monitor concrete containment buildings in nuclear power plants today as well as potential techniques that are used in other closely related fields. This project has been conducted as a literature study along with interviews of experienced engineers within the field of monitoring of concrete structures and/or nuclear power plants.

³ The stiffness of steel can of course be influenced by degradation such as corrosion and may vary in different parts depending on welds etc.

The aim of this report is to summarize the findings of this study and is intended to be used as a guideline for engineers that are planning to perform monitoring on concrete containment buildings in nuclear power plants.

1.3 LIMITATIONS

This project focuses on existing (already built) nuclear containment buildings. Some type of sensors can only be used when installed before casting the concrete. Hence, these types of sensors are only mentioned briefly.

Another limitation of this study is that the work is focused on monitoring of the behaviour and response of the structures. Hence, methods such as non-destructive testing methods or methods intended for inspections are not covered in this report. These two types of methods are primarily intended for obtaining a snapshot of the current status of a part of the structure, i.e., finding internal damage or identifying cracks etc.

Considering the limited budget for the project, it has not been possible to test or evaluate different type of sensors or equipment within the scope of this project. Hence all information is based on the findings from other sources.

2 Nuclear buildings

2.1 GENERAL DESIGN

There are two different types of reactor containment buildings: Boiling Water Reactor (BWR) and Pressure Water Reactor (PWR) where the Swedish nuclear plants were of the following types as shown in Table 1.

Table 1 Type of nuclear power reactors in Sweden

Reactor	Capacity (MW)	Type	Built	Decommissioned
Barsebäck 1	600	BWR	1975	1999
Barsebäck 2	600	BWR	1976	2005
Ringhals 1	881	BWR	1976	2020
Ringhals 2	905	PWR	1975	2019
Ringhals 3	1074	PWR	1981	-
Ringhals 4	1130	PWR	1983	-
Forsmark 1	1014	BWR	1980	-
Forsmark 2	1121	BWR	1981	-
Forsmark 3	1172	BWR	1985	-
Oskarshamn 1	473	BWR	1972	2017
Oskarshamn 2	638	BWR	1975	2015
Oskarshamn 3	1450*	BWR	1985	-

Several different designs exist for the different types of reactor types. In Figure 2—1, examples of typical reactor containment buildings for BWR (Forsmark I) and PWR (Ringhals III) are shown. The PWR reactor containment building is subjected to outside air conditions on

its external surfaces. The BWR reactor containment building is instead protected from the outside air by a building. Due to the different designs of BWR and PWR nuclear reactor buildings and that these are exposed to different climatic conditions, hence they may have slightly different response during both normal conditions but also during a potential incident.

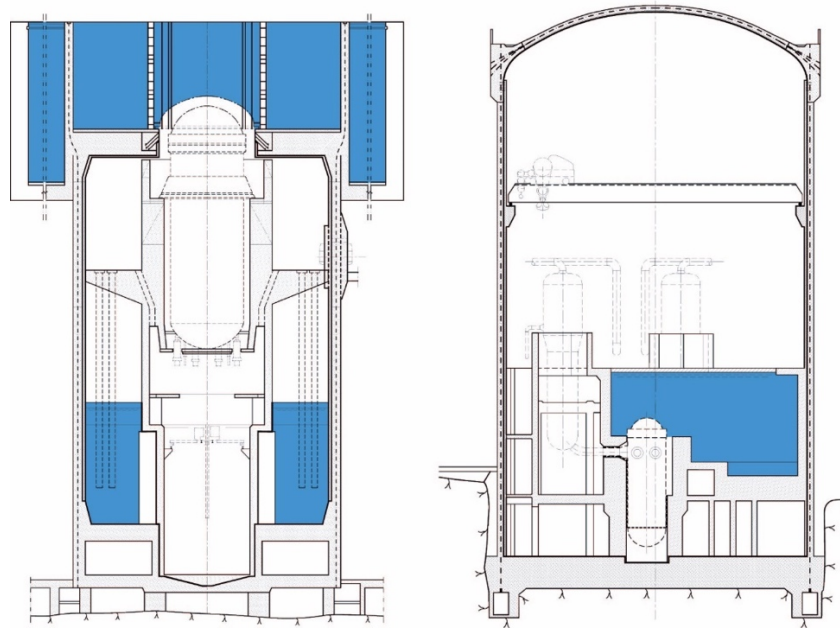


Figure 2—1 Illustration of typical Swedish reactor containment buildings, BWR reactor (Forsmark I) to the left and PWR reactor (Ringhals III) to the right. From Malm et al. (2013) and based on Roth et al. (2002).

2.2 NORMAL CONDITIONS

During normal conditions, i.e. during operation, the containment wall is subjected to a small overpressure and different parts of the containment building is subjected to heating from by the reactor. An example of the thermal conditions inside a BWR containment building was presented by Könönen (2012), here seen in Figure 2—2. In the PhD thesis by Oxfall (2013), a monitor campaign was conducted to map the climatic conditions in BWR and PWR containment buildings regarding both temperature and relative humidity. One example of the results is presented in Figure 2—3, which shows the variation in temperature and relative humidity in the cylinder wall in the upper drywell of Forsmark II. The results show that the measured

temperatures are in general lower than the design temperatures presented by Könönen (2012). As seen in the figures the temperature in the upper drywell is typically 30 – 40 °C according to Oxfall (2013) compared to 50 °C according to Könönen (2012). Oxfall also showed that the relative humidity is high inside the containment wall (> 75 %) despite more than 30 years of service. This has also been shown by several other research projects se for instance: Nilsson and Johansson (2009), Åhs and Nilsson (2016), Bernstone et al. (2017), Malm et al. (2021).

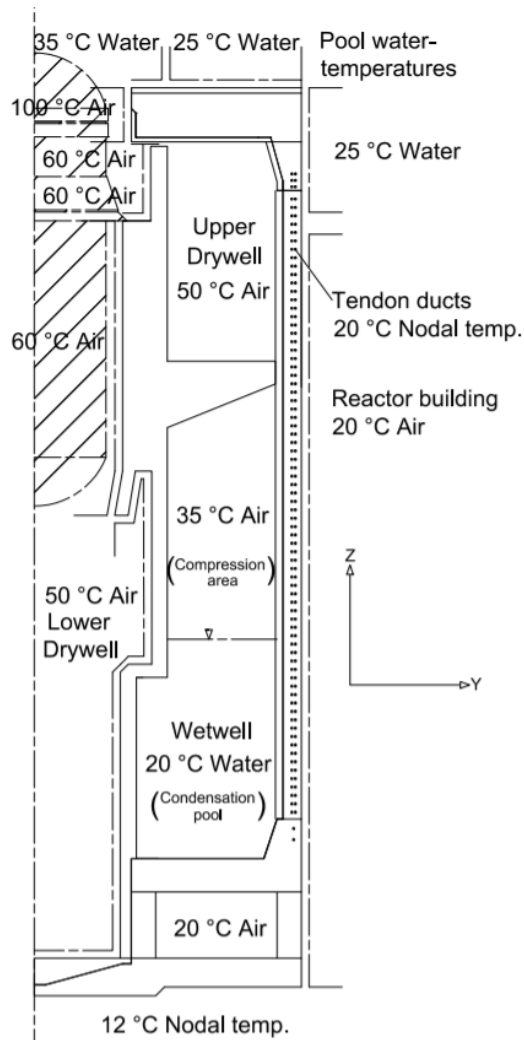


Figure 2—2 Example of ambient air temperatures in a BWR containment building, from Könönen (2012).

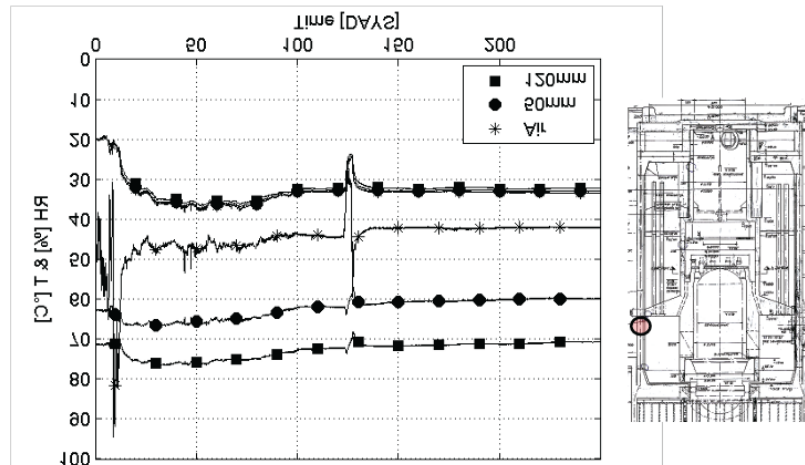


Figure 2—3 Variation in temperature (symbols at 20, 40, 60, etc. days) and relative humidity (symbols at 10,30,50, etc. days). From Oxfall (2013).

Considering the small temperature variations expected in nuclear containment, quite limited variations in normal behavior are expected. The variations are expected to be a bit larger in a PWR containment considering that its external surfaces are subjected to the ambient outdoors conditions. Since, small variations in conditions are expected, a detailed model is required in order to define warning levels that can identify if an unnormal behavior occurs.

The long-term behaviour of the containment building is an important aspect that has a significant influence on its response, Lundqvist (2012). The long-term effects are caused by that the materials behaviour will change over time. For the pre-stressed tendons, this is primarily related to relaxation of the steel which results in lower pre-stress. It should be noted that other long-term effects that causes deformation in the containment building, such as shrinkage and creep of the concrete, also will result in loss of pre-stress. Both the shrinkage and the creep are dependent on the moisture condition of the concrete material, these are often referred to as drying shrinkage and drying creep. Creep is also influenced by temperature, where the creep rate increases for higher temperatures. For instance, Vidal et al. (2013) showed that the basic creep was between 2.0 and 3.7 higher for concrete subjected to 50 °C than concrete subjected to 20 °C. The high temperatures also influence the concrete material properties such as

the elastic modulus, compressive and tensile strength for newly cast concrete primarily based on how it influences the hardening and evaporation of water. However, in the case of reactor containment buildings the concrete has already aged and elevated temperatures thereby has minor influence of the properties, see Jönsson and Tornberg (2013).

All these long-term effects will result in increasing displacements during normal conditions as the stiffness of the containment is successively reduced. This was already illustrated in Figure 1—1, where the exponential decay of the response is attributed to the long-term effects. The long-term effects may thereby have a significant influence on the response during normal operation and must be considered when evaluating the structural behaviour.

2.3 BEHAVIOUR DURING A POTENTIAL FAILURE EVENT

A segment of a cylinder wall in the containment building is illustrated in Figure 2—4. In the figure, the main load carrying mechanisms are shown. During pressure tests and in case of a Loss Of Coolant Accident (LOCA), the internal surfaces of the containment building are subjected to an internal overpressure. This pressure causes the cylinder to increase in diameter and is counteracted by the load capacity of uncracked concrete, tendons (F_s), reinforcement (F_i and F_y) and the steel liner (F_p).

An example based on analytical calculation of the load and displacement curve of the cylinder wall in a reactor containment building is shown in Figure 2—5. In the figure, the radial displacement at the mid height of the cylinder wall is plotted as a function of increasing internal overpressure. Initially, the containment building has deformed inwards due to the prestress of the horizontal tendons (point a in the figure). As the internal pressure is increased, the containment building acts linear elastic until the concrete starts to crack (b) and at point (c) the concrete is assumed to have obtained macro cracks. After this point, the load is carried by the reinforcement, steel liner and the prestressing tendons. In this specific case, the steel liner starts to yield first (d), which results in redistribution of forces and yielding of the reinforcement I. The stiffness of the containment is successively reduced as a result of concrete cracking and yielding of steel. When the tendons start to

yield (f), a significant reduction of the stiffness occurs, and the failure occurs soon after this. An example of a failure mode caused by increasing over pressure is shown in Figure 2—6. In this figure, the failure mode of the reduced scale reactor containment (scale 1:4) performed at Sandia National Laboratory (Hessheimer and Dameron, 2006) is presented.

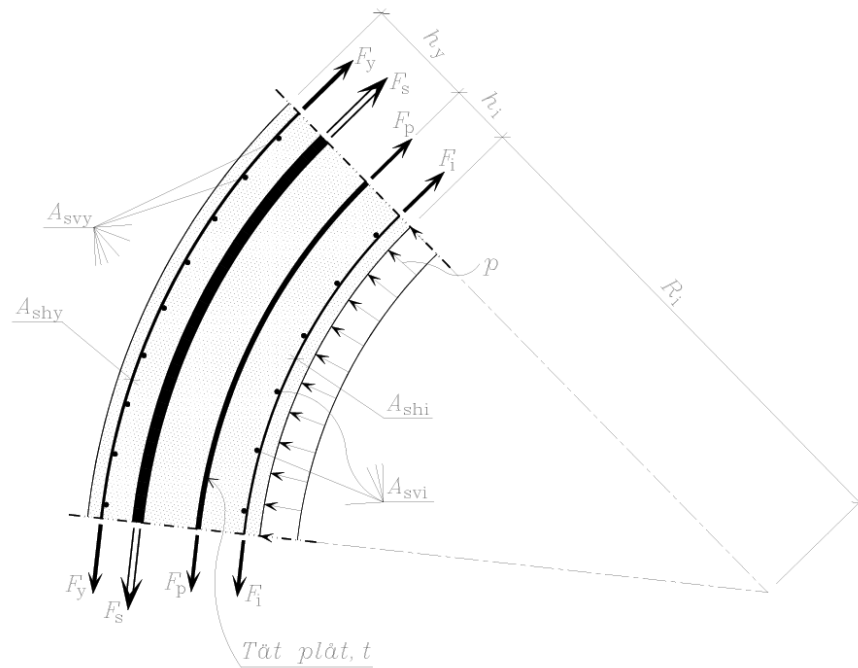


Figure 2—4 Illustration of a wall segment in a cylinder wall of the reactor containment, from Roth et al. (2002).

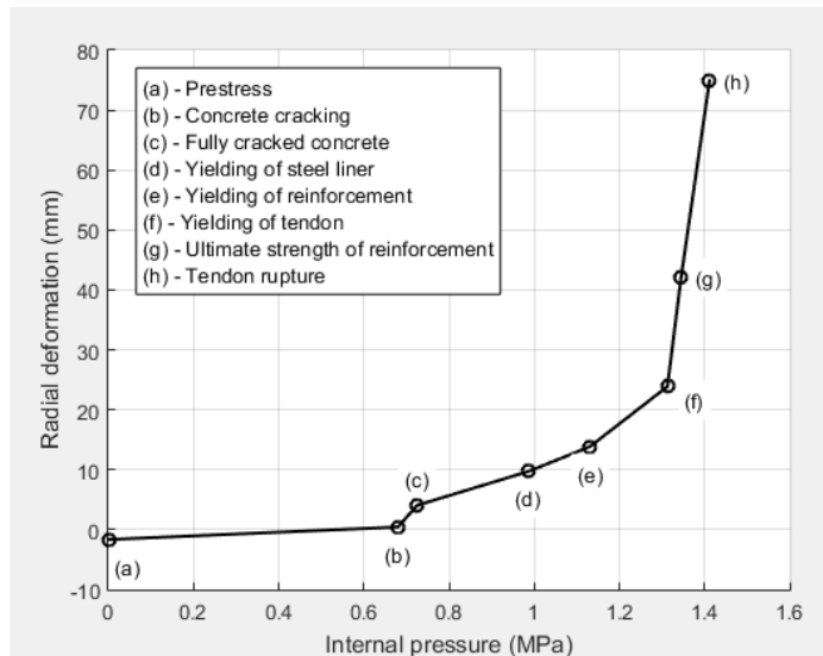


Figure 2—5 Example of theoretical load and displacement curve of a reactor containment. From Malm (2015).

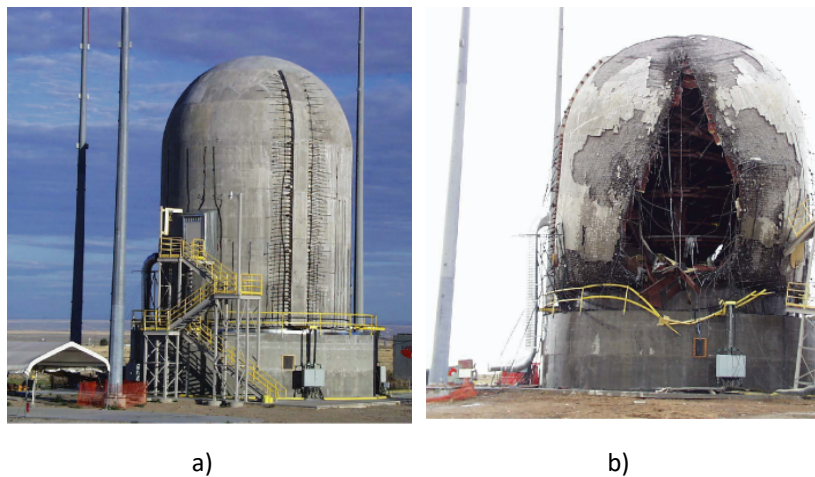


Figure 2—6 Sandia 1/4 scale reactor containment test, a) after construction, b) after failure caused by increasing internal pressure. From Hessheimer and Dameron (2006)

The displacements are expected to be rather small as long as the reactor containment is in its linear elastic regime, as illustrated in Figure 2—5. The Swedish nuclear containment buildings have very

high safety levels and are designed to stay in this elastic regime until the internal pressure is below 150 % of the design pressure. As shown previously, significant load capacity remains even after this stage and the ultimate failure occurs theoretically at a pressure that is > 350 % of the design pressure.

2.4 NEED FOR MONITORING

As described earlier in Section 2.2, the normal behaviour during operation and the long-term behaviour of the containment building is greatly influenced by the temperature and moisture conditions. Both the temperature and the relative humidity are monitored with sensors that would be denoted as support instrumentation, see Section 1.1.4, since these provide information that are important to obtain a good understanding of the response. Hence, for these types of sensors it is not reasonable to define any real-time warning or alarm values.

During normal operation small variations in deformations are expected due to the small variation in temperature and moisture for the different regions of the containment. This should however be monitored to assure that the response is as expected. The radial displacement of the containment wall at mid height is an example of a suitable parameter to monitor to obtain a good measure of the global behaviour of the containment wall. Monitoring the displacements at a few strategic positions is a good option for assessing the normal behaviour and it can also be utilized for calibration of different models. Other examples, of suitable aspects to monitor during normal conditions are the relative displacements over joints etc. or monitoring the variation in crack width if any cracks exist. Another aspect that is interesting to monitor is the strain in the containment, using local sensors or distributed sensors.

Another important aspect is to monitor the variation in pre-stress especially considering that the pre-stress is expected to reduce from long-term effects, see Section 2.2. This can however be difficult depending on different pre-stressing system and especially depending on if the tendons are cement grouted or not. In case of non-grouted (unbonded) tendons it is possible to monitor the variation in tendon force, see Lundqvist (2016), Ansell (2018). The bonded tendons may be possible to monitor only if sensors were installed already during construction, i.e. before grouting. Otherwise, other aspects have to be monitored such as the global displacements etc, which can serve as a

proxy for determining the pre-stressing forces. It should be noted, however, that it is difficult to obtain early warnings of loss of pre-stress from these measurements and typically a significant reduction has to have occur before it will be noticeable, see Hassanzadeh et al. (2018)

During pressure tests, the leakage is an important aspect to monitor. This is both related to the total amount of leakage and to identify where any leakage occurs. This is especially interesting from a point of view to assess if the amount of leakage changes from different pressure tests, i.e. as a result of aging of the containment.

The type of measurements that were mentioned for monitoring the normal conditions and the long-term behaviour of the containment are naturally also important for monitoring potential failure events. It should be noted that different potential failure modes may occur depending on the studied event (or load case), hence it is typically necessary to place sensors in different locations to cover the different potential failure modes.

Simulations are an important aspect to determine where to place sensors, which type of sensors to use and their required measuring range and accuracy. Using simulations to assess the behaviour during a potential failure mode is a key aspect in determine critical locations that should be monitored. Hence, these types of analyses are suitable to determine where to place the sensors and also to determine which factors to monitor and thereby also the suitable measuring range of the sensors. Using the same type of numerical simulations but for normal conditions gives information about the required accuracy of the sensors.

3 Instrumentation in existing containment buildings

The instrumentation and monitoring of the nuclear containment buildings have varied over the years. The intent of this chapter is not to give a complete overview of the monitoring performed on different nuclear containment buildings. Instead, the purpose is to exemplify how a few containment buildings have been monitored over the years based on information available in the literature.

In the report by Lundqvist (2016) a few examples are given regarding monitoring of Swedish and Finnish reactor containment buildings as well as monitoring of waterways. In addition, a brief overview of containment buildings in USA are presented. In Gasch et al. (2018) a case study regarding monitoring of the Finnish reactor containment building Olkiluoto 2 (OL2). There are a few examples of monitoring of containment building based on research projects as well. In these cases, reduced scale experiments were conducted to assess the behaviour of containment buildings, such as the Vercors-project in France and the ISP 48 project Sandia in USA. These research projects contain many sensors intended to obtain a detailed recording of the response of the containment and may also include more unconventional type of sensors intended to test new technologies. Hence, the monitoring used in these projects cannot be considered representative for a nuclear containment building but can instead be useful to show the capabilities and limitations of different sensors and to increase the knowledge regarding nuclear containment buildings.

3.1 MONITORING THE EARLY BEHAVIOUR OF CONTAINMENT BUILDINGS

The early behaviour of containment building includes aspects intended to assess the casting and hardening of concrete, this was for instance made in the Vercors project, Corbin and Garcia (2016). It also includes measurements performed on nuclear powerplants during the Initial Structural Integrity Test (ISIT) that was performed directly after construction of the Swedish power plants. Lundqvist (2016) exemplifies the instrumentation and the monitoring performed at

Ringhals 1 (R1) and Oskarshamn 1 (O1) during the years 1972 and 1968 respectively. Another example presented by Lundqvist (2016) is the instrumentation of the newly built reactor containment building Olkiluoto 3 (OL3), which has a vast number of strain gauges etc installed already during construction.

All of these examples are related to newly built reactor containment buildings and hence is out of the scope of this report since it should be limited to existing containment buildings. Hence, these cases are not the focus of this report.

3.2 STRUCTURAL MONITORING

Limited information can be found in the literature regarding instrumentation used in existing nuclear containment buildings. One example, from Gasch et al. (2018), is regarding measurements of Olkiluoto 2 (OL2). In this report, it is mentioned that relative humidity sensors and temperature sensors are installed on several locations to monitor the ambient climate inside the reactor containment building. All of these are seen as support instrumentation, hence intended to provide input that can be used in future assessments/analyses. In Gasch et al. (2018), it is recommended that a BWR reactor containment should be monitored at four different elevations and at three points along the perimeter. By measuring the displacement in three points along the perimeter it is possible to capture uneven deformation. This is illustrated in Figure 3—1. In Gasch et al. (2018), it is recommended that the displacement, strain (in hoop direction) and the temperature is measured at these locations. In addition, it was also recommended that the relative displacement between the intermediate slab and the cylinder wall was measured at these three locations along the perimeter. Finally, recommendations are given that the relative displacement between the biological shield and the roof is measured.

It is also mentioned in the report that the OL2 containment building is instrumented based on these recommendations but no details regarding the exact amount and placement of sensors installed in OL2 is given in the report.

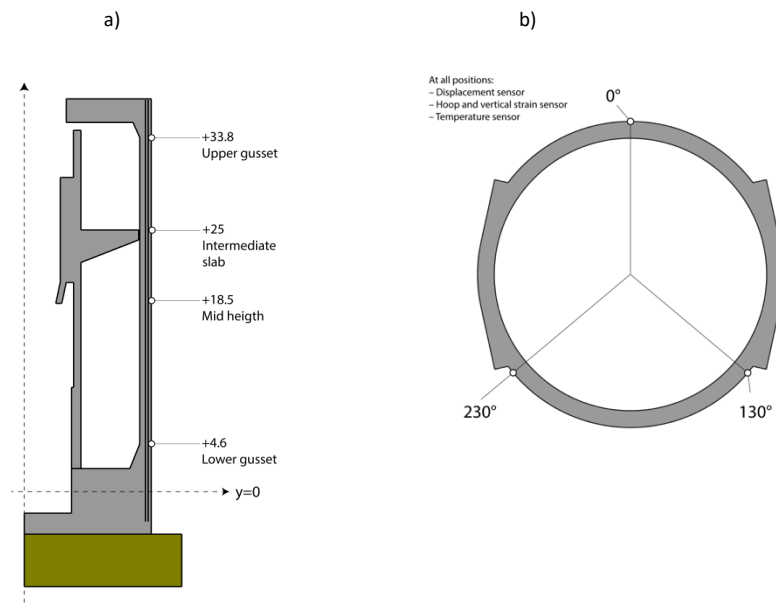


Figure 3—1 Illustration of locations suitable for deformation measurements of a BWR containment, from Gasch et al. (2018).

The French electricity company EDF operates many PWRs, these have a structural monitoring program as described in table 2. The instrumentation varies between facilities, with newer ones typically having more instrumentation than older ones. Many of the sensors are cast into the concrete and therefore are not easily replaced or have their function checked out. To compensate for this, additional sensors have been installed after construction, such as the strain meter mentioned in section 4.5.4.

Table 2 Instrumentation used at EDFs containment buildings, Courtois (2019).

EDF containment instrumentation		
Instrument	Quantity	Purpose
Hanging pendulum	4	Measure radial deformation of containment wall.
Invar wire extensometer	4	Measure height variations of containment wall.
Vibrating wire extensometers	~50	Extensometers are cast into the concrete to measure the deformation locally.

Temperature sensor (Pt 100t)	~25	Temperature sensors are cast into concrete to measure its temperature.
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In the report by Lundqvist (2016), it is mentioned that the pre-stressing force is measured using hydraulic jacks in the Swedish containment buildings that were built with unbonded (un-grouted) tendons, i.e. Forsmark I – III and Ringhals II – IV. According to Lundqvist (2016), this is performed during periodical in-service inspections. Due to the manual recordings, these measurements are not possible to use in a warning system. Instead, Lundqvist (2016) describes that certain horizontal and vertical tendons are continuously monitored with load cells in Forsmark I and in Forsmark II. These sensors could thereby be used in conjunction with warning values to assess if the pre-stress losses exceed a certain threshold.

3.3 LEAKAGE MONITORING

In the report by Karlsson (2004), an on-line monitoring system used for gas leak detection in reactor containment buildings is described. An OLM system is a group of measuring methods meant to monitor the containment building during normal operational conditions. The system measures the normal variations in for example pressure, temperature, or trace gas. When the system finds a deviation, it alerts the operator that there might be a leak in the containment structure.

According to Karlsson (2004) OLM systems are commonly used for leakage monitoring internationally. It is pointed out, however, that OLM systems have a lower accuracy than the traditional containment leak-testing methods. The purpose of the system is instead to reveal large leaks earlier than the scheduled tests which are done with a few years separation. From a Swedish context where the steel liner is embedded in the cylinder wall, leakage detection can be even more difficult using such an online monitoring system. Ringhals previously had a CAT-OLM (Containment Air Test On Line Monitoring) in place that was based on the SEXTEN system used in France, Karlsson (2004). However, experiences with the system showed that it did not perform well in practice.

In the Vercors-project, the leakage measurements were performed where a plastic hood was placed over cracks or joints and the air flow was measured using air flow sensors during the pressure tests.

3.4 LIST OF SENSORS WITH DOCUMENTED USE IN CONTAINMENTS

Deformation measuring sensors		
Instrument	Facility	Measurement
Hanging pendulums	Vercors (experimentally), EDF facilities (France)	Diameter variation of containment wall
Invar-wire extensometer	EDF facilities (France), Vercors (experimentally)	Vertical variation of containment wall
Strain gauges	Vercors (experimentally)	Vercors: Strain measurement on containment wall surface and on steel tendons
Strain meter	EDF facilities (France) (experimentally)	tangential strain of containment wall
Tilt sensor, levelling pot	EDF facilities (France)	Deflection of bottom slab
Ambient climate measuring sensors		
Instrument	Facility	Measurement
Temperature sensors	Vercors, Olkiluoto	Temperature in air and concrete, (can be installed in concrete through drilling)
Relative humidity sensor	Olkiluoto	Air humidity
Barometer		Air pressure
Other types of sensors		
Instrument	Facility	Measurement
Load cells	Vercors (experimentally), Forsmark	Force in tendons
pulse sensors	Vercors (experimentally)	gas permeability in concrete
Photogrammetry	R.E. Ginna NPP, (experimentally)	Concrete strain in containment wall and roof
Concrete humidity sensor	Ringhals, Forsmark (experimentally)	Relative humidity and temperature in concrete

4 Deformation based sensors

This chapter describes sensors which are currently used to measure deformations in containment buildings or other similar civil structures. The sensors can be divided into global and local deformation sensors where global sensors capture the movement over a large section of the structure while a local sensor is used to monitor the movement in a single location, for example over an expansion joint.

Different techniques can be used to measure deformations, these include LVDTs, vibrating wires and potentiometers. These are described briefly in sections 4.1 to 4.3.

4.1 LVDT

LVDTs or linear variable differential transformers can be used to measure relative displacement. The sensor measures displacement through induction where displacement causes a change in the induced voltage through the sensor, Malm (2015). Due to this measuring technique LVDTs have a good thermal stability to temperature gradients.

4.2 VIBRATING WIRE

Vibrating wire sensors consist of a wire tensioned between two points and set into vibration. The frequency of vibration is dependent on the tension in the wire. When the structure experiences strain, it causes a change in tension of the wire, which in turn changes the measured frequency.

Vibrating wires are used for many types of sensors such as strain gauges, crack width sensors and load cells and have a high long-term stability.

4.3 POTENTIOMETER

Potentiometers consist of a resistive element and a sliding contact. A displacement will cause the contact to slide across the resistive element causing a change in the electrical resistance between the contact and the ends of the element. The change in resistance can be

used to measure the displacement. They can be used to measure displacements in the range of a few millimeters up to a few centimeters.

4.4 GLOBAL DEFORMATION SENSORS

4.4.1 Hanging pendulum

A hanging pendulum is used to measure the horizontal deformations of a concrete structure. The pendulum consists of a steel wire anchored at the top of the structure with a weight at the bottom. The weight is often placed in a dampening fluid to reduce vibrations. The deformation can be measured either manually or automatically. For a containment building the pendulum is used to measure the diameter variation between two points along the cylinder wall height. Several reading tables can be installed along the length of the pendulum to track the displacement more accurately. See figure 4—1 to 4—3 for a pendulum installation in a French facility.

The measurement area of pendulums typically varies between 50-150 mm in the radial direction. In the tangential direction the range is often slightly less. The recommended measuring range is stated in ICOLD bulletin 158 (2018) as 150 % of the expected deflection. The measurement accuracy of a pendulum is stated as ± 0.2 mm. The accuracy is highly dependent on how the readouts are taken from the pendulum. An automatic measurement reading unit will be more precise than if the measurements are taken manually.

Furthermore, automatic measurement readings besides being more precise also has a high sampling ratio to capture rapid movements. One automatic logging device has a resolution of 0.01 mm and a accuracy of ± 0.05 mm in the radial and tangential direction, for movements below 30 mm, (Sisgeo, 2022).

In Figure 4–1, a pendulum system with an automatic logger is shown. As mentioned in section 1.1.2, automatic logging can be used with a short time interval between readings to capture the behaviour during short term events. For continuous monitoring over long time periods it is common to take readings every hour or every 10 minutes.

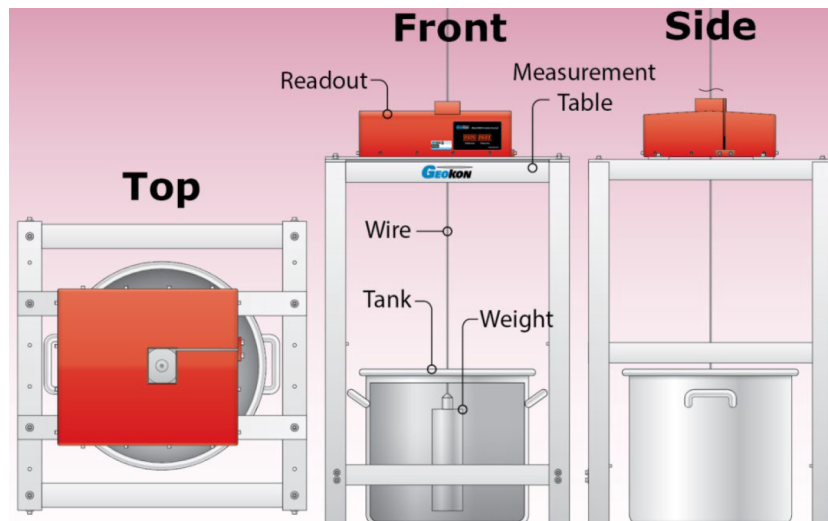


Figure 4–1 Hanging pendulum with a measurement table, automatic readout, and a tank with fluid to dampen vibrations in the wire, (Geokon, (2022))

The pendulum only measures the deformation in a single section; therefore, it is recommended by ICOLD to combine the pendulum with other independent deformation measurements.

A hanging pendulum can be used to measure the radial movement of a vertical containment wall. When considering the necessary accuracy of the pendulum it is of interest to consider different events that will cause a radial displacement of the structure. One example is the loss of tension in one of the horizontally placed prestressed tendons.

The loss of a horizontal tendon will cause a lengthening of the circumference of the cylinder wall. The ability for a sensor to capture the event depends on how large of an area the deformation occurs over. It also depends on how close the sensor is to the lost tendon. In

the below simplified example, it is assumed that the tension loss of the tendon affects an area equal to the thickness of the cylinder wall in width and height. It is also assumed that the response of the cylinder wall is symmetrical, in practise the loss of one tendon would cause an imbalance as the circumference of the wall is enclosed by two cables each covering half a turn around the cylinder wall.

The below example aims to give an idea of the necessary accuracy of a sensor to detect the loss of tension in a horizontal cable. The force in the cable is decided as 4.75 MN and the radius of the containment as 17.15 m.

$$f=4.75 \text{ MN} \quad R_m=17.15 \text{ m} \quad O = 2\pi * R_m = 107.8 \text{ m}$$

The local change in tension when one cable is lost and the resulting strain can then be described as,

$$\sigma = \frac{f}{A} = 3.9 \text{ MPa}$$

$$\varepsilon = \frac{\sigma}{E} = 1.1 \times 10^{-4}$$

The change in circumference of the wall is 12.1 mm. The change in radius is 1.9 mm. If it instead is assumed that the lost cable affects an area along the whole height of the containment wall, the radial displacement would be around 0.05 mm – which is unlikely to be measurable with a pendulum.

In the report by Hassanzadeh et al. (2018) it was calculated using FE-analysis that the radial displacement during a normal pressure test would be about 5 mm. The deformation would occur at midspan between two buttresses. A deformation of this size should be measurable by most pendulum sensors assuming they are placed somewhat close.

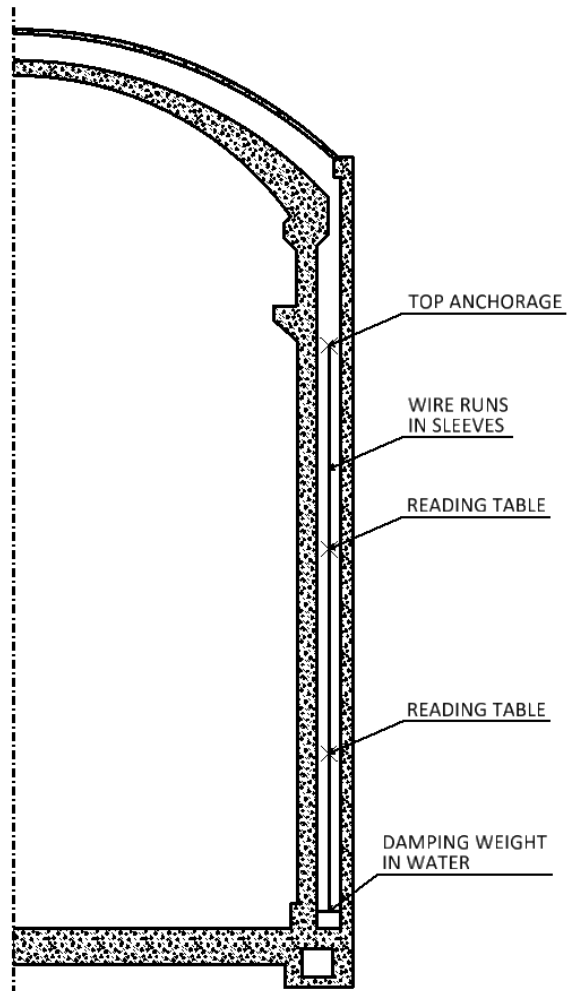
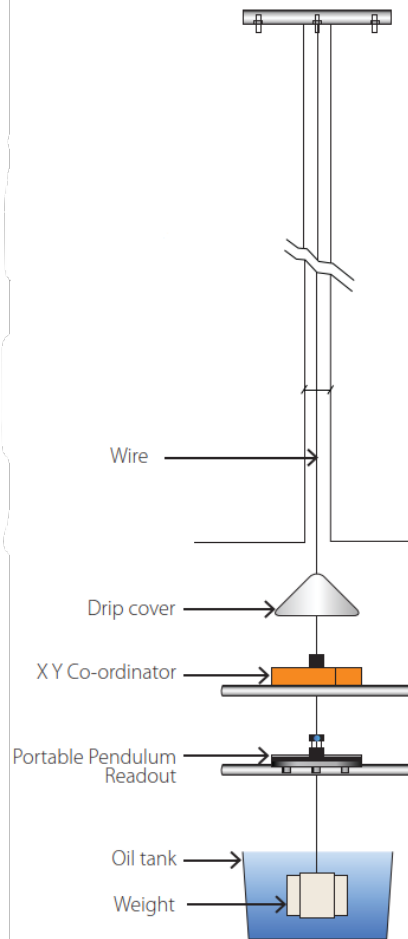


Figure 4—2 Section showing pendulum placement in the French mockup containment VeRCoRs. The pendulum is used to monitor the inner wall, which is reinforced with prestressed tendons, Oukhemanou, (2016).



A)



B)

Figure 4—3 A) Damping weight in water and reading table for a pendulum, Oukhemanou, (2016)
 B) Illustration of a pendulum system, Soil Instruments, (2023).

As mentioned in Section 3.2, recommendations on instrumentation with pendulums were made for the BWR containment building of OL2. The recommendation was to install 3 pendulums along the perimeter of the containment. Each pendulum was suggested to have 4 reading tables at different elevations.

The pendulums were to be placed on the outside of the wall to make access easier and to reduce the risk of radioactive contamination, Gasch et al. (2018).

In the Vercors-project the behaviour of a PWR containment was analysed by building and instrumenting a containment one third the normal scale. There 4 pendulums were used with 3 reading tables along each pendulum. A section of the containment is shown in Figure 4.2. The typical PWR containment in France is fitted with 12 pendulums with one reading table for each pendulum, Oukhemanou et al. (2016).

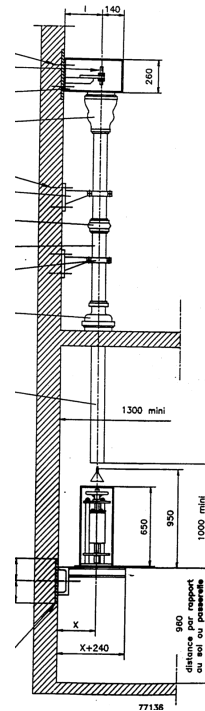
4.4.2 Invar-wire extensometer

An invar-wire extensometer can be used to measure movement along the height of a wall. Invar is a material with a very low thermal expansion coefficient (around $1.2 \cdot 10^{-6} \text{ K}^{-1}$), which is one tenth that of steel). For this reason, it is used as a wire to measure movements along its length. For containment buildings the wire can be set up along the height of the containment wall to measure the height variations of the structure, Courtois (2019). The measurements are taken continuously using an LVDT sensor connected to a data logger. The set up used in French containment facilities is stated as having an accuracy of $\pm 1 \text{ mm}$ or better for a measuring range above 40 meters, Courtois (2019).

In the Vercors project, invar wires were placed at 4 points equally spaced along the perimeter of the containment wall. The wires were anchored at the top of the wall, just below the rounding of the roof, and the measurements were read at the level of the bottom slab. A principle of the sensor is seen in figure 4—4 b).



a)



b)

Figure 4—4. a) Invar-wire extensometer installed on a containment wall. b) principle of an invar wire extensometer, EDF (2019).

When considering the necessary accuracy of the sensor it is relevant to consider what event is of interest to capture. The loss of tension in one or several vertical pre-stressed tendons effects the safety of the structure and could hopefully be captured by an extensometer.

Assuming a containment building with 153 vertical tendons, each having a prestress force of 4.75 MN. The cross-sectional area of the cylinder wall decided as 41.8 m². The compressive force and stress on the cylinder wall can be described as,

$$n=153 \quad f=4.75\text{MN} \quad A=41.8 \text{ m}^2$$

$$F_v = n \times f = 727 \text{ MN}$$

$$\sigma = \frac{F_v}{A} = 17.38 \text{ MPa}$$

When the tension is lost in one tendon the force is reduced to 722 MN and the stress to 17.27 MPa. The reduced compressive stress of 0.11 MPa would cause a lengthening of the wall such that,

$$\epsilon = \frac{\sigma}{E} = \frac{0.11 \text{ MPa}}{35 \text{ GPa}} = 3.25 \times 10^{-6}$$

The displacement over a 50 meter is then calculated as,

$$d_v = \epsilon \times L_v = 3.25 \times 10^{-6} \times 50 \text{ m} = 0.16 \text{ mm}$$

The calculated displacement is likely to small to be detected by an extensometer. A loss of 10 % of the tendons would instead cause a lengthening of the wall of 2.4 mm which likely would be captured by the extensometer. However, the possibility to discover a loss of tension depend on where the extensometer is placed in relation to the lost tendon. As well, if the loss of tension happens in one concentrated area it is more likely to be detected by a sensor than if it occurs more uniformly across the perimeter of the wall.

The above example assumes the containment wall has no penetrations and the response is homogeneous to the loss of cable tension. In practice if one tendon was to break it would cause an unsymmetrical response where one side of the wall is lengthened, and one is compressed. To capture if the cross-section of the wall has tilted it would be necessary have at least 3 extensometers along the wall perimeter.

4.4.3 Tilt sensor

A tilt sensor measures the change in angle over for example a concrete wall or a slab. The change of angle of the structure can be translated to a corresponding deformation. Both one and two directional tilt sensors exist. A tilt sensor measures the change in angle locally but several sensors can be placed along the height of a structure to capture the global behaviour. One tilt sensor has a measuring range of $\pm 5^\circ$ and a stated accuracy of 0.01° . For civil structures such as dams and containment buildings, it is however stated that the accuracy of the sensor is low in relation to the expected movement as the change in angle is very small, ICOLD (2018). Therefore, it is suggested to only use tilt sensors as support instrumentation along with for example pendulums. A possible use of a tilt sensor is to measure for the effects of settlements on the structure. It can also be used as a complement to a pendulum to measure the horizontal deflection of a containment wall.

The deformations during normal operations are likely to be small for the containment wall along with the angle change. However, one possible use of tilt sensors is to measure the effects of foundation settlements on containment buildings. Previously, tilt sensors have been used in French containment buildings to measure the displacement of the ground slab during pressure tests. Several two directional tilt sensors were installed along the slab to estimate its displacement. These measurements have since been discontinued because of retrofitting of the slab, (B. Masson, mail correspondence, 20/12 2021).



Figure 4—4 Uniaxial tilt sensor, also exists as biaxial, Jewell Instruments 2021.



Figure 4—5 Tilt sensor installed near the crest of a concrete buttress dam.

4.4.4 Total station

Total stations, common for surveying and construction, can be used to measure the global displacement of a structure. On dams this is often done by having mounted prisms or dubs which are measured from a predefined point where the total station is placed. The displacement of the point of the prism or total station can be calculated from the change in horizontal/vertical angle as well as the distance between.

The range is improved if there is a clear line of sight between the total station and the target. The accuracy depends on the distance as well as the angle of refraction but can be estimated as ± 2 mm, Ekström and Lier (2013). For one specific make of total station the accuracy is stated as ± 2 mm for measurements between 0-500 m and ± 4 mm for measurements beyond 500 meters, Leica (2020). The precision of the instrument is dependent on the reliability of the mounts of prisms placed on the structure. Permanently installed prisms can increase the precision meaning that the several measurements will have a lower spread in their results.

4.5 LOCAL DEFORMATION AND STRAIN MEASUREMENTS

Local deformation sensors are used to measure the relative displacement between two points in proximity. Local sensors can for example be used to monitor the movement of a single crack in the concrete, or the strain along a tendon.

When monitoring the movement of a crack using a crack width sensor, the sensor is embedded in the concrete on either side of the crack. Since the sensor captures movement over a larger area than the actual crack (see Figure 4—6), it is unknown how much of the movement takes place in the crack. To evaluate this, complementary instrumentation can be used such as measuring the strain on either side of the concrete with strain gauges.

4.5.1 Crack width sensors

Crack width sensors are used to measure the relative displacement of two points on either side of a concrete crack. To ensure the measured displacement is that of the crack, the attachment points of the sensor should be placed as close to the crack as possible. The accuracy of crack width sensors and other sensors with similar applications is often stated as a percentage of the full range of measurement. One

manufacturers sensor has a stated accuracy of $\pm 0.1\%$ of the full measuring range, the smallest standard measuring range of the sensor is 12.5 mm which gives an accuracy of $\pm 12.5 \mu\text{m}$, Geokon (2023).

The crack width can be measured either in one or three dimensions. The three-dimensional sensors are larger and require more complex attachments. Several one-dimensional sensors can also be placed in several directions to capture the behavior, see Figure 4—6.

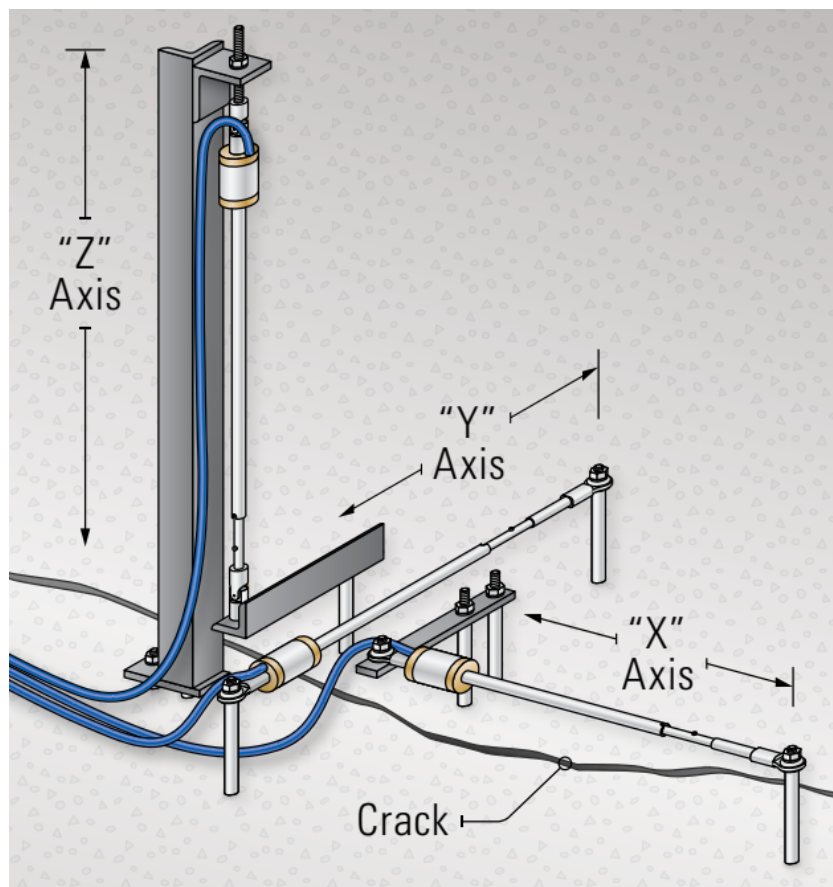


Figure 4—6 The behavior in all three axes can be captured using three one-dimensional sensors placed in several directions, Geokon (2023).

Besides measuring crack width, displacement sensors of a similar type can be used to measure the relative displacement between two close points on a structure. A possible measurement is the relative displacement between the cylinder wall and the middle slab of the biological shield. This can be measured with for example a displacement sensor between the parts. For instance, Figure 4-7

shows an axisymmetrical model of a Swedish BWR containment building analyzed by M. Könönen (2012). There the contact between the middle slab and the cylinder wall is analyzed. Results showed the middle slab moving toward the cylinder wall when under load from design temperature and dead-weight. Gasch et al. (2018) recommended also using a displacement sensor between the biological shield and the roof. The report recommended placing the sensors at three positions along the perimeter of the containment, see Figure 3—1 b.

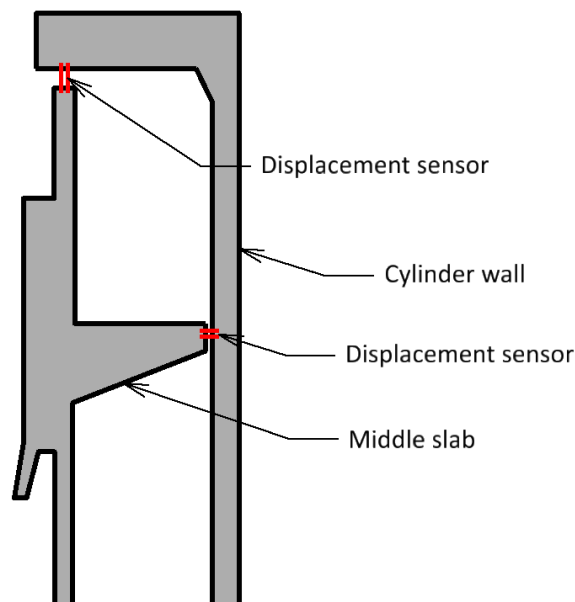


Figure 4—7 Possible location of a displacement sensor to measure the displacement between the cylinder wall and the biological shield as well as the displacement between the biological shield and the roof of the containment.

4.5.2 Joint meter

Joint meters can be used for measuring the relative displacement in the rock-concrete interface. The sensor is installed by drilling a hole through the foundation and the sensor is placed in a socket between the rock and concrete.

One joint meter manufacturer has a stated accuracy of $\pm 0.1\%$ of the full measuring range, the smallest standard measuring range of the sensor is 12.5 mm which gives an accuracy of $\pm 12.5 \mu\text{m}$ in laboratory conditions, Geokon (2023).

Joint meters were used as instrumentation in a full-scale test of a concrete plug meant for sealing deposition tunnels at the SKB Äspö Hard rock laboratory. The sensors were cast into the interface between rock and concrete to measure their relative displacement over time as the concrete plug was subjected to water pressure on one side, see Figure 4—8.



Figure 4—8 Joint meters used to measure the relative displacement between concrete and rock, Malm (2015).

4.5.3 Strain gauge

When a containment structure is pressure tested it will result in stress along the tangential direction of the surface (hoop stress), Gasch et al, 2018. A pressure test will also result in vertical strain along the cylinder wall. This can be recorded with a strain gauge. To compensate for temperature changes causing thermal expansion of the strain gauge, it is often combined with a temperature sensor. Alternatively, the temperature can be measured nearby by a separate sensor.

Strain gauges can be added both during construction and while in operation. When casting, strain gauges can be placed along a reinforcement bar or freely in the concrete. In Figure 4—9 a rebar cage is shown with both a vertical and tangential strain gauge that are to be

cast into the concrete. There also exists sensors already mounted to plates or reinforcement bars to ensure adhesion to the concrete.



Figure 4—9 Two strain gauges mounted in a rebar cage before casting. Oukhemanou, (2016).

When placing strain gauges on an existing structure the sensor can be attached in several ways. It is possible to mount strain gauges to both steel and concrete using adhesives, the adhesive used is dependant of the material of whatever the strain gauge is attached to, Parande, et al (2013). The surface of the structure requires some preparation to ensure good bonding. The adhesive must transfer the force from the surface to the strain gauge and maintain bonding over time.

A drilled and grouted anchor attachment can be seen in Figure 4—10.

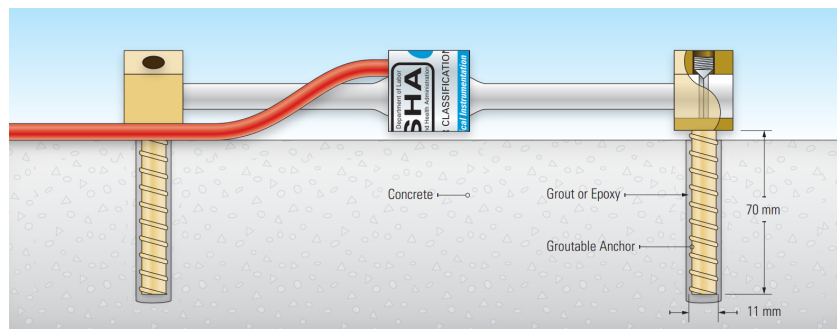


Figure 4—10 "Strain gauge attached to concrete via grouted concrete mounting blocks" Geokon, 2019

One strain gauge which uses a vibrating wire sensor has a measuring span of $3000 \mu\epsilon$ with a resolution of $1 \mu\epsilon$, Sisgeo (2016). Assuming an elasticity modulus of $E_{cm} = 30 \text{ GPa}$, the measuring range corresponds to a material stress of 90 MPa and the resolution to 30 kPa . Since the tensile strength of concrete in a typical Nordic containment building is around 3 MPa , this is well within the measuring range for capturing the opening of cracks in the concrete. The accuracy of strain gauges can be improved upon by calibrating the sensors to the deformations expected in the structure. The calibration is often done during installation and not during the life span of the strain gauge. To achieve redundancy several strain gauges are often placed in the same area.

4.5.4 Strain meter

A strain meter made from an invar bar has been tested experimentally for measuring tangential strain of a containment wall, A. Simon et. Al (2013). The bar is 1 meter long and is placed horizontally along the surface of the containment wall, on both sides connected to an anchor embedded 300 mm in the concrete, see Figure 4—11. The two sides move freely in the length direction with the right side of the rod slides inside the left side where the displacement sensor is placed. The displacement sensor consists of an LVDT sensor which measures the relative displacement between the right and left side of the bar. The sensor is connected to a logger for continuous monitoring. The accuracy of the instrument in a laboratory setting is $\pm 12 \mu\epsilon$.



Figure 4—11 Surface strain meter installed on the outside of a containment wall. The displacement sensor is left side of the 1 m invar bar, A. Simon et. Al (2013).

4.5.5 Fiber optic cable

Fiber optic cables can be used to measure strain in concrete structures. The process consists of embedding the cable in the concrete or installing it on the surface of the concrete. Light signals are transmitted through the cable and when strain is applied to the concrete it alters the physical properties of the cable causing a change in the signal, from which it is possible to determine the corresponding strain in the concrete.

For containment buildings the cables have mainly been used to monitor strain and temperature inside the concrete by installing the cable during construction before the concrete is cast. This was done at Vercors where the cable was used to measure strain both along the perimeter of the wall and over its height, see Figure 4—13. However, tests have been performed where fiber optic cables have been installed on the surface of bridges to monitor strain at the surface, see Figure 4—12.

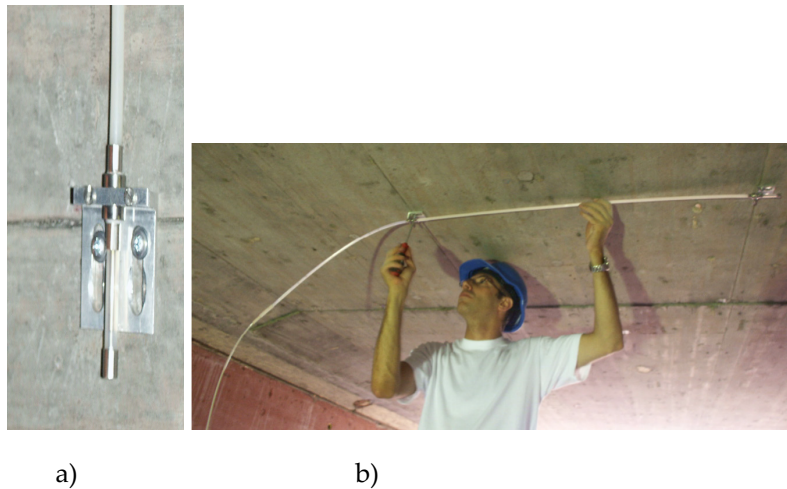


Figure 4—12 Fiber optic cable, a) shows the bracket used to mount the cable and b) shows the installation, Enckell (2006).

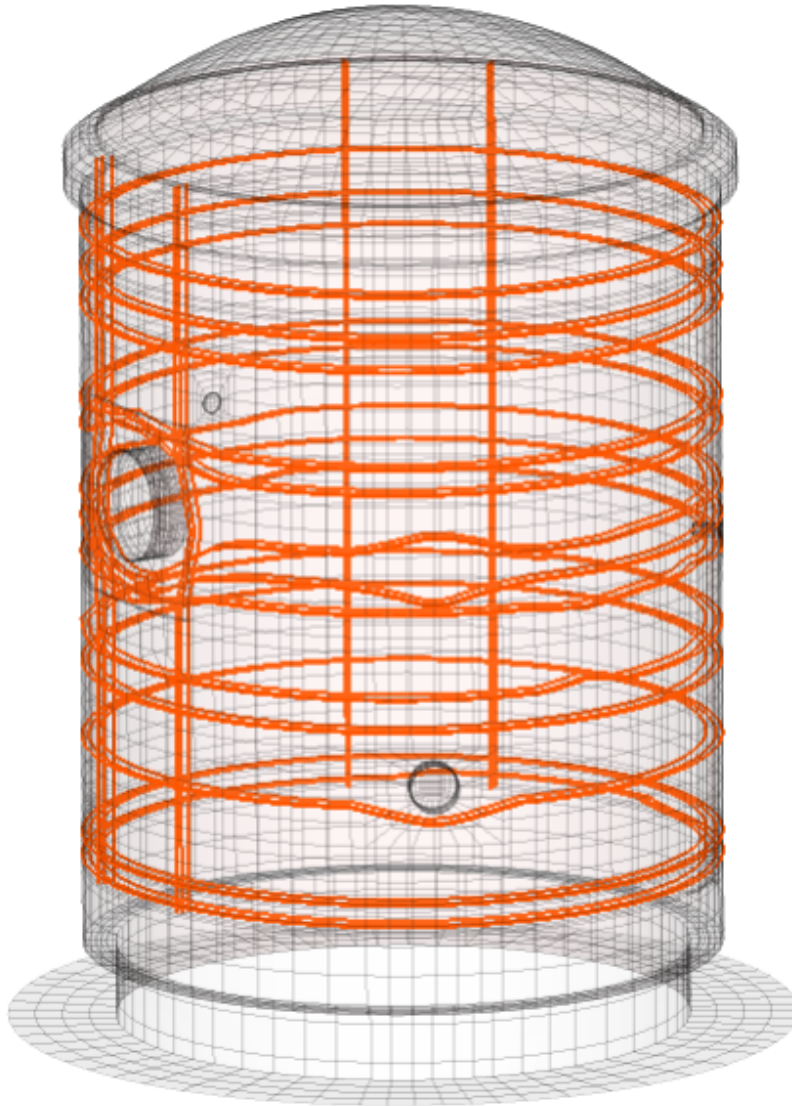


Figure 4—13 Placement of fiber optic cables cast into the Vercors containment wall.

4.5.6 Foundation measurements

Extensometers are common sensors in the foundation of concrete structure. It measures the displacement in one direction between two points.

One vibrating wire extensometer for boreholes has a stated accuracy of $\pm 0.1\%$ of the full measuring range, the smallest standard measuring range of the sensor is 12.5 mm which gives an accuracy of $\pm 12.5 \mu\text{m}$ in laboratory conditions, Geokon (2023).

An extensometer could for example be placed in a borehole in the rock near the containment to measure possible movements in the rock. The borehole can be drilled at an angle for the extensometer to capture horizontal movements. It is possible to install several extensometers anchored at different levels to measure deformation across different zones if it is of interest to measure deformation across for example a rock fissure. An illustration of an installed extensometer is presented in Figure 4—14.

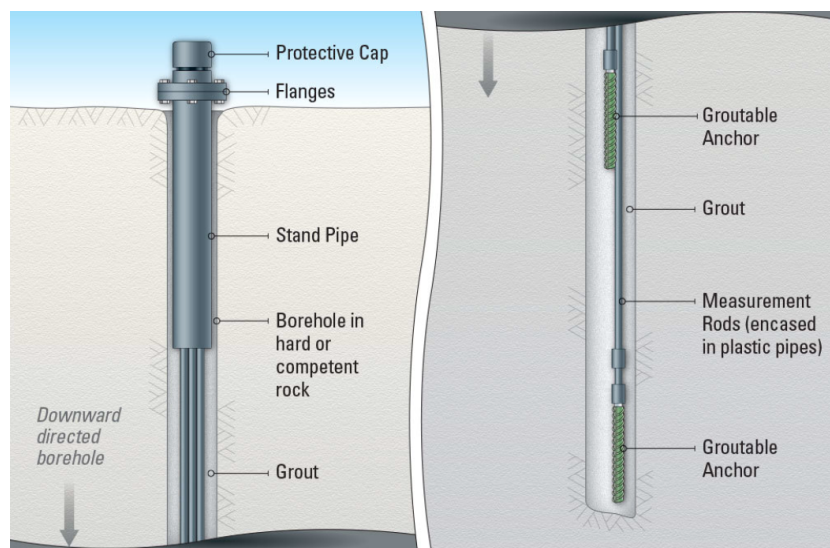


Figure 4—14 Illustration of an extensometer with measurement rods anchored at several levels. Geokon, (2019).

4.6 SUMMARY OF DEFORMATION SENSORS

Deformation measuring sensors			
Global deformation sensors			
Sensor	Measurement range	Accuracy	Note
Hanging pendulums	50-150 mm	± 0.2 mm	A well proven sensor used for many civil structures. It can only measure over vertical sections.
Invar-wire extensometer	-	± 1 mm	Invar wires are used as vertical extensometers with LVDTs to measure height variations over long sections >40 m.
Tilt sensor, levelling pot	1.1°	$\pm 0.01^\circ$	Measures the deflection of a structure.
Total station	500 m	± 2 mm	Total stations can be both permanently mounted and mobile.
Local deformation sensors			
Sensor	Measurement range	Accuracy	Note
Strain gauges	3000 $\mu\epsilon$	± 15 $\mu\epsilon$	Vercors: Strain measurement on containment wall surface and on steel tendons.
Strain meter	-	± 12 $\mu\epsilon$	Measures the surface strain in concrete over a larger section.
Crack width sensors	10 mm	± 12.5 μm	A wide range of sensors can be used to measure local displacement.
Fiber optic cable	0.4 m	± 20 $\mu\epsilon$	Measures strain along the length of the cable. Can also be used to measure temperature.
Joint meters	10 mm	± 12.5 μm	Measures relative displacement in interface between materials.
Foundation extensometer	10-50 mm	± 12.5 μm	

5 Ambient climate-based sensors

In this chapter sensors not directly linked to the structure are covered. The sensors can for example measure air temperature or pressure which is necessary to evaluate the performance of the containment. Changes in for example internal pressure in the containment building should be reflected in the deformation-based sensors.

The ambient temperature outside of a containment building differs depending on reactor type and thereby the chosen building design. A BWR containment is enclosed by a shell building and thereby protected from the outside climate. The typical PWR on the other hand has no building envelope and the containment building is exposed to the outdoor climate.

5.1 AIR PRESSURE SENSOR

The modern air pressure sensors measure the atmospheric pressure based on the effect the pressure has on a flexible structure such as a membrane, ST (2021). There are two typical ways to measure the air pressure, resistive or capacitive barometric pressure sensors.

The range of one resistive pressure sensor is 26 – 406 kPa with an accuracy of ± 0.05 kPa, the accuracy varies slightly with the pressure, as well, the range and accuracy vary greatly between different products. Modern air pressure sensors are very compact, the one shown in Figure 5—1 has the dimensions 2.8 x 2.8 x 1.95 mm.

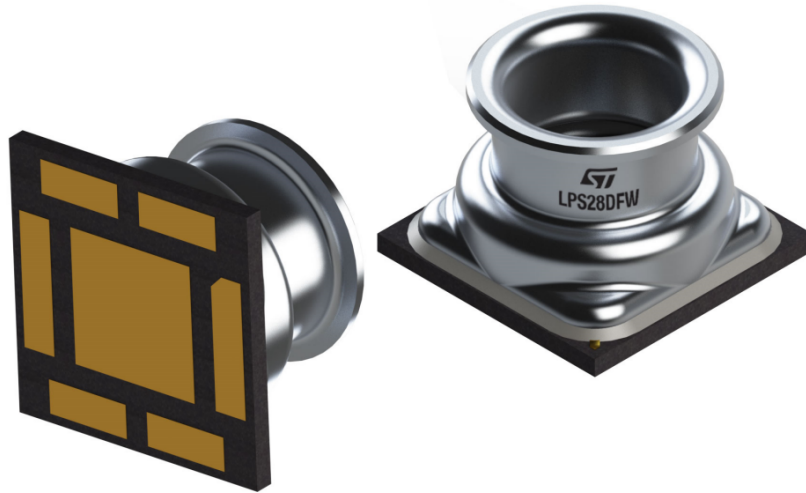


Figure 5—1, Air pressure sensor, ST (2021)

Air pressure sensors can easily be used for long term monitoring, the drift is generally low, ± 0.1 kPa/year for one sensor. The sensor also corrects for temperature effects by having an internal temperature sensor. The capacitive sensors typically have better temperature stability than the resistive sensors. Redundancy can be achieved by installing several sensors.

5.2 TEMPERATURE SENSOR

There are several types of temperature sensors, for example thermocouples and thermistors. A thermocouple generates a temperature-dependent voltage potential which can be used to measure the temperature. The thermocouples often have a larger measuring range than the thermistors. Malm, et al (2019).

Thermistors are a type of resistor where the resistance is dependent on the temperature. A common thermistor sensor is the Pt100 where Pt refers to platinum and 100 refers to the sensor having a resistance of 100 ohms at 0 °C. Pt1000 sensors also exist and can be useful for measuring over long cable lengths since the resistance of the cable is relatively smaller than the resistance measured by the sensor. Pt1000 sensors can therefore be used to check the function of Pt100 sensors placed in pools.

Normal thermometers have a measuring range of -30 °C to +40 °C when measuring air and water temperature. However, sensors with

larger stated ranges can be found, for example $-20\text{ }^{\circ}\text{C}$ to $+80\text{ }^{\circ}\text{C}$, Geosense (2021). Thermometers in concrete measure from $-10\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$, ICOLD (2018). Temperature sensors are divided into classes depending on their accuracy, the most common sensors have an accuracy of $\pm(0.3+0.005|t|)\text{ }^{\circ}\text{C}$. Where t is the temperature in Celsius.



Figure 5—2 To the left, a temperature sensor for use in water and concrete, Geosense (2021). To the right, temperature sensor in a rebar cage to be cast into concrete, Oukhemanou (2016).

The concrete temperature is regulated in the design codes of containment buildings. For normal operation the highest long-term concrete temperature allowed is $66\text{ }^{\circ}\text{C}$. Higher temperatures are however allowed locally. For example, around steam pipe penetrations the maximum allowed temperature is $93\text{ }^{\circ}\text{C}$.

High temperatures inflicted on the structure short term or due to accidents are also regulated. The surface of the concrete is then allowed to reach $176\text{ }^{\circ}\text{C}$. In an accident scenario where a pipe break causes steam or water jets the temperature is locally allowed to reach even higher, up to $343\text{ }^{\circ}\text{C}$.

The temperature varies significantly in different zones inside the containment. An example of the climate zones is illustrated in Figure 2—2, Könönen (2012). Installed sensors should be able to capture the temperatures of the different zones to aid in evaluating the structure. Temperature sensors are also needed to compensate for the thermal expansion of sensors such as strain gauges which often have temperature sensors built in or placed in close proximity, Gasch et al, (2018).

Higher range thermometers exist such as infrared thermometers. The most common are infrared pyrometers which measure the temperature on a spot, often using a laser. See Figure 5—3 for an example of an infrared pyrometer. These can measure surface

temperatures in the range of -50°C – 400°C (up to 3000°C), with an accuracy of $\pm 1^{\circ}\text{C}$, Micro-Epsilon (2021). However, for ambient temperatures the range drops to -20°C to 130°C with a accuracy of $\pm 5^{\circ}\text{C}$.



Figure 5—3 Infrared thermometer, Micro-Epsilon (2021)

5.3 HUMIDITY SENSOR

Air humidity sensors are often combined with temperature sensors to be able to give the relative humidity of the air. One sensor has a measuring range of RH is 0 – 100% with an accuracy of $\pm 0.8\%$ RH. The operating temperature range for one type of sensor is -40 to 125 °C, Texas Instruments (2020).

Humidity is measured in containment buildings as it can affect building components. If there is high humidity and temperature condensation will occur on cold surfaces. This can cause corrosion on metallic building components, Oxfall (2016). The relative humidity also impacts the drying of the concrete, a lower humidity along with high temperature can accelerate the drying of the concrete.

The relative humidity in containment buildings is not regulated in any way, Oxfall (2016). The air is however dehumidified during operations. In some containment structures where the tendons have not been injected, dried air is ventilated to the tendons through the ducts, Roth et al. (2002). The IAEA also recommends that the relative humidity is monitored inside the containment to detect leakage from the primary water circuit, Oxfall (2016).

5.4 SUMMARY OF AMBIENT CLIMATE-BASED SENSORS

Climate sensors			
Sensor	Measurement range	Accuracy	Note
Air pressure sensor	26-406 kPa	± 0.05 kPa	
Temperature sensors	-10 °C to +60 °C (concrete) -20 °C to +80 °C (Air)	± 0.3 °C	Temperature sensors with larger measurement ranges and higher accuracy exists. For larger ranges the accuracy may be lower.
Humidity sensor	0-100%	± 0.8 %	

6 Other types of sensors

This chapter presents sensors that can be used to monitor containment buildings but that do not fit into the earlier chapters. The chapter covers both sensors which are currently in use and sensors that so far has only been used experimentally.

6.1 ACCELEROMETER

Accelerometers can be used to measure the effects of vibrations on structures. Such as the acceleration caused by traffic on bridges or tunnels. The measured acceleration is integrated over time to get the velocity. The velocity in turn can be integrated over time to get the change in position over time (deformation).

Several types of accelerometers exist such as piezoelectric accelerometers (not sensitive to electromagnetic fields), capacitive accelerometer, force balanced accelerometer and micro-electro-mechanical systems (MEMS) accelerometers, Andersson, et al, (2007). The measuring range is $\pm 1 \text{ m/s}^2$ and accuracy in acceleration is 0.3 mm/s^2 and time 0.005 seconds, ICOLD, (2018).

Internationally, accelerometers are also used to measure the effects of earthquakes. In Sweden the nuclear structures are the only buildings designed to withstand earthquakes. However, earthquakes are both rare and random so any attempt to capture the effects of an earthquake would require continuous monitoring with accelerometers.



Figure 6—1 A MEMS gauge placed on the walkway of a concrete bridge, KTH (2007).

6.2 LOAD CELL

Containment walls and roof are reinforced with prestressed tendons in both the horizontal and vertical direction as mentioned in section 2.1. It is important to monitor the status of the tendons as these prevent cracks in the concrete and ensure air tightness. Since the tendons are under constant stress they undergo relaxation, as well the concrete undergoes creep and shrinkage, reducing the pre-stress force in the tendons. Only tendons which are not grouted can be monitored with a load cell.

A load cell is installed at the anchor point of the tendon to measure the force between anchor head and anchor plate. However, it does not capture which component of the change in force is due to relaxation in the cable contra creep deformation in the concrete.

Strain gauges can be used to indicate changes in the tendon force. However, they cannot be used to tell the exact force in the instrumented tendon. The strain gauges are more suitable for installing on individual BBRV strands than VSL cables as these are intertwined.

There are several types of load cells. Some measure force as the hydraulic pressure between two stiff steel plates, others by using vibratory wire strain gauges and translating it to force. There exist several load cells with different measuring ranges. One model can measure forces in tendons up to 5000 kN with an accuracy of $\pm 0.5\%$, Glötzl (2017).

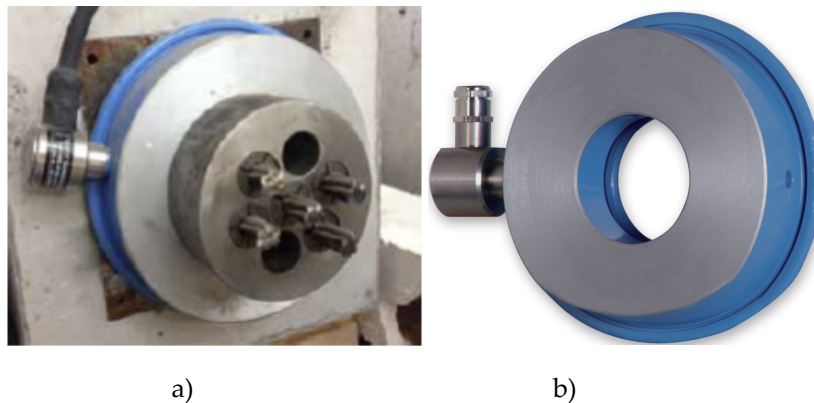


Figure 6—1 A VSL cable instrumented with a load cell, Ansell (2018).

There are two main types of prestressing cables used at Swedish containment buildings, VSL and BBRV. The key difference being that for the VSL cables several steel strands are intertwined into a few cables which are anchored. In the BBRV system each wire runs parallel and are anchored individually. Due to the fixed length of the cables and the large diameter of the anchor heads, BBRV-type cables are difficult to instrument with load cells after they have been installed. In Energiforsk report 2018:542, several ways of instrumenting BBRV-type cables with load cells for continuous monitoring are evaluated.

6.3 CONCRETE HUMIDITY SENSOR

The relative humidity (RH) in the concrete influences long term deformations. The RH changes over time as moisture is redistributed within the containment wall. As the concrete dries over time, it contributes moisture to the air inside the containment. For Swedish

containment buildings the drying will continue across the lifespan of the structure although most of the drying has already taken place, Oxfall (2016).

In the doctoral thesis by Oxfall, (2016), a measurement setup for monitoring moisture and temperature inside the concrete of a containment building was designed and evaluated. The setup included a probe for measuring relative humidity as well as temperature. The humidity sensor used has an accuracy of $\pm 0.8\%$ RH.

The measurements must be taken at several depths in the wall to obtain the moisture profile. Along with the RH the temperature is also measured, a high temperature in combination with a low RH in the ambient air may lead to an increase potential for the concrete to dry out, Oxfall (2016). The temperature sensor was a Pt1000 temperature sensor with an accuracy of $\pm(0.3+0.005|t|)$ °C (class B).

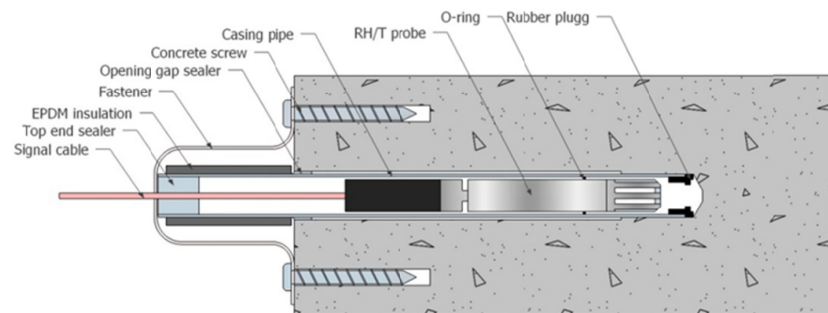


Figure 6—2 In situ setup used for measuring relative humidity and temperature in the concrete, Oxfall (2016).

To accurately measure how the RH varies along the wall thickness; sensors will have to be installed at several depths in the concrete. Several boreholes must be drilled, each with a sensor installed at a certain depth. The borehole must be sealed from the outside air as seen in Figure 6—2.

6.4 PHOTOGRAMMETRY

The movement in a structure can be recorded with photos and video. This is made possible by placing easily recognized markers on the structure or by looking at the contrast of the structure to its background. By picking individual points and following their movements the displacement can be estimated (this is often referred to as image correlation techniques). The accuracy of the method is

dependent on the distance between the object and the camera as well as the resolution of the camera used.

Photogrammetry have been used before to monitor concrete strains during structural integrity tests of a containment at the R.E. Ginna NPP in the U.S. by Hohmann et al. (2012). In the case study digital cameras were used to capture the local deformation of the containment wall and roof during a pressure test of the containment building. The digital cameras used during the test were placed 1.5 m from the wall of the containment, see Figure 6—2.



Figure 6—3 Cameras used to capture strains in the concrete, Hohmann et al. (2012).

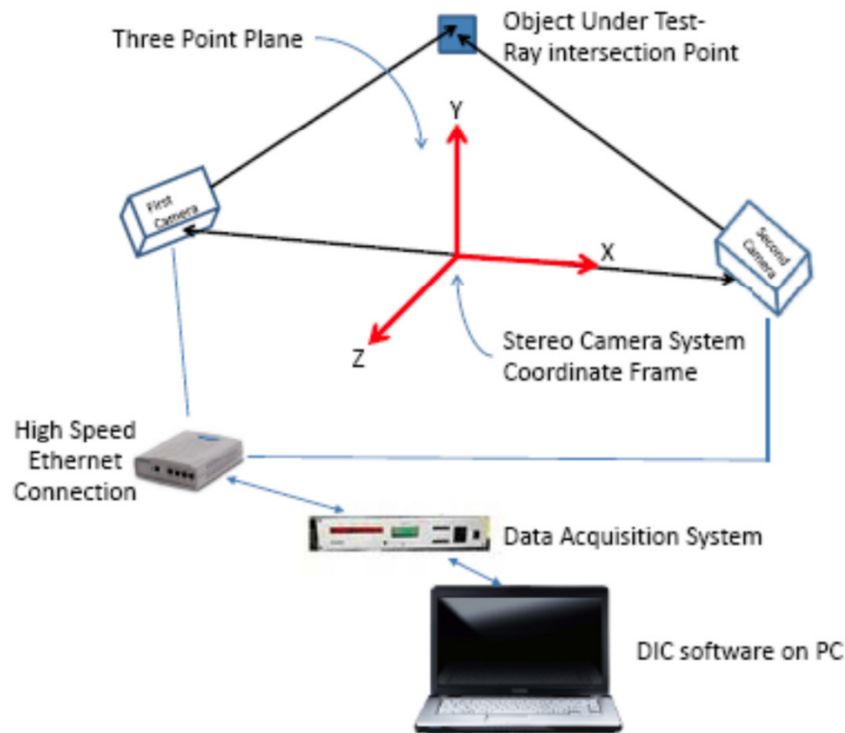


Figure 6—4 Components used in a photogrammetry setup, Hohmann et al. (2012).

The setup was successful for capturing deformation during a pressure test. However, this does not guarantee that the technique will be useful for long term surveillance as the deformations during normal operation will be much smaller than those experienced during a pressure test.

6.5 LASER SENSOR

Deformations between two points can be measured with a laser aimed at a sensor plate. The laser can for example be placed at the base of a containment and the sensor at some higher elevation to measure changes in the containment wall's diameter between the two points. The sensor captures movement by registering the position of the laser on the sensor plate. The sensor is connected to a data logger for continuous monitoring.

There are possible advantages of using a laser sensor as a replacement for, for example a traditional hanging pendulum. The laser is not sensitive to touch or vibrations in the way that a pendulum wire is. It

can also be placed more freely than a pendulum as it does not have to be placed vertically. It can theoretically be used to measure displacement between any two points, presuming there is a clear line of sight between them.

Tests with a laser pendulum have been performed on a Swedish concrete dam. Early tests have shown that the mount of the laser is sensitive to differential shrinkage from temperature fluctuations when the mount consisted of a simple cantilever holding the sensor. When the mount was replaced with the one seen in Figure 6—5 the issue was solved. The measuring range of the sensor is dependent on the quality of the laser as well as the size of the sensor plate.

However, the system is still sensitive when measuring over large distances as a small change in the angle of the laser gives a large observed deformation at the sensor.



Figure 6—5 Laser mounted near the base on a Swedish concrete dam

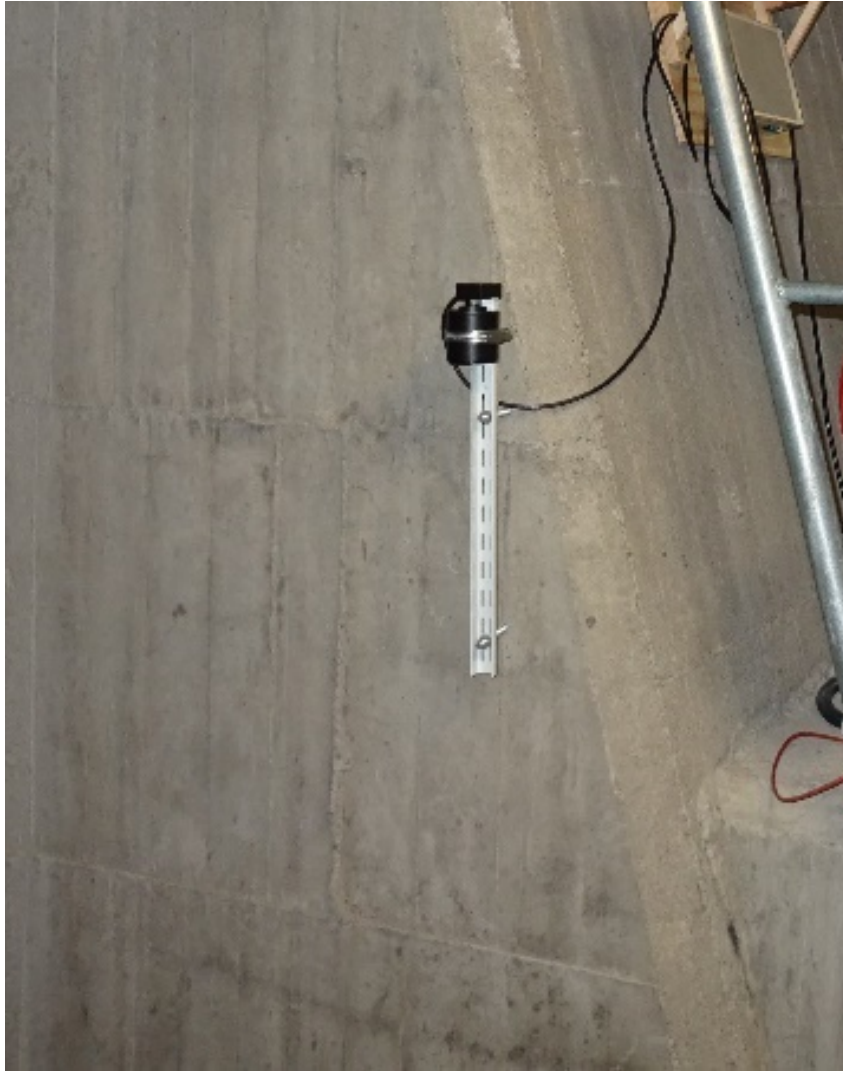


Figure 6—6 Sensor mounted near the crest of the dam.

6.6 PULSE SENSOR

A pulse sensor is a sensor used to locally measure the gas permeability in a containment building, it was used experimentally at the Vercors mock-up facility, Agostini et al, 2016. From the measured gas permeability, the water saturation in the concrete is then inferred. The method used in the experiment is only applicable to structures under construction as the sensors must be cast into the concrete. The relation between the concrete's moisture content and its effective gas

permeability is measured in a lab from a sample of the same concrete as used in the construction. In the VeRCoRs project the pulse probes were cast into the wall of the containment building, see Figure 6—7.



Figure 6—7 Pulse sensors to be cast into concrete, Oukhemanou (2016).

The pulse probes are connected to a gas injection device and gas is injected into the probes. The injection is halted, and the pressure fall off is measured. From this the mean volume flow rate can be calculated as well as the effective permeability. A monitoring system is schematically shown in Figure 6—8.

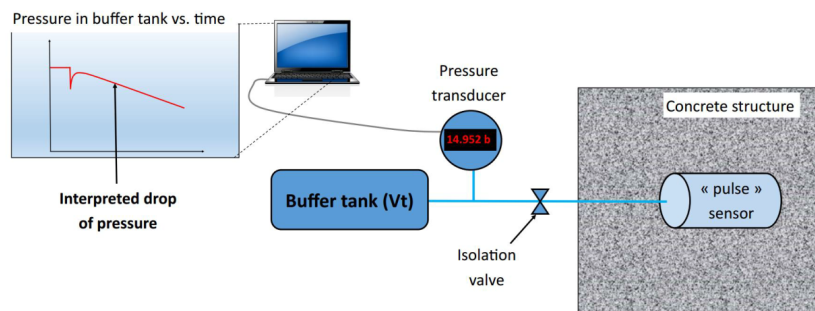


Figure 6—8 Schematic diagram of the pulse probe measuring system.

7 Measurement systems

A measuring system includes, besides the sensor also a power supply, a way of logging and storing the measurement data as well as translating the signal data from the sensor into the quantity being measured.

How the signal from the sensors is processed and stored depends on the IT-structure of the facility. Because of this the following chapter is mainly focused on how the measurement data is transferred.

7.1 SIGNAL AND POWER

The sensor transfers the signal to a logging unit. This can be for example a datalogger or a PLC (programmable logic computer). A datalogger is specialized for collecting and recording data while a PLC can do a much wider range of tasks such as controlling sensors. The signal from the instrument to the logging unit is often analog and transferred through a copper cable. The logging unit is typically placed in an instrumentation enclosure. The enclosure can include signal conversion from the analog sensor signal into digital data which in turn can be processed, stored, or transmitted. However, it can vary between systems where different components are placed.

The instrumentation enclosure is connected by fiber optics cable to a CPU which in turn is connected to a local network. Between the CPU and the instrument enclosure the fiber connection may be routed through multiple ODFs (optical distribution frame) used to organize and manage optical fibers and their connections. This connection should be done as a “redundant fiber ring”, meaning that the CPU and enclosure are connected using two fiber optic cables taking different paths, each cable being bi-directional to ensure communication even if one part of the network has an interruption.

It is preferential that signal transfer is done using fiber optic cables and not wirelessly transmitted since wireless transmission is not as reliable.

The instrumentation enclosure should be connected to a power source with an UPS (uninterruptible power supply) for operational reliability. The power connection to the instrumentation enclosure can also be done with two separate power cables to attain redundancy. A

surge protection may be necessary if sensors or cables are placed on the outside of the facility or in water.

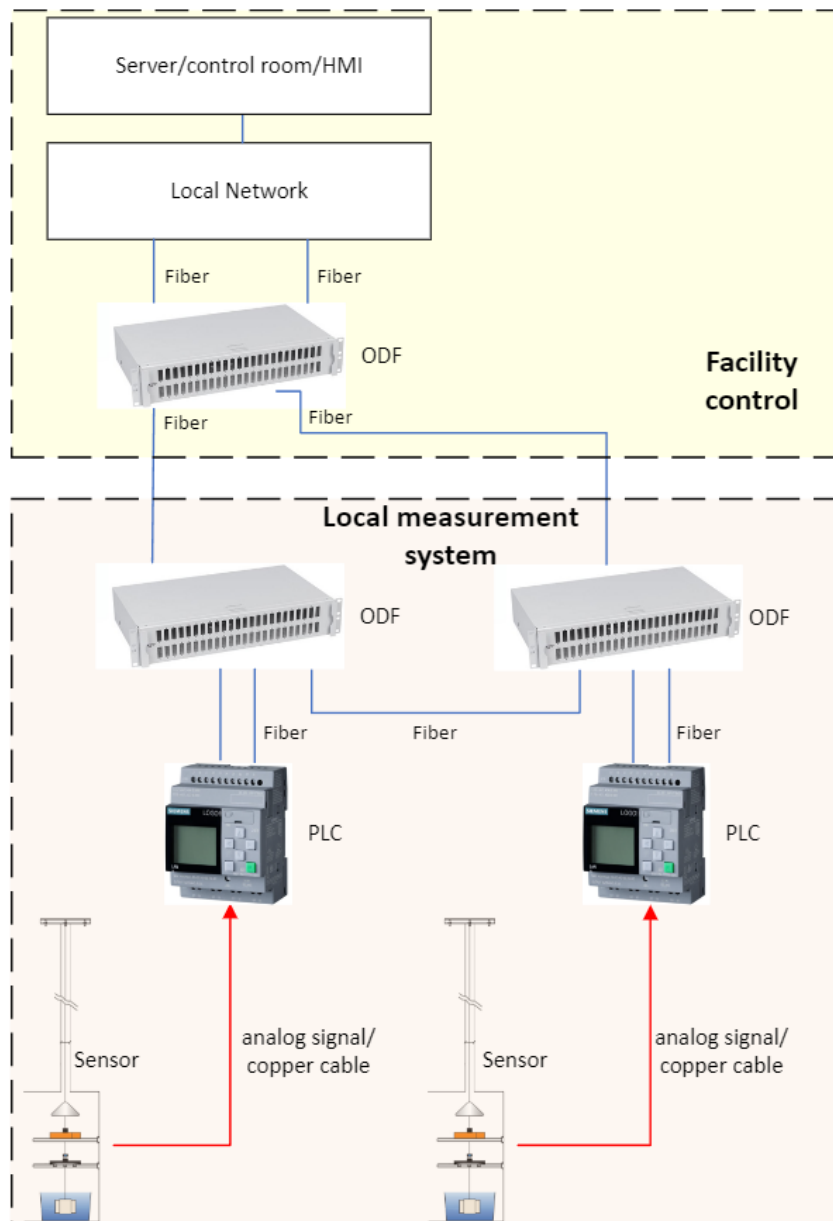


Figure 7—1 Overview of an example measurement system. In systems of this design, it is possible to have galvanic isolation between the local measurement system and the overhead system.

When designing a measurement system for a facility it is of importance to know:

- Is there an existing system at the facility to which new instrumentation should be connected to?
- How should the data be presented?
- How is the network system structured?
- How is the electrical system structured?
- It should be considered during design of the system that more sensors may be added later. Which in turn can result in a need for extra room for more instrument enclosures etc.

7.2 PROGRAMMING THE SYSTEM

The Instrumentation enclosure can be connected to an HMI (human machine interface), which displays the locations and measured values of the connected sensors. This can help in function check out of the sensors since it makes it easier for the personnel to detect deviant measurements. Each sensor should be labeled with a unique name both out in the facility as well as in the interface on station computers.

The signal from the sensors must be interpreted correctly and the interface has to be understandable for the measurements to be possible to evaluate. To achieve this the programmer should be well understood with how the sensors function and how to present the measurements in a way that makes sense to those operating the facility, this is discussed more thoroughly in chapter 7 in the report by Enzell et al. (2019).

The programmer is often brought in as an external competence when the automated measurement system is installed. However, it can be of great use if someone who works on a regular basis at the facility has some knowledge of the programming and is able to do basic maintenance of the code.

7.3 FUNCTION CHECK-OUT OF SENSORS

Sensors will regularly have to be tested to ensure they maintain the correct function. Sensors that do not fulfill their desired function will have to be replaced. Recommended testing intervals for a couple of sensors are presented in Table 3, from Enzell et al. (2019).

Table 3 control intervals for displacement sensors.

Control interval for sensors					
Sensor	Control method	First 3 months	First year	Year 2-3	Long term
Hanging pendulum	Make a reading with a manual instrument. Check the readout against a falsified movement.	Every other week.	Every other month.	Twice per year.	Once per year. Every other year.
Tilt sensor	Check against a digital spirit level. Compare with measurements to those gathered with other sensors.	Every other week.	Every other month.	Twice per year.	Once per year. Once per year.
Extensometer	Measure the distance between control points inside the extensometer head using a digital calliper.	Once a month.	Twice per year.	Once per year.	Once per year.
1D-Crack width sensor	Measure the distance between control points using a digital calliper.	Once per month.	Twice a year.	Once per year.	Once per year.

Deformation based sensors are typically tested by adding a fictive movement with a known magnitude and confirming that the sensor registers the same movement. An example of this is the laser sensor mentioned in section 6.5 where the laser is placed on a calibration plate. When the laser is moved a certain distance and direction along the calibration plate, the same movement should be registered by the sensor plate on the other side. Pendulums can be tested by manually moving the pendulum wire and checking that the sensor registers a movement of the same size and direction.

Temperature sensors can be tested by lowering them into zero-degree water. Pt100 sensors placed in pools can be controlled by lowering a pt1000 sensor to the same level and comparing the measured temperature.

7.3.1 Substituting embedded sensors

Since sensors cast into concrete cannot be function checked out, they have to be replaced by other sensors placed on the concrete surface. This was the case with the strain meter mentioned in section 4.5.4 which has the purpose to measure the strain that was previously measured using strain gauges that were embedded in the concrete during construction. In the report by Simon et al. (2013) it was confirmed that the surface placed sensor captured the same behaviour of the structure as the sensors embedded in concrete. See Figure 7—2 Deformation measured using surface placed strain meter (orange) compared to an embedded sensor (blue). The top graph represents the power output of the power plant which correlated with the measured deformation, Simon et al. (2013).

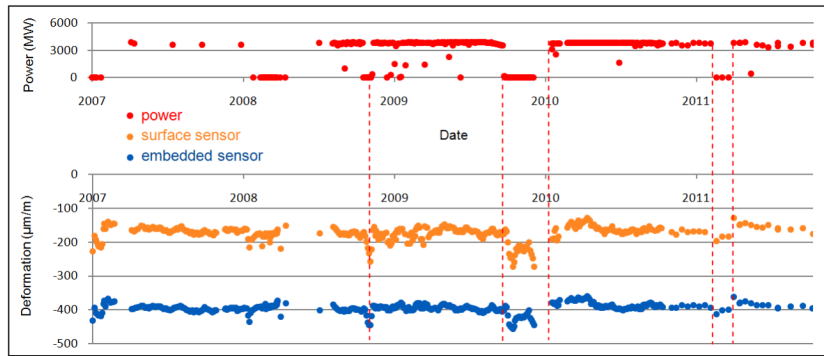


Figure 7—2 Deformation measured using surface placed strain meter (orange) compared to an embedded sensor (blue). The top graph represents the power output of the power plant which correlated with the measured deformation, Simon et al. (2013).

8 Discussion and conclusions

This report has been written to give an overview of instrumentation that can be used for existing reactor containment buildings in the Nordic countries. Possibilities and limitations of different sensors and measurement systems have been described.

The sensors should capture the behavior of the containment during normal operations as well as during a pressure test and potential failure modes. Behavior during normal conditions should mainly vary with changes in temperature and humidity – why these parameters are important to monitor as well in order to evaluate the measured deformations.

During a pressure test or in case of a loss of coolant accident the pressure in the cylinder will increase, causing the cylinder wall of the containment to increase in diameter and length. Therefore, these parameters are important to measure to understand the global behavior of the structure. Deformation sensors which have been used successfully for this purpose include the hanging pendulum, for measuring radial displacement, which has been used in the Vercors project as well as in EDF's reactor containments. Other sensors with widespread use include the invar-wire extensometer used for measuring vertical displacements and load cells for measuring the force in individual tendons.

Measuring local deformations over joints and strain in concrete can aid in assessing the normal behavior of the structure. The measurements can also be used to calibrate models. One local deformation sensor that has showed promise is the strain meter used in French facilities to measure relative displacement between two points at the surface of the containment wall.

Support instrumentation is necessary to evaluate measured deformations. At OL2 temperature sensors as well as humidity sensors are used to monitor the climate in different zones of the containment building. Furthermore, a concrete humidity sensor can be used to measure relative humidity in the concrete which is helpful for evaluating long term deformations.

8.1 RECOMMENDED SENSORS FOR A CONTAINMENT BUILDING

The instrumentation for a containment building should include global deformation sensors. To capture radial deformations along the perimeter of the containment wall, at least 3 measurement points are needed. A proven instrument recommended for this application is the hanging pendulum. Each pendulum should have reading tables on at least three levels along the wall height, one being placed at the midpoint. However, 3 measurement points are a minimum to define a circle and in practice 4 pendulums should be installed to achieve some redundancy. To measure the height variations across the containment wall, extensometers are recommended. Extensometers using invar rods/wires with LVDT sensors have been used at French nuclear facilities where 4 extensometers were installed alongside the pendulums.

Load cells can be used to monitor the forces in individual tendons assuming they are not grouted. The load cells should be placed in a way to maximize the chances of detecting irregularities in the behavior of the structure.

Monitoring of temperature in air, preferably in concrete as well to be able to evaluate deformations caused by changes in temperature. The relative humidity should be measured in the containment wall along with the temperature to aid in evaluating deformations. The monitoring should be done at several locations around the structure to capture the behaviour of different zones inside the structure. Air pressure should be monitored inside the containment since the response to changes in internal pressure is important when evaluating the performance of the structure.

Tilt sensors are not recommended for measuring the deflection of containment walls as experiences from related fields indicate that the accuracy of the sensor is too low to capture the anticipated movements. A possible use for tilt sensors is to measure the deflection of the ground slab during pressure tests, as mentioned in 4.4.3. However, more information is needed about the outcome of this measurement campaign.

Total stations have a rather low accuracy compared to the other sensors studied why it is deemed unlikely to be of use as part of a monitoring program for the containment building. A use case for total

stations could be to measure the movement of supporting structures such as access platforms and gangways.

8.1.1 Local deformation sensors

Invar strain meters have showed good results as a way of locally measuring the strain in concrete along a containment, the studied case used the sensor to measure the strain along a 1-meter section of containment wall. However, the instrument has not seen wide usage yet.

Fiber optic cables can possibly be used to measure displacement in the concrete. However, the cases studied in this report indicated that fiber optics performed best when cast into the concrete.

8.1.2 Ambient climate-based sensors

Measurements of temperature, air pressure and humidity are necessary to be able to evaluate the results of the deformation sensors. The installed sensors should capture the different temperature zones in the containment building as well as outside. This is necessary to be able to evaluate the deformation measurements.

8.1.3 Recommendations for measurement systems for a containment building

The sensors discussed in this report are mainly meant to be used for continuous monitoring of the structure. Therefore, the measurement system must be able to handle large quantities of data. The system should also be reliable over time and have built in redundancy.

To achieve this, the measurement system should use fiber optics as a communications medium between the logging unit and the overhead systems. The connections should be made as redundant fiber rings. The power supply to the instrumentation enclosures / dataloggers should have UPS capabilities to reduce the risk of losing data due to power failure.

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INSTRUMENTATION OF NUCLEAR CONCRETE CONTAINMENT BUILDINGS

Containment buildings make up the last layer of protection at a nuclear power plant. To ensure their continued function across the lifespan of the facility, surveillance of their structural health is important. In this report sensors for monitoring containment buildings have been documented, including sensors for measuring deformations, temperatures, and humidity. As well as what is required from a measurement system.

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