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Monitoring the post-tensioning tendons of nuclear containments to increase safety

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ABSTRACT: Nuclear containments designed with a Pressurized Water Reactor have several safety barriers in case of a leak in the primary coolant circuit. The global structural barrier is made of a concrete containment prestressed by large post-tensioning tendons. This barrier is guaranteed leak proof in case of an accident.

In some designs, the tendons are replaceable, meaning the post-tensioning can be upgraded at any moment of the structure's lifetime. In other containment designs, when the tendons are bonded, they are not replaceable, making any direct upgrade of the post-tensioning tendons impossible. In both cases, specialized post-tensioning companies use specific equipment and methods, adapted to the size and the layout of the post-tensioning, to install the tendons. Faced with the fact that any intervention on tendons -whether to replace or upgrade them - is difficult or impossible, and moreover generates heavy exploitation costs, a better use of the monitoring made during the tendon installation has been explored. Thanks to the enhanced monitoring tools, operators, owners and authorities can validate operations as well as detect any deviation in time for an upgrade, thus reducing the need for any intervention.

All operations concerning the supply of post-tensioning material (such as cables and anchorages) are well defined and tested in factories with well-known processes. On site, the correct installation of tendons is mainly guaranteed by operators. Stressing and definitive protection by cement or grease in particular are generally monitored by an operator who then delivers manual records. The recent monitoring technologies can now easily provide more repeatable measurements and more information on several parameters than in the past. These parameters, like for example the real time stressing curve at high measurement speed and the forces in each individual strand, can help to establish the tendon performance and durability. Moreover, they encourage improvement by suggesting ways to improve the installation process.

In a first step, particular procedures and tools have been set up and adapted to each of the several post-tensioning operations in the nuclear project. In a second step, the monitoring equipment has been adapted to comply with site conditions and the targets for each operation (measured values, frequency, precision).

This article presents the preliminary results of this equipment that has been validated after full scale tests and will be used in the latest containment design.

1 INTRODUCTION

Post-tensioning is a technique that has been used for over 50 years. Since the very beginning of the construction industry, post-tensioning has been used in the design of large nuclear containments. VSL's first project, the Rancho Seco in California, USA started in 1969, already used this technique with a high performance design of up to 55 x 0.5 inch-strands per tendon protected by grease. This tension design is one still used today for nuclear containments.

The purpose of post-tensioning in nuclear containments is to provide structural integrity and air tightness to the inner containment in case of a loss of the cooling water in the primary circuit. Should this happen, the air pressure inside the containment can increase to over 5 bars without causing any damage thanks to the post-tensioning of the walls at the time of construction. Post-tensioning is thus considered as a safety class element in nuclear containment design. Its sustainability must be taken into account in the estimation of these structures' safety.

2 COMPONENTS OF THE POST-TENSIONING SYSTEMS

The main components of the post-tensioning system include:

- A casing to install the tendon inside the concrete: it is a duct made of corrugated steel sheath, plastic or steel pipes.
- An anchorage serving to transmit the force applied by a jack on the tendon to the structure.
- The tendon itself, made of several strands, that transfers the force to the structure through the casing in deviations on its full length and through the anchorage at the ends.
- A filling product to protect the strands from any corrosion: the product can be soft (anti-corrosive grease) or hard (high performance cement grout) depending on the tendon design (unbonded or bonded).

All the steel elements of these systems (i.e. ducts, pipes, anchorages, strands) are manufactured in a factory following industrial process and quality control.

The final assembly and adjustment of these components (i.e. duct placement, tendons installation, stressing and filling with final protection) is made on site.

3 POST-TENSIONING STEPS AND RISK ANALYSIS.

We can consider that there are three steps in the completion of a post-tensioning system for a particular structure:

-Structural design (Engineer)
-Components design & Manufacturing (Specialized sub-contractor)
-Installation on site (Specialized sub-contractor)

It is obvious that the sub-contractor has little influence on the structural designs, that component design and manufacturing are largely dependent on the industry and that the control of the installation on site depends on the quality control of the project.

We can now proceed to defining the risks of the post-tensioning system, differentiating them by origin. We call internal causes those which deal with a flawed component and external causes those which are related to the use of these components. Table 1 shows with which solutions each risk should be met, differentiating them into two categories: the short term and the long term. Short term risks refer to incidents that may happen during manufacturing or installation; long term risks refer to ageing issues which may alter the ability of the system to fulfill its function.

One should note that short term action helps to prevent damage to the PT system and enhance its durability, whereas long term actions help to prevent any damage that can be done to the overall structure in case of any defect in the PT system.

		Short Term risks: Manufacturing and design	Long term risk: Material ageing or mechanical ageing
Internal causes	Flaw in material	Continuous control during manufacturing in safe industrial environment	Structural monitoring
External causes	Design condition (Post-tensioning system , structural design)	Design review at several levels and licensed PT system based on highest standard (ETAG 013, ASME, ETC-C)	Extensive review and testing of the system associated with long experience feed back
	External defect (Overloading, sealing defect, lack of filling)	Quality control during installation	Structural monitoring

Table 1. Existing preventive action for the different risks affecting the PT system

Cell by cell comments of Table 1:

a. Short-term risks of the “internal causes” are limited by continuously controlled processes in factories.

b. Medium and long term risks of the “internal causes” are limited by the monitoring of the structures: continuous monitoring when the tendons are cement grouted or with periodic measurements on tendons for containments with replaceable tendons.

c. The “external risks” on the structural design and the design of the post-tensioning systems are limited in the short and long term by experience feedback on many projects and laboratory validation tests. They are limited by the use of calculation codes and post-tensioning systems which have been widely validated for a long time now.

d. The “external risks” related to the implementation of prestressing are dealt with by the implementation of a quality control on site. Usually this system is based on check lists, punctual measurements and go/no go procedures.

As highlighted in Table 1 the quality control on site is one of the keys for the sustainability of the post-tensioning system (bullet point -d).
Indeed, installing cables is a very technical operation with both delicate time constraints and delicate environmental conditions; it is monitored by self-checking quality systems and relatively little systematic and independent continuous control. What the enhanced monitoring tools do is improve the monitoring quality of an installation and ensure a continuous record of several parameters during the most technical phase.

This first step in the risk analysis has shown that quality control is worth improving in PT installations. A more detailed analysis will reveal what exactly should be controlled and how a short term monitoring can improve long term performance.

4 REVIEW OF THE AGEING PHENOMENA

The various symptoms which can affect the structure have been classified in Table 2 according to the different part of the structure they interact with:

	Symptoms			
Elements	Environment	Concrete	Steel	Post-tensioning function
Defect	Existing environmental condition Change of soil or foundation condition	Creep Shrinkage	Corrosion Relaxation	Fatigue Higher friction Force dispersion

Table 2. Symptoms of ageing on concrete structures with post-tensioning

Environment-linked symptoms are evaluated and taken into account during the design of the project. The possibility of a change of any of these conditions (change in seismic risk, in temperatures, or corrosiveness of the environment) can lead to a complete review of a project. Containments with replaceable tendon designs are best adapted to such big changes, allowing the required flexibility.

Table 3 identifies the relation between a defined risk, and the operations carried out during the manufacturing or during the installation of the post-tensioning system on the site.

RISK	**Incidence during material manufacturing**	**Incidence during installation**	**Repair Possibility**	**Control Possibility**	**Location**
Relaxation	Limited	Possible	Very limited for bonded system, significant for replaceable system	Long term monitoring	Strands
Corrosion	Limited	Possible			Anchorage tendon
Creep, shrinkage	Limited	Limited			Concrete containment
Post-tensioning function	Limited	Possible		Control during installation and then long term monitoring	Strands Anchorage tendon

Table 3. Review of the Ageing Risks on the Post-Tensioning System

Table 3 shows which elements are most reliable in safety-matters. Risks undergone during the installing process could largely be prevented and kept under control by introducing systematic control systems. In any case, it is noteworthy to say that the prevention of risks thanks to short term monitoring does not rule out the need to carry out long term detection monitoring.

5 NEW CONTROL METHODS

The new control method help you control that the post-tensioning operations have been carried out without any deviation from the planned design and procedures. Based on previous analysis we propose hereafter several methods that can address some particular risks such as the relaxation and the corrosion of steel.

Relaxation of steel is due to force dispersion: if the strands of the same tendon are not stressed at the same level, the overloaded strands can undergo higher relaxation than the others.

Corrosion of steel is prevented by grouting the duct for bonded systems. Proper grouting operations should not let air seep in the ducts. All these parameters, such as the flow rate, the pressure in various points and the density of the grout can be controlled by monitoring.

Over/under-stressing and higher friction can be detected through proper force and elongation monitoring. Furthermore during lock off of wedges, high speed monitoring enables one to have a more precise appreciation of the remaining force in the tendon at the end of the stressing operation.

6 VALIDATION ON THE MONITORING OF THE FORCES ON ALL THE STRANDS OF A TENDON.

This equipment helps to detect a poor installation or preparation of strands that may lead to a fast increase of force in some strands or an absence of force in others if not detected at an early stage. Thanks to this monitoring system, the full record of such parameters (such as the force in each strand, see Figure 1) giving a clear picture of tendons after their installation can be delivered to owners and authorities and serves to increase their trust in safety barriers made of concrete containments with post-tensioning systems.

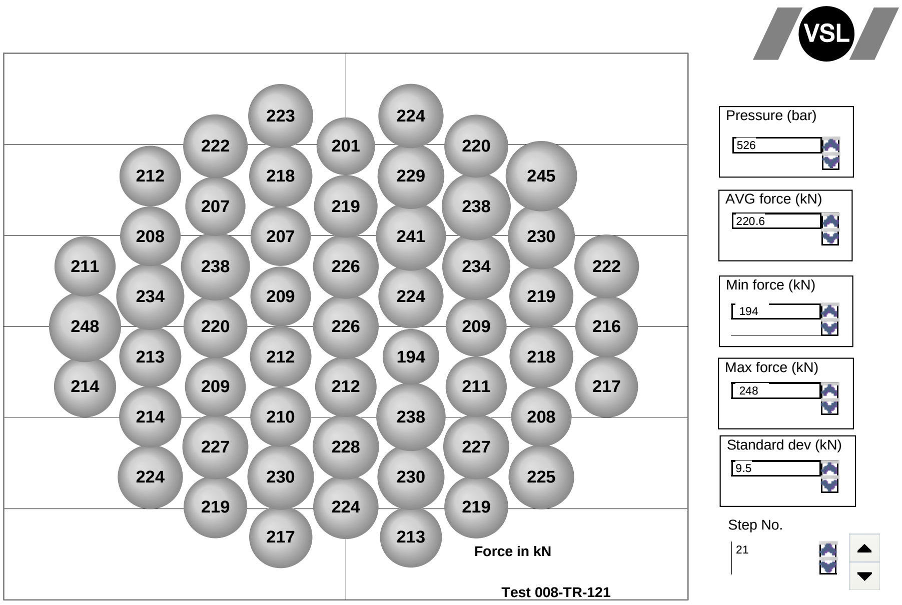

Figure 1. Measurement of the force in each strand available at the end of the stressing operation on site

7 HIGH SPEED MONITORING OF THE FORCE IN JACKS DURING THE TRANSFER OF THE FORCE FROM JACK TO ANCHORAGE.

During this step there is a pre-defined and accepted force loss due to the stroke necessary for the wedges to permanently grip the strands.

The very accurate monitoring of this step allows us to determine precisely at which level of force the tendon has been locked and whether this step corresponds to the hypothesis made in the design (see figure 2).

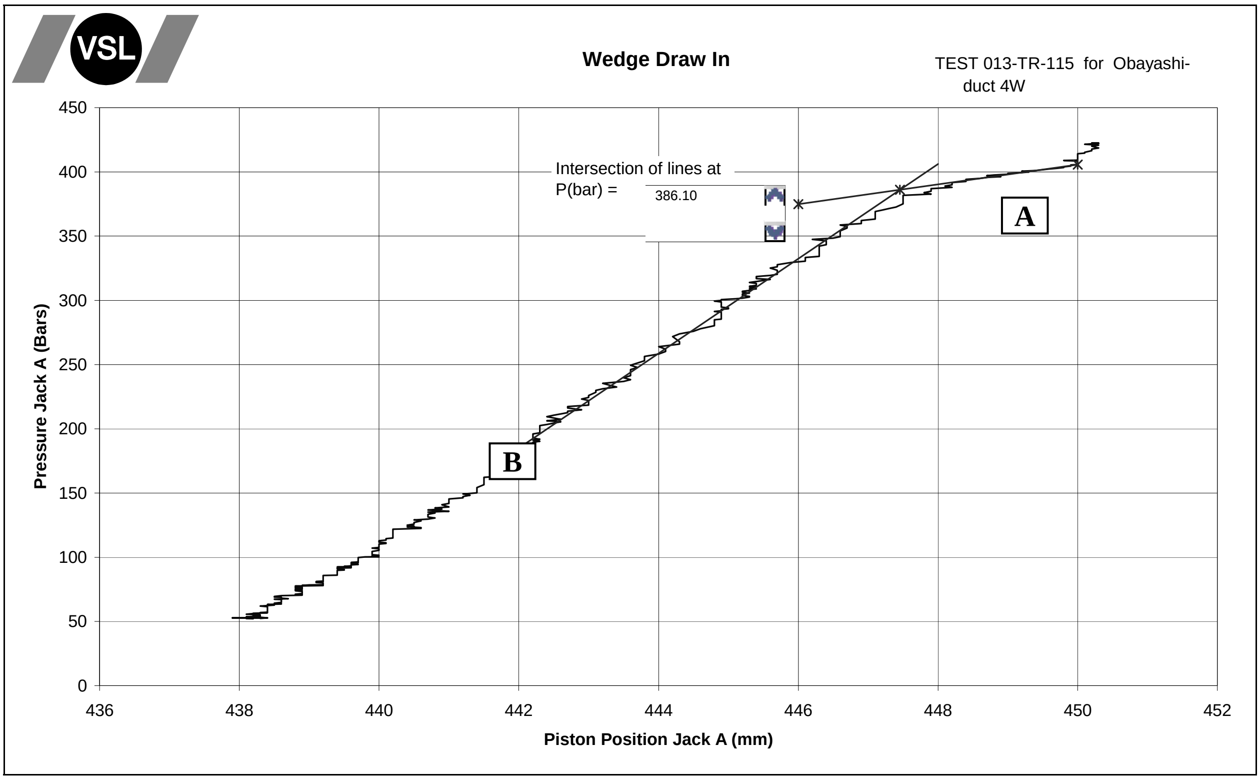

Figure 2. Analysis of the closure of the jack during wedge draw in allowing the determination of the remaining force in the anchorage after release

In Figure 2, we see on the X-ordinate the stroke of the jack during its closure after the final stressing. On the Y-ordinate we see the reduction of pressure in the stressing chamber of the jack.

The two straight lines correspond to the linear regression analysis of the two parts of the curves. The intersection corresponds to the change of status of the tendon from locked in the jack to locked to the final anchorage.

During the first stage (A)(Figure 3), the tendon is still pulled by the jack and then the full length of the tendon (158 m in this case) acts as a long spring with a small stiffness. The full tendon has an extension of 100 mm for 100 bars. The slope of the regression line on stage (A) is close to flat in the proposed scale.

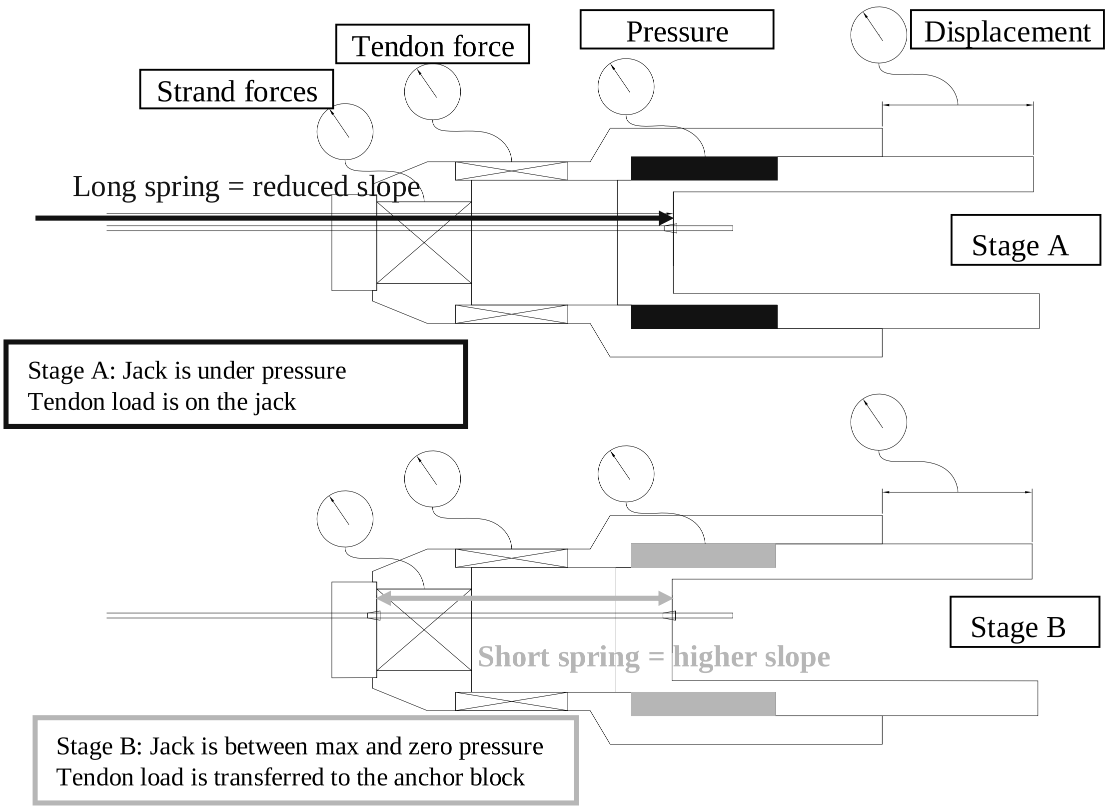

Figure 3. Sketch of the jack during load transfer to the structure

During the second stage (B) the force of the tendon is transferred to the anchor block and the tendon in the jack corresponds only to a very short spring (about 1100 mm) that has an extension of 2 mm for 100 bars. The slope then becomes higher.

8 CONTINUOUS MONITORING OF THE GROUTING PARAMETERS

During the grouting operations, operators specifically concentrate on the information relevant to the process such as flow rate, pressure and information received from other operators located on various vents. They do not record any intermediate step between the beginning and the end of the grouting.

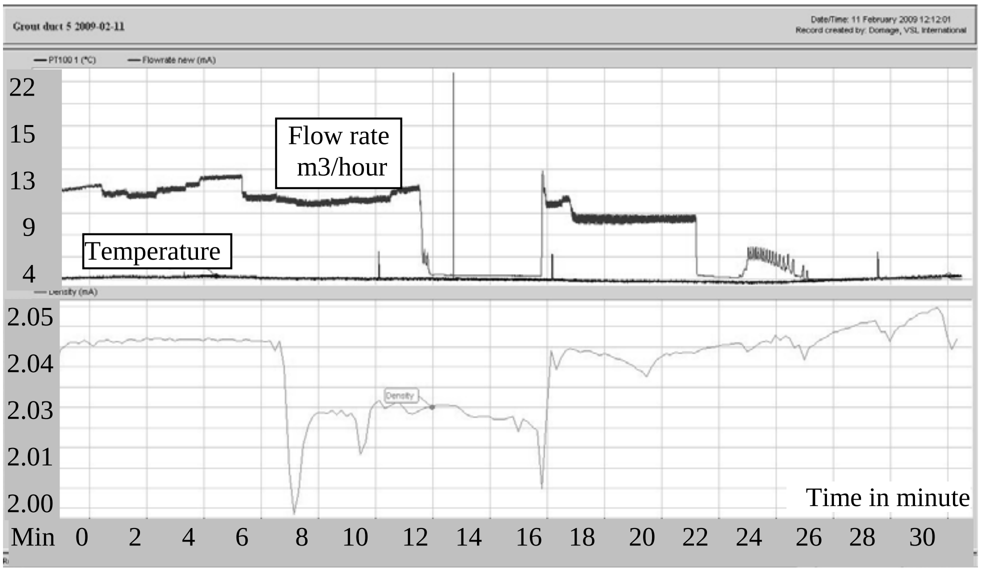

Figure 4. Monitoring of the grouting operation with the flow rate and the density of the grout

The automatic recording of some simple parameters (such as the pressure at the entry and at the exit of the tendon) or more sophisticated ones (such as the grout volume and grout density) helps to qualify with certainty the compliance of the grouting procedure. This automatic check ensures that the grouting will provide the expected durability (see figure 4 and 5).

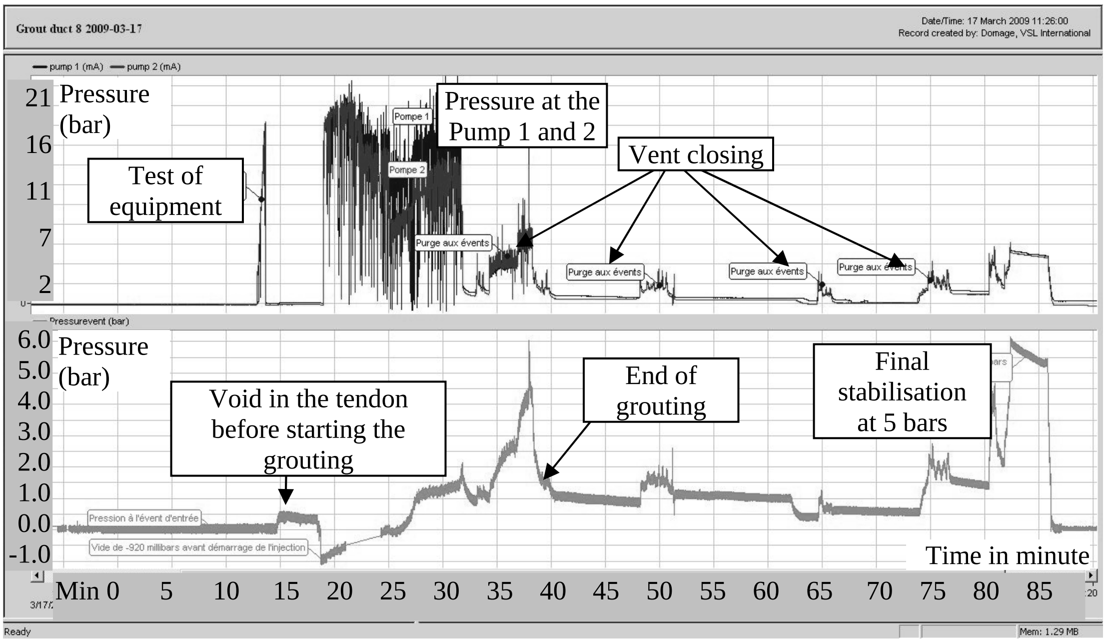

Figure 5. Monitoring of the pressure at the pump and at the vent during the grouting operation

Further monitoring can also be implemented during the grouting. A quality sensor serving to control the correct filling of the duct during the grouting process and to ensure that it is carried out with the proper material has been developed. The sensing element operates locally and has to be carefully placed in certain areas of the tendon layout, in:

-Areas where a specific risk of corrosion may occur, in the case of poor filling;
-Areas where filling is more difficult.

9 CONCLUSION

Links between several operations carried out by specialized post-tensioning companies and the safety and sustainability of the structures installed have been identified.

The use of monitoring based on simple technology (for example grout pressure) or more sophisticated technology can increase our control during installation and improve the evolution of a tendon during the whole lifetime of a containment.

These monitoring tools and their management may be costly; consequently, their implementation depends on how efficiently they reduce risks that threaten the viability of containments.

These tools serve to improve the feedback on the quality of the site’s installation, not to reduce the requirements for dedicated procedures, post-tensioning systems or equipment used for nuclear containments.

These monitoring methods will enhance the safety of containments, complete the current quality systems applies on site and optimize the long term monitoring made on nuclear containments.