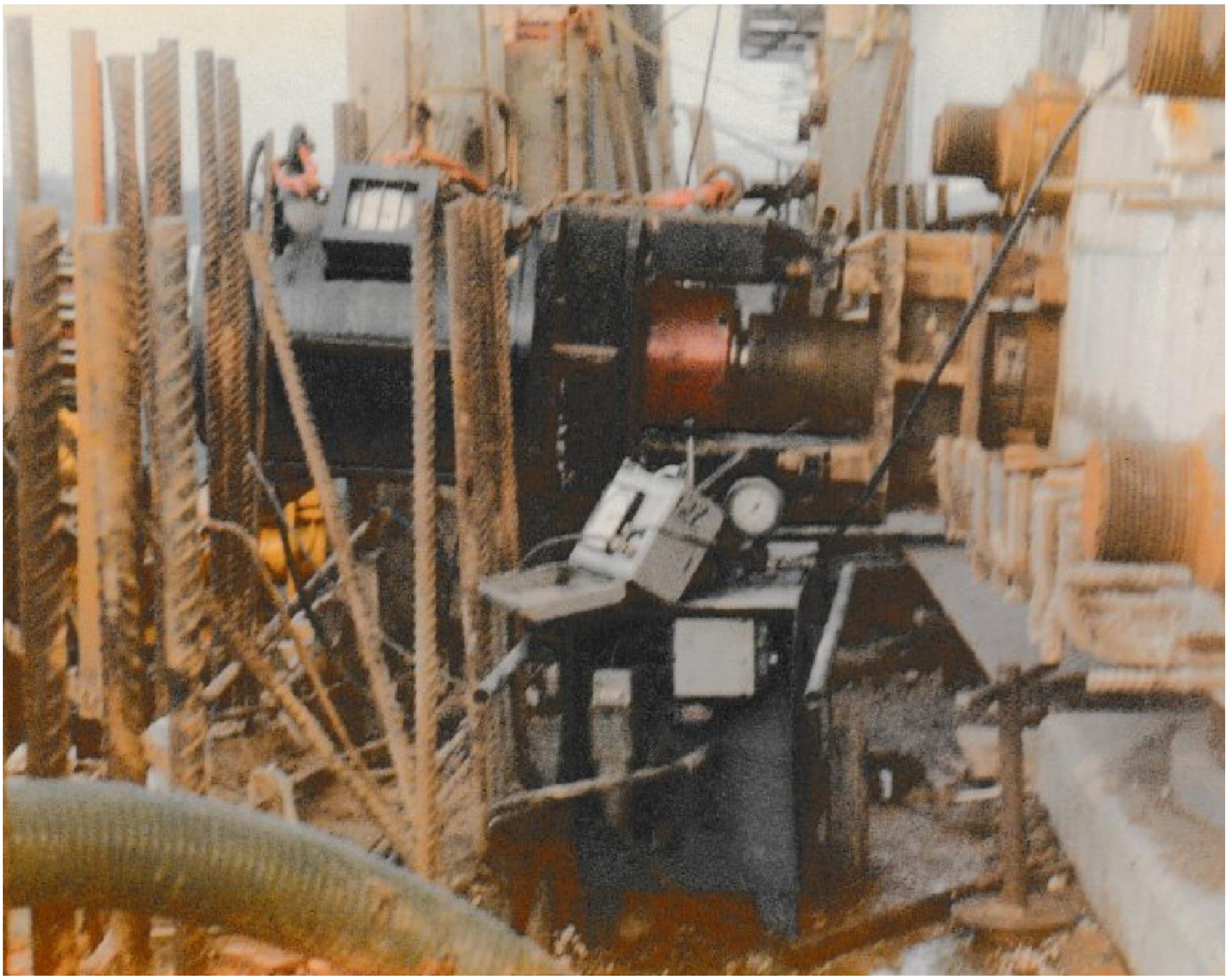
Office for Nuclear Regulation

Research into the management of post-operational pre-stressed structures

Advice on ungrouted post-tensioned structures

Reference: ONR894-REP001

Issue 2 | 22 December 2023



Job number 292732-01

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1. Introduction

Arup was appointed to conduct an independent civil engineering desktop study into the management of post-operational pre-stressed nuclear power plant pressure vessel structures for the Office for Nuclear Regulation (ONR). The aim of the research was to assit consideration of the civil engineering hazards associated with the post-operational phase.

The research focused on the UK context, where Advanced Gas Cooled Reactors (AGRs) and some Magnox reactors contain un-grouted pre-stressed concrete reactor pressure vessels (PCPVs). During service, these PCPVs have provided support, and served as the primary containment and biological shielding to the nuclear reactor core. However, during the post-operational phase, the PCPVs may be subject to evolving demands borne out of changes in loading, environmental conditions, controlled and uncontrolled de-stressing of the post-tensioning tendons, and/or material degradation. There will also be opportunities and/or needs for changes in examination, inspection, maintenance and testing (EIMT) regimes, including the possible adoption of new and emerging technologies for monitoring purposes. Licensees are responsible for identifying and carrying out the necessary engineering studies, while ONR is responsible for regulating the activities of the licensees to promote compliance with regulatory expectations.

This report forms the output of Arup’s appointment and presents relevant good practice (RGP) relevant to the research topic. It has been written for ONR civil engineering inspectors as the primary audience and any points for consideration (PfC) herein are for the inspector’s consideration on a project-by-project basis.

1.1 Terminology

Post-operational and decommissioning

This research considers the post-operational phase. Licence Condition (LC) 35 [1] requires that this is divided into stages where appropriate, but ONR is not prescriptive on how many stages or their makeup.

ONR TAG 17 [2] Annex 6 describes the post-operational phase using seven stages: inactive quiescent storage, post-operational clean out (including defueling), care and maintenance, decommissioning, demolition, site remediation and delicensing.

While ‘decommissioning’ features as one stage within the above list of stages, there are instances in nuclear-sector literature where it is appropriate to interpret ‘decommissioning’ as interchangeable with the entirety of civil engineering activities that take place ‘post-operation’. This broader use of the term ‘decommissioning’ aligns with the term’s use in other civil sectors and also with its use as a heading in ONR’s Safety Assessment Principles (SAPs) [3] and ONR TAG 26 [4], which states *“decommissioning is assumed to start on cessation of operations and continues until the defined end-state has been demonstrably achieved”*.

With this report focusing on the civil engineering management of the PCPV, we have used and/or referred to the stage names that are used in TAG 17 Annex 6.

Pre-stressing and pre-stressing components

The following list, defines and gives basic commentary on terms relating to pre-stressing systems as they apply within the context of PCPVs. Terms are listed in alphabetical order:

• Anchorage	A component, typically cast steel, that locks the pre-stress axial tension into the tendon by bearing against, and creating a balancing compression in the concrete. An anchorage is provided at each end of a tendon and can be also used at intermediate points in staged construction.
• Bonded	Equivalent to *grouted*; describing a tendon that has a shear connection to the surrounding concrete along the tendon’s length. Tendons without grout are known as *ungrouted* or *unbonded*.
• Cable	Similar to *Tendon, mono-strand tendon*, or *strand*. Cable is a more common term when a tendon is not encased in the concrete.
• Channel	A profile protruding from or cast within the outer profile of the concrete PCPV that locates externally-wound strands. Curvatures in channels cause the strand to bear against and exert pressure on the concrete (through the channel wall).
• Dead end	An end of a post-tensioning tendon that is anchored without jacking.
• Deviator	A part of the structure, typically reinforced concrete, that changes the orientation (direction) of one or more external tendons, and thus is subject to a discreet reaction from the deviated tendons. The force applied at the deviator is in simple terms the vector sum of the pre-stress force.
• Duct	The sheath, typically steel within PCPVs, but more recently high-density polyethylene (HDPE), that is used to create the conduit through the concrete that accommodates a tendon. Curvatures in ducts cause tendons to bear against and exert pressure on the concrete (through the duct wall). Friction between the tendon and the duct wall leads to a build-up of loss in pre-stress force with distance along the tendon, which can be significant with long and tightly curved tendons.
• External	Used to describe tendons or cables that are outside the concrete volume.
• Grease	A non-structural material sometimes used surrounding tendons in ungrouted ducts to provide protection against corrosive substances. The presence or omission of grease can affect the friction loss.
• Grout	A material, typically cementitious, surrounding tendons within ducts, that bonds the concrete and tendon along the tendon’s length, preventing subsequent slip. Grout can provide good corrosion protection to the tendon, but voids in grout can trap air and water promoting localised corrosion. Grout is omitted in ungrouted pre-stressing systems.
• Internal	Used to describe pre-tensioned tendons that are cast into concrete, or post-tensioned tendons located within ducts that are themselves cast into concrete.
• Live end	An end of a post-tensioning tendon that is jacked (prior to being anchored). A tendon will have one or two live ends.
• Loss	The reduction in pre-stress relative an initial condition. Losses can be instantaneous (e.g. friction, jacking and anchorage losses) or long term (concrete creep and strand relaxation). They can be uniform along the tendon or a function of position (e.g. friction). They can be defined in terms of force, stress or strain, often being defined as a percentage of either the peak pre-stress or the desired initial pre-stress.

	Friction loss increases with distance from the tendon’s live end(s). If a tendon is jacked from one end, the peak friction loss will be at the tendon’s dead end. If a tendons is jacked from both ends, the peak friction loss will be towards the tendon’s centre. Losses can be calculated, often based on test data.
• Passive	In the context of concrete reinforcement, passive refers to reinforcement that is not pre-stressed. Passive reinforcement is traditionally steel bars.
• Pre-stressing	A system that acts in tension, applying an equal and opposite compression to concrete prior to the application of externally-applied loads.
• Post-tensioning	Pre-stressing that is stressed after the concrete is cast and sufficiently hardened, with stress applied directly to the concrete during the stressing operation. Post-tensioning can have external tendons or internal with tendons housed in ducts. Post-tensioning is common for insitu concrete construction and was used for PCPVs.
• Pre-tensioning	Pre-stressing that is stressed between anchor blocks prior to the concrete being cast. The pre-stress force is subsequently transferred to the concrete once the concrete has sufficiently hardened. Pre-stressing can have external tendons, internal tendons housed in ducts, or internal tendons that are cast into the concrete; the latter is most common. Pre-tensioning is most common in precast concrete elements.
• Strand	A twisted buildup of wires. Irrespective of the structural application, most pre-stressing strands are composed of 7 wires, 6 of which are helically wound around a central core wire. 19 wire strand is also available, where the wires are laid in 2 concentric circles (layers) around the single core wire. Both 7 and 19 wire strands come in two forms: compacted or uncompacted. Uncompacted strands are as described above, whereas compacted strands are made from uncompacted strands by drawing the strand through a hardened steel dye which effectively squeezes the outer strands against the core strand (the outer wires are deformed in this process to a more oval shape reducing the gaps between wires in the process and reducing the overall outer diameter without reducing the cross-sectional area. Drawing through the dye also work hardens the steel and reduces the percentage of strand relaxation loss that occurs in the long term. The process of drawing through a dye is known as dye-forming and strand manufactured in this way is marketed as ‘dyform’ strand. There is little pattern to when or where compacted and uncompacted strands are used.
• Tail	A projecting length of tendon, outside the concrete, beyond the anchorage.
• Tendon	A collection of strands or wires, grouped together into a single entity for stressing. The anchorages will often govern the number of strands or wires that can be grouped into a tendon. Standard anchorages for tendons made of strands are available for varying numbers of strands, from one (known as mono-strand tendons) up to 37.
• Wire	A single high strength steel rod, typically of 7mm diameter, so as to be reasonably flexible, that can be up to several km in length. The typical yield stress of pre-stressing wire is 1860MPa (c/f 500MPa for modern passive reinforcement).

Acronyms and abbreviations

ACR	Alkali-carbonate reaction
AGR	Advanced gas cooled reactor
ASR	Alkali-silica reaction
CDM	Construction Design and Management
CEGB	Central Electricity Generating Board
CGS	Concrete gravity structure
EIMT	Examination, inspection, maintenance and testing
HDPE	High-density polyethylene
IP	Intellectual property
LC	Licence Condition
LOCA	Loss of cooling accident
LTDS	Long term drying shrinkage
NDA	Nuclear Decommissioning Authority
NDT	Non-destructive testing
NPP	Nuclear power plant
ONR	Office for Nuclear Regulation
PCPV	Pre-stressed concrete reactor pressure vessels
PfC	Point for consideration
RGP	Relevant good practice
RH	Relative humidity
SAP	Safety Assessment Principle
SQEP	Suitably qualified and experienced person
SSC	Structures, systems and components
TAG	Technical Assessment Guide
V&V	Verification and validation

1.2 Reference information

A full list of references is provided in Section 12.

ONR SAPs and Licence Conditions [1] set regulatory requirements and expectations that have been used to frame the points for consideration for the post-operational performance of PCPVs. The SAPs that are most relevant to civil engineering during the post-operational phase are listed in Appendix A with commentary added. This commentary is specific to the application of the SAPs in the context of PCPVs, adding contextual interpretation of the SAPs beyond their original intention. It is provided for the consideration of ONR, to apply as required.

While all Licence Conditions (LC) apply during decommissioning, LC 35: *Decommissioning* is the most pertinent. It applies to all post-operational stages of a plant's lifecycle[1].

Other LCs that apply to the scope of this study include:

- LC 20 and 22, relating to modification of plant
- LC 27, 28 and 29, relating to EIMT
- LC 30 and 31, relating to shutdown
- LC 32, 33 and 34, relating to radioactive waste.

Supplementing the SAPs and LCs are the Technical Assessment Guides (TAG). TAG 26 provides cross-cutting guidance on decommissioning, while TAG 17 including annexes provides guidance on civil engineering, with Annex 6 relating directly to post-operation.

1.3 Points for consideration

The following sections of this report provide discussion on matters relating to PCPVs. They provide background information, identify and describe options that each licensee may contemplate, and the implications of the decisions they may take. The discussion is summarised via a series of points for consideration (PfC), presented in each section and collated in Section 11.

Some of the PfCs relate to high-level post-operational phasing decisions, while others relate to more detailed matters that may or may not be relevant for a given PCPV or post-operation/decommissioning strategy.

The PfCs are not intended to be obligatory and ONR inspectors should judge their priority and/or relevance on a case-by-case basis.

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[1] None of the LCs has title that explicitly corresponds to the other stages of the post-operation phase as defined in TAG 17 Annex 6 (see Section 1.1).

2. Background on post-tensioned concrete

2.1 Historical development of post-tensioned pre-stressed concrete

Structures withstand loads by deformation, leading to an equilibrium balance that can be considered in terms of stresses and forces or energy. The ability to accept deformation is dependent on the properties of the materials that are used.

Common building materials include timber, iron, steel, aluminium, masonry and concrete.

Steel and aluminium tend to be ductile, performing almost equally well when subjected to tensile and compressive forces. In contrast, masonry, concrete and most irons tend to behave very differently in tension and compression. They are characterised as brittle materials (i.e. not ductile).

Reinforced concrete was developed in the late 19th century (1880 – 1900) to overcome the brittle nature of concrete. Its development coincided with the wider transition from wrought iron as a structural material to steel. At a basic level, reinforced concrete works by embedding steel bars in the concrete at locations of tension. However, among the reasons that the system is successful:

- Reinforced concrete only requires circa 2% to 6% steel by volume, capitalising on the low cost of concrete relative steel.
- Steel and concrete have similar coefficients of thermal expansion.
- When cast, concrete creates an alkaline environment, whereas steel requires an acidic environment to corrode.
- Concrete provides protection to the steel against fire and other extreme heat.

A fundamental property of normal reinforced concrete is that, at the time of construction, the concrete and reinforcement are unstressed; stress develops in the materials when the system is loaded by an applied action.

As the understanding of reinforced concrete developed, a number of Engineers (Gustave Magnel, Robert Maillart and Eugene Freyssinet amongst others) noticed that a performance enhancement was theoretically possible by placing stressed steel into the concrete elements. This is now known as “pre-stress” and the resulting meta-material is called “pre-stressed concrete”.

Further development work resulted in pre-stressed concrete being sub-divided into pre-tensioned pre-stressed concrete and post-tensioned pre-stressed concrete. This sub-division is based on whether:

- the reinforcement is stressed against external restraints prior to casting the concrete around it. Releasing the external restraints after the concrete has hardened transfers the stress to the concrete (pre-tensioned).
- the concrete is cast with ducts embedded in it allowing that the reinforcement to be added after. Once the concrete is hardened, and then tensioned using external jacks (post-tensioned).

In both pre- and post-tensioned concrete, the outcome is similar; under no externally applied load, the reinforcement under tension acts against the concrete under an equal and opposite compression.

Most pre-stressed in-situ construction, including PCPVs, adopts post-tensioning, while most factory-manufacture precast concrete elements adopts pre-stressing.

2.2 Mechanics of reinforced and post-tensioned pre-stressed concrete and the significance of pre-stressing pressure vessels

As stated above, plain (unreinforced) concrete has high compressive strength relative to its compressive strength. Typically, a standard concrete mix design could be expected to carry a direct compressive stress in excess of 20 N/mm^2 (20 MPa). However, the same material would fail in tension at a tensile stress of around just 2 N/mm^2 (2 MPa).

If subjected to a bending moment, a plain concrete element would be exposed to a maximum compressive stress at say the top surface, but an equal and opposite tensile stress at the bottom face. If the load increased, it would result in the concrete failing suddenly at a peak stress equal to the concrete's relatively low tensile capacity (Figure 1). A similar failure would occur if a plain concrete element is loaded in pure tension.

However, moreover, the tensile strength is unreliable as concrete will often crack during its curing at early age. Hence, the conventional approach for strength design is to assume concrete has no tensile strength and therefore no capacity to resist either a bending moment or tension force.

Adding conventional (unstressed) steel reinforcement (with a tensile strength in the order of 200 to 500 MPa typically) to the concrete element, and ensuring the reinforcement is firmly bonded to the concrete, allows the reinforcement to carry the tensile component of an applied bending moment. Furthermore, by tailoring the area ratio of reinforcement to concrete, designers can ensure the concrete can be subjected to its full compressive capacity. To achieve maximum efficiency, and also a ductile failure, the reinforcement must be able to yield. However, because concrete cannot sustain large compressive strain, there is a practical upper bound limit on the steel's yield strength; at higher steel strength grades, the concrete can crush in compression before the steel yields. As a result, there is a theoretical maximum on how much a concrete element can be reinforced to withstand bending.

The steel reinforcement can also only withstand tension when strained. As a consequence, reinforcement does not prevent tensile strains or concrete cracking. Cracks will form when the concrete reaches its tensile strain limit.

By adding a pre-existing tension (i.e. pre-stress) to the reinforcement, the concrete is placed into compression when no external loads are applied. Subsequently applied bending moments or tension forces cause strains, just as they do in un-stressed reinforcement but, because the concrete is pre-compressed, these will initially cause a reduction in concrete compression without tensile strains or cracking.

Strength

By using pre-stress, a member that is subject to a dominant bending moment can be designed so that both concrete and steel reach their strength limits simultaneously with much higher strength steel than would be possible with unstressed reinforcement, while also maintaining more of the concrete in compression (Figure 1).

The higher strength steel also helps structures subject to a dominant tension force (such as a pressure vessel) withstand large tension forces with less steel (by area) than is possible with lower strength reinforcement.

The pre-compression of the concrete also means that pressure vessels can withstand tensions with less (or possibly no) tensile strain experienced by the concrete. The impact on cracking is discussed below.

Cracking

As a brittle material with low tensile strength, cracking in concrete is expected anywhere where the concrete is subject to modest tensile strain. Pre-stressing suppresses the onset of tensile strains and cracking. In most contexts, including PCPVs, this suppression has the advantage to better protect the embedded steel from corrosive substances. Uncracked concrete is not impermeable, but cracks form leak paths for contaminates to reach the embedded steel, bringing forward corrosion initiating and accelerating its rate thereafter.

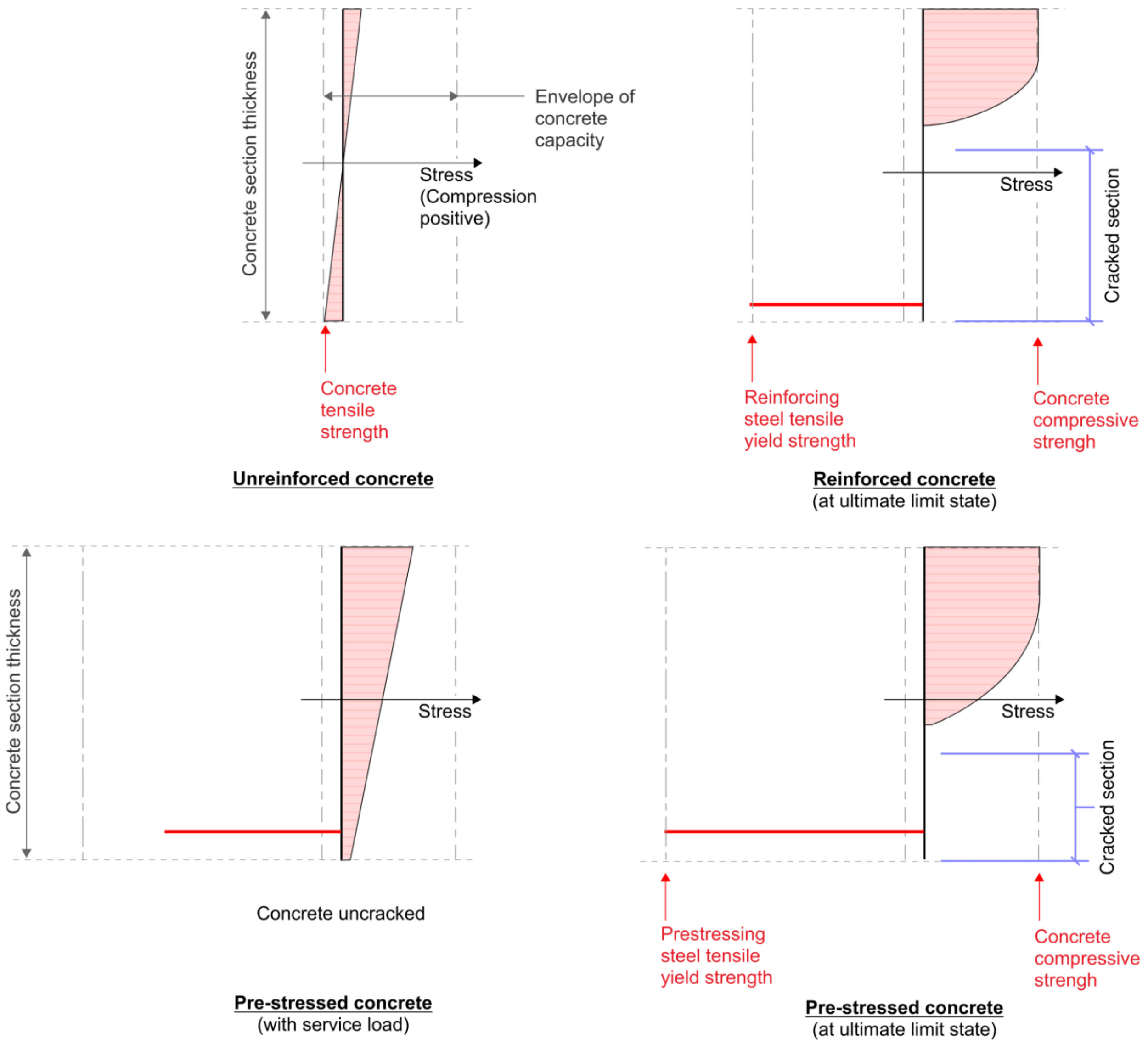
Through-thickness cracks are rare in pre-stressed concrete elements subject to dominant bending moments because part of the concrete will typically remain in compression. This is often the basis for justifying the leak-tightness of water retaining structures. However, the tendency for through-thickness cracks to form is much more likely in concrete structures such as pressure vessels subject to a dominant tensile force. The use of pre-stressing in these structures can prevent or delay the onset of cracks; it can also ensure peak pressures are sustained without enduring strains that risk rupturing less ductile linings.

Stiffness and damping

Linked directly to suppressing the onset of cracks, pre-stress has the effect to stabilise the stiffness of concrete structures, and it can also change the damping (energy dissipation) of a structure under cyclic load. Both of these are significant for the seismic performance of PCPVs.

Creep

Pre-stress acts to put concrete in a state of long-term compression which can cause concrete to creep. This is generally considered a detrimental behaviour, causing deformations. In an indeterminate pre-stressed structure, creep can also cause a reduction in the level of pre-stress, a redistribution of stress and a reduction in concrete confinement[2].



Unreinforced concrete

Reinforced concrete
(at ultimate limit state)

Pre-stressed concrete
(with service load)

Pre-stressed concrete
(at ultimate limit state)

Figure 1. Comparative stress distributions of unreinforced, reinforced and pre-stressed sections when subject to a bending moment. Represented in these figures, concrete has a non-linear stress-strain response in compression at high stress.

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[2] Confinement has the effect to increase the compressive stress and strain capacity of the concrete but countering the tendency for unconfined concrete to split with cracks forming parallel to the principal compression.

2.3 Hazards associated with post-tensioned concrete

A post-tensioned tendon failure has at least two conventional hazards associated with it:

First, the loss of structural strength associated with a tendon failure can cause a structure to collapse. The same is theoretically true in normal reinforced concrete when a reinforcing bar fails. However, because tendons use much stronger steel than normal reinforcement, the significance of a tendon failing is often greater. Furthermore, whereas reinforcement failures are often preceded by large displacements and cracking, tendon failures can occur with less observable warning. Tendon failures are also more common than normal reinforcement failures. Overall these characteristics mean that the risk associated with this hazard is usually higher in post-tensioned concrete than it is in normally reinforced concrete. That said, a structural collapse is more likely to materialise in a post-tensioned bridge with say 10 tendons acting permanently against the self-weight of the bridge (see Section 3.2.1) than in a PCPV with hundreds of tendons (see Section 3.1).

Second, by virtue of being stressed, tendons store substantial elastic energy. If an ungrouted tendon or anchorage fails, this energy can be released explosively, potentially leading to the tendon and/or anchorage becoming hazardous projectiles with substantial momentum. Very modest tendons can be lethal if they strike critical parts of the human body; the larger tendons used in PCPVs would be more likely to cause death by virtue of their larger impact area and mass. They would also be more likely to cause secondary hazards by virtue of the damage they can cause if striking nearby structures, systems and components (SSCs).

In a PCPV context, loss of pre-stress could also cause loss of radiological containment and/or biological shielding by virtue of allowing concrete cracks to open.

Most tendon failures occur during normal service, typically because of corrosion, or during jacking operations. Somewhat counterintuitively, failures rarely coincide with design-basis load events, principally because such low probability load events are very rare for most structures.

3. Use of post-tensioning

3.1 Post-tensioning in UK Magnox and AGR PCPVs

The earliest nuclear power plants (NPPs) in the UK were Magnox plants, constructed between the late 1950s and early 1970s. The Magnox technology was followed by the AGR technology, with AGR plants constructed between the mid 1960s and late 1980s.

Instances of both Magnox and AGR plants contain PCPVs, but the design of the PCPVs is far from consistent between plants. Even 'sister stations'[3] have meaningful differences and, across the UK fleet, the PCPV designs differ to the extent that a single approach to post-operational management is unlikely to be viable.

The contrasting attributes of three plants of similar age are listed in Table 1 to help illustrate the variability. The plants presented in this Table were chosen based on the availability of comparable information. The table is not intended to be representative of all plants, nor identify either prevalent or unique designs.

Going some way to explain the variability, in 1967, the Central Electricity Generating Board (CEGB) wrote[4]:

- "*An attempt is made to strike reasonable balance between imposing conventional pre-stressed concrete design practice and allowing the vessel designer complete freedom within a functional specification, in order to achieve rapid vessel development*". ([5.7] synopsis)
- *"The type of pre-stressing wire or strand itself is of little consequence and the CEGB make no attempt to specify this or nominate any specialist anchorage system. This is firmly held to be a question of choice for the individual designer"* ([5.7] paragraph 22).
- *"The most serious limitation placed upon the free choice of pre-stressing system is likely to arise indirectly should the purchaser decide that he* [/she/they] *wishes to retain the facility to restress and/or replace cables at any time during the life of the plant"* … *"The current CEGB specification requires tendons to be capable of being restressed and/or replaced at any time during the life of the plant and this inevitably leads to ungrouted tendons"* ([5.7] paragraphs 23 and 24).

Post-tensioning in PCPVs	
PfC 3.1	Based on the level of variability across PCPVs, we would expect the post-operational management plan for each PCPV to be tailored to the characteristics of the PCPV and its surroundings.
PfC 3.2	We consider it necessary that the relevant characteristics of each PCPV structure are understood in advance of developing a plant-specific post-operational management plan.

Figures 2 to 4, beneath Table 1, are referenced within the table.

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[3] 'Sister stations' are stations with significant commonality, developed from a common design.

[4] These quotes are taken from a paper presented at an Institution of Civil Engineers (ICE), British Nuclear Energy Society and Joint British Committee for Stress Analysis conference that took place between 13 and 17 March 1967 titled Conference on pre-stressed concrete pressure vessels. The papers and discussion from this conference are published in ICE conference proceedings [5].

Table 1. Comparison of PCPV structures at Oldbury, Wylfa and Dungeness B [5]

	Oldbury	**Wylfa**	**Dungeness B**
Technology	Magnox	Magnox	AGR
Geometry	Cylindrical	Spherical	Cylindrical
Internal dimensions	23.5m diameter. 18.3m height.	29.3m diameter	20.0m diameter. 17.7m height.
Concrete thicknesses	4.6m walls. 6.7m top and bottom slabs.	Variable, 3.34m minimum	3.8m walls 6m top and bottom slabs *Note 1*
Pre-stressing layout	See Figure 2. 22×160 helical tendons in walls at ±45˚. >1000 horizontal tendons in top and bottom slabs.	See Figure 3. 1338 tendons in total: 2×218 internal 'small circle' tendons anchoring on vertical faces. 528 internal 'great circle' tendons anchoring on horizontal faces. 384 horizontal hoop tendons, externally, passing through 16 vertical deviator ribs.	See Figure 4. 384 vertical tendons. 366 circumferential barrel tendons. 108 circumferential tendons in each of the top and bottom slabs. *Note 1*
Tendons	12No. 15.2mm 7-wire strand.	36No. 15.2mm 7-wire strand (each splitting into 3No. 12-strand tendons at anchorages)	163No. 7mm wire.
Ducts	89mm seamed welded mild steel.	140mm helically formed.	140mm galvanised mild steel,, 22SWG thickness. *Note 1*
Anchorages	Freyssinet forged steel cones with concentric wedges, with >0.9m projecting strand 'tails'.	Freyssinet forged steel cones with concentric wedges, with >0.9m projecting strand 'tails'.	BBRV[5] type with buttonhead system; basic element at each end of tendon, with pull ring to connect the basic element to the pull-sleeve of the jack.
Restressing	By either jacking the tendons through the anchorage or shimming the entire anchorage away from the concrete.	By either jacking the tendons through the anchorage or shimming the entire anchorage away from the concrete.	By jacking the pull ring against the bearing plate.
Embedded instrumentation	Sonic strain gauges, Moisture content gauges, and thermocouples.	Vibrating-wire strain gauges and thermocouples.	Vibrating-wire strain gauges and thermocouples. *Note 1*
Note 1: Relevant information was provided by EDF in absence of details being available in [5].			

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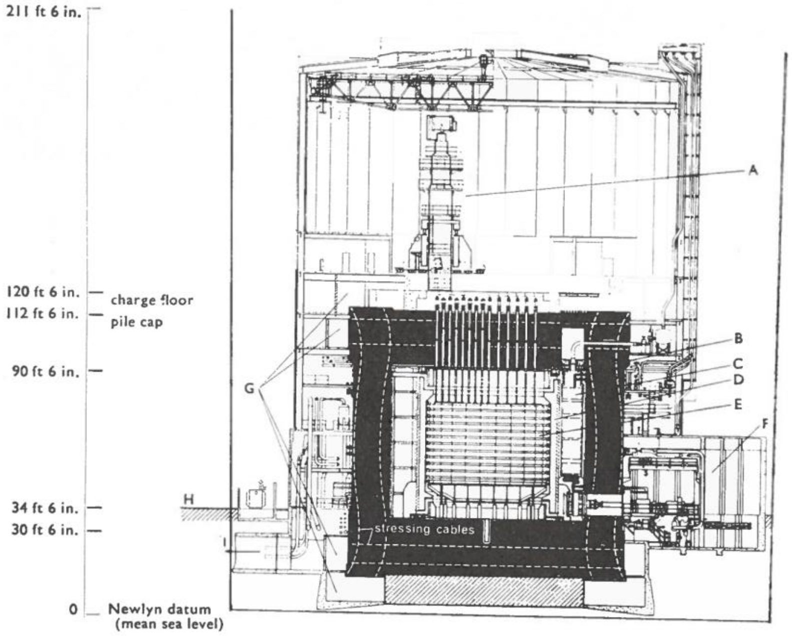
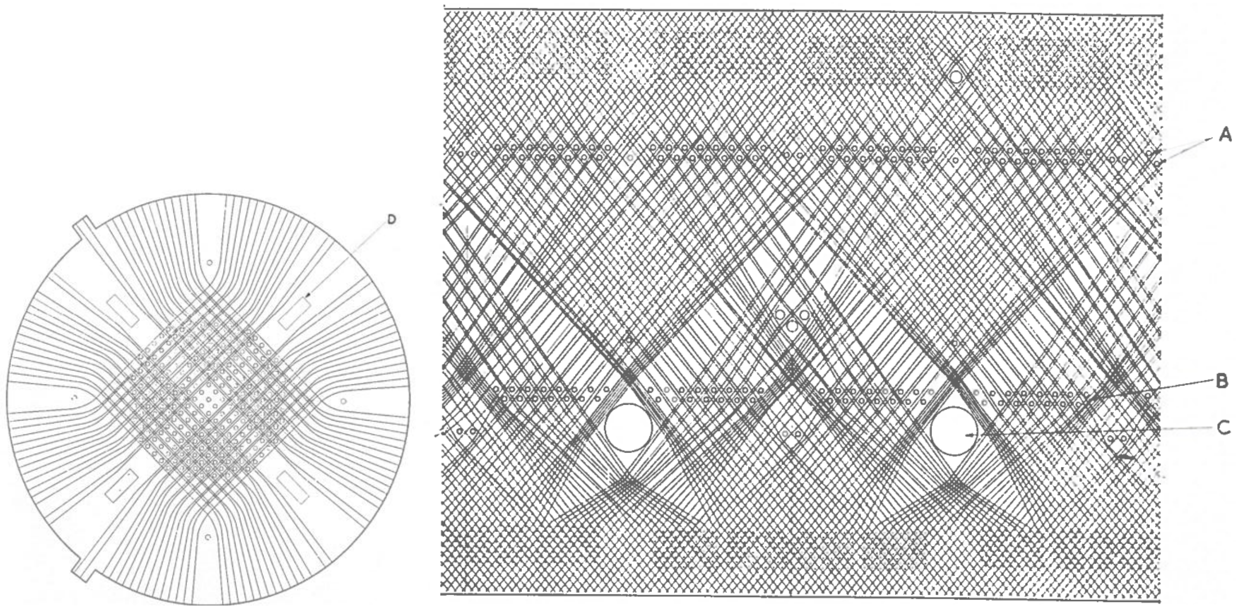
[5] BBRV is a post-tensioning system named after its developers Birkenheimer, Brandestini, Ross, and Vogt.



Vertical-cut section showing pre-stressing profiles (dashed)



Horizontal-cut section through ends

Developed half-elevation

Figure 2. Oldbury PCPV pre-stressing layout (source: [5])

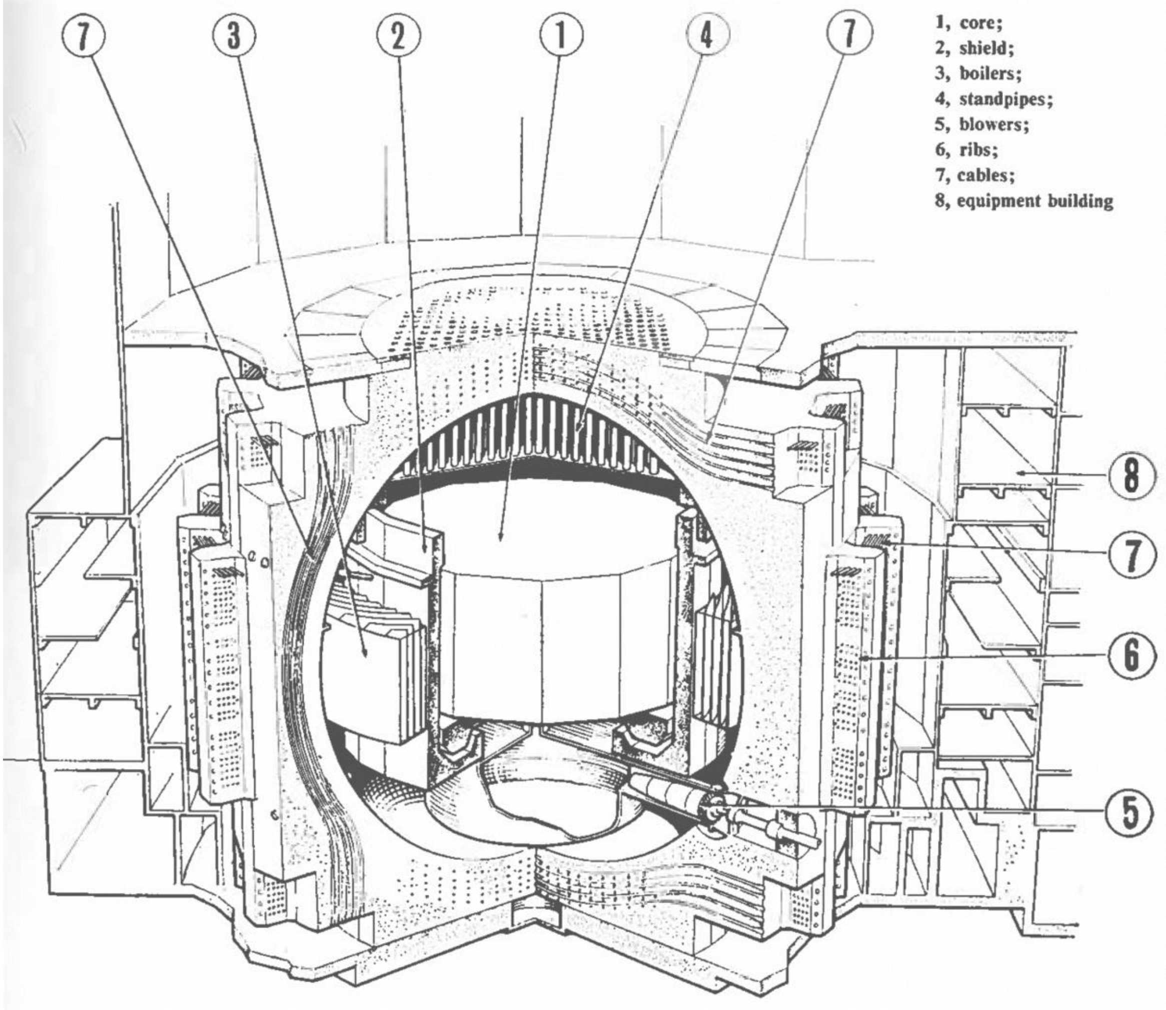
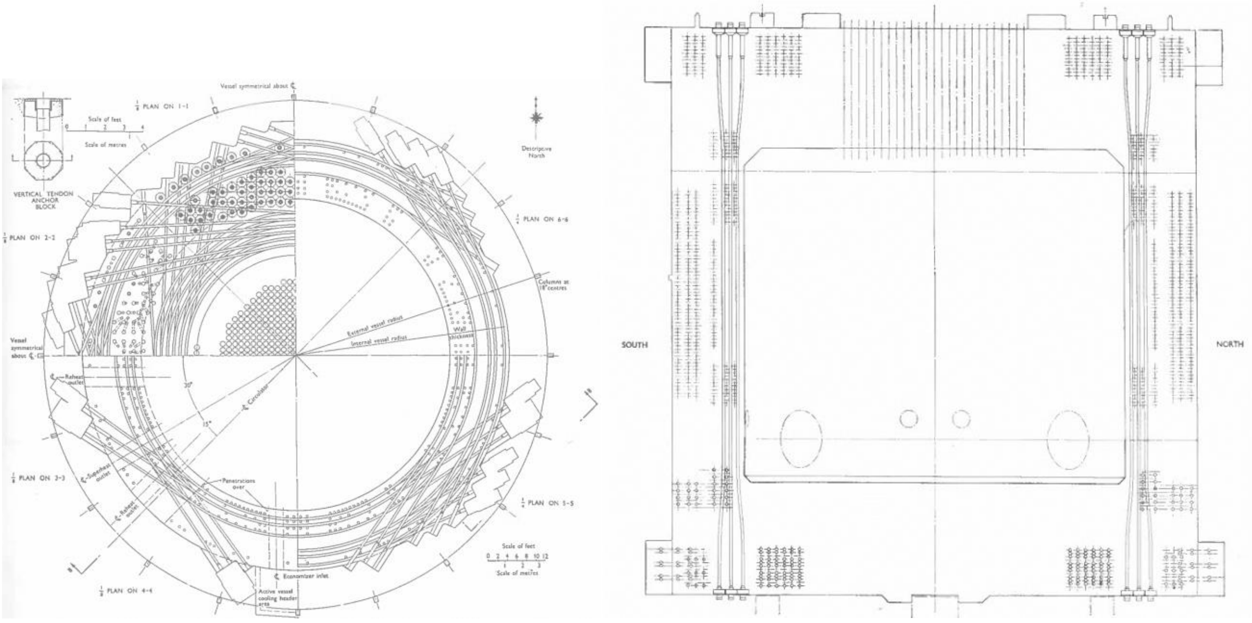


Figure 3. Wylfa PCPV isometric cut-away showing internal and external pre-stressing tendons (source: [5])



Horizontal-cut sections

Vertical-cut section

Figure 4. Dungeness B PCPV pre-stressing layout (source: [5])

The construction of the three PCPVs listed in Table 1 coincided with the development of BS 4975 *British Standard Specification for Pre-stressed concrete pressure vessels for nuclear engineering*, first issued in 1973 and updated in 1990 [6]. Collectively, the ICE Proceeding Papers [5] and BS 4975 provide useful insights into the considerations that informed the design and construction practices, much of which is useful for all parties considering a plant's post-operational management. Selected salient information from these references is included below.

While these references provide useful information in the public domain, this information is limited and we understand that more substantial design, construction, operation, inspection and maintenance records are held by the licensees for each plant.

Post-tensioning in PCPVs	
PfC 3.3	We would expect licensees to have access to and make appropriate use of all relevant retained historical information relating to a plant as they develop and implement the post-operational management plans. Relevant historical information may include: drawings, specifications, calculations, design commentaries, test records, in service monitoring records, etc.)

Oldbury [5.1]

- (Paragraph 8), "*A lack of data on which to base precise predictions on the shrinkage and relaxations of concrete over a long period of years … it was decided at an early stage that the pre-stressing system should be capable, at any time during the life of the station, of being retensioned or even replaced*"

  We can assume from these statements that there is most likely a range of tolerable pre-stress, with the design likely to have established both minimum and maximum levels.

- (Paragraph 36), details are provided on the source of the limestone aggregates. This information is rarely recorded, but useful for establishing parameters for simulating creep.

Wylfa [5.2]

- (Paragraphs 33 and 38), *"When concreting of the vessel has reached lift 16, one band of hoop tendons is pre-stressed just below the equator to control construction stresses"* .. *"In July 1966 the first band of hoop cables in lift 12 close to the equator were pre-stressed"* … *"*[Concreting is to be] *completed during November 1967. … "Pre-stressing will start in mid-January 1968 and will be complete by the end of May 1968"*.

  These statements, in combination with Figure 5, give insight into the pre-stressing requirements in temporary condition and the age of the concrete when pre-stressed. They imply some pre-stressing was needed in the fully constructed (but otherwise unloaded) condition and/or in a partially constructed / deconstructed (but otherwise unloaded) condition. This is different to the cylindrical PCPVs which had pre-stressing applied once fully constructed.

  Note that Figure 5 also includes a "temporary support column" beneath the overhang on one side of the PCPV. While the detailed reasoning for this support is not known, it suggests the partially constructed PCPV was not self-supporting at all stages of its construction.

  The implication of both the stressing sequence and temporary support column are discussed further in Section 4.

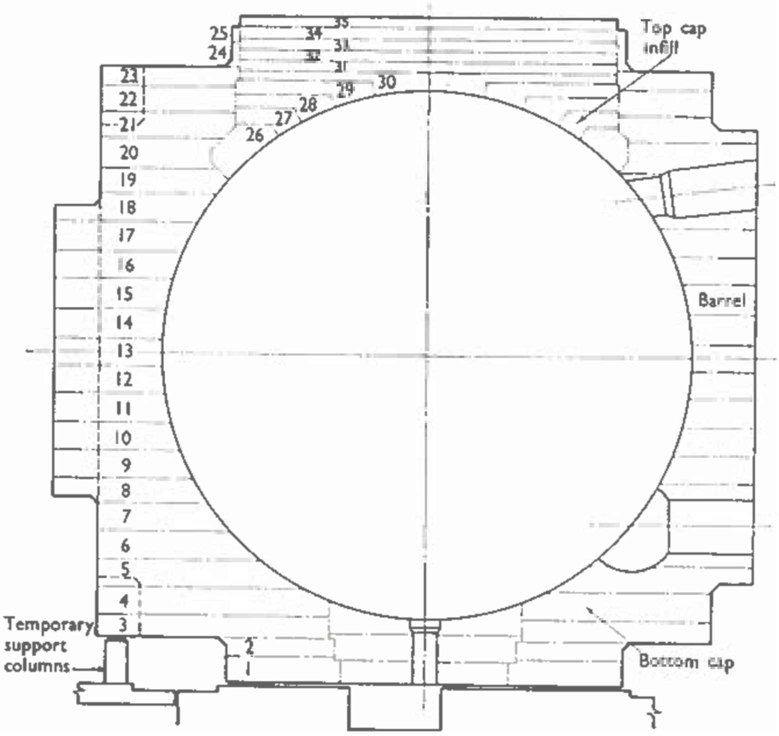


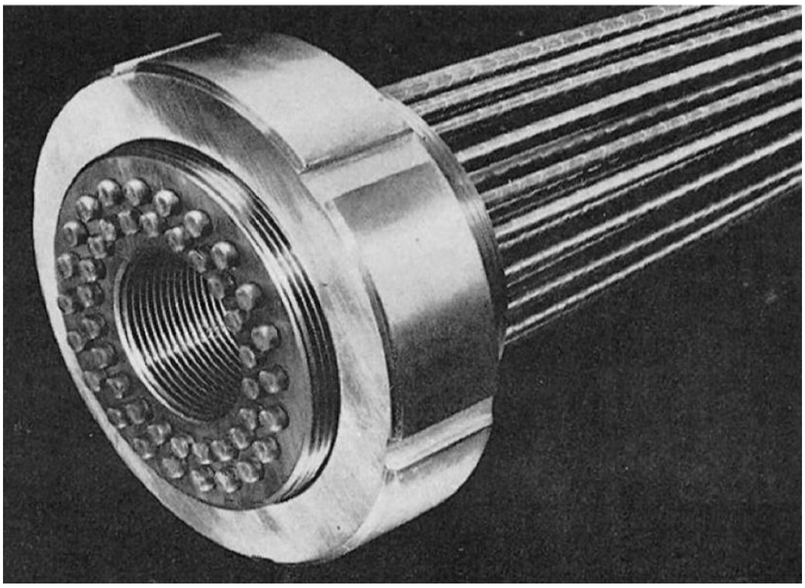
Figure 5. Wylfa PCPV in cross section with annotated concreting lift numbers (source: [5])

Dungeness B [5.3]

- (Paragraph 8) – "*Each tendon consists of 163 steel wires of 7mm diameter … The anchorages are of the BBRV type, in which the ends of the wires are nail headed over a single flat end washer. The tendon is stressed as a single unit by jacking this washer*"

  Figure 6 dates from the 1950s and is of a similar BBRV nail head anchorage for a smaller 42 wire tendon. Note that these tendons either do not have wires wound into strands or else have the strands locally unwound at their ends so that the separated wires can pass individually through the anchorages.

Jacked anchorage:



Fixed anchorage:
(with protruding grouting pipe)

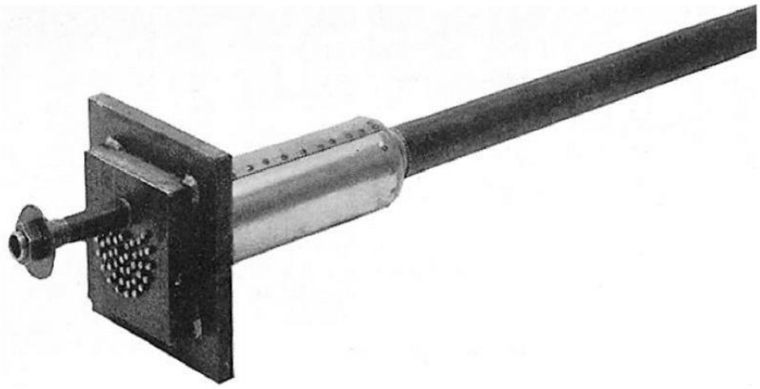


Figure 6. 1950s BBRV nail head anchorage system

Note, nail heading is more properly, but less commonly described as swaging.

Papers outlining design considerations associated with material behaviours

ICE Proceeding Papers 12 to 18 [5.12 to 5.18] discuss the contemporary understanding of concrete behaviour and ICE Proceeding Papers 19 to 27 [5.19 to 5.27] discuss the contemporary understanding of the steel pre-stressing tendons, both as of 1967.

Collectively, these papers describe matters including irradiation and thermal effects, tendon stress loss, concrete creep and concrete shrinkage. The papers demonstrate a high degree of understanding and consideration in the 1960s of these effects and how they were accounted for. Comparing the available information with modern day equivalents reveals that the material constituent models[6] (i.e. the theoretical formulations) are not consistent but credible[7].

Figure 7 is provided as an example comparison. It plots cumulative shrinkage against time. The curves for Wylfa extend to 10,000 days (27 years) and it is not reported what was assumed thereafter. Our expectation is that the designers may have assumed all shrinkage would have occurred by this time. By comparison, EN1992 predicts that approximately 95% of total shrinkage occurs by 10,000 days.

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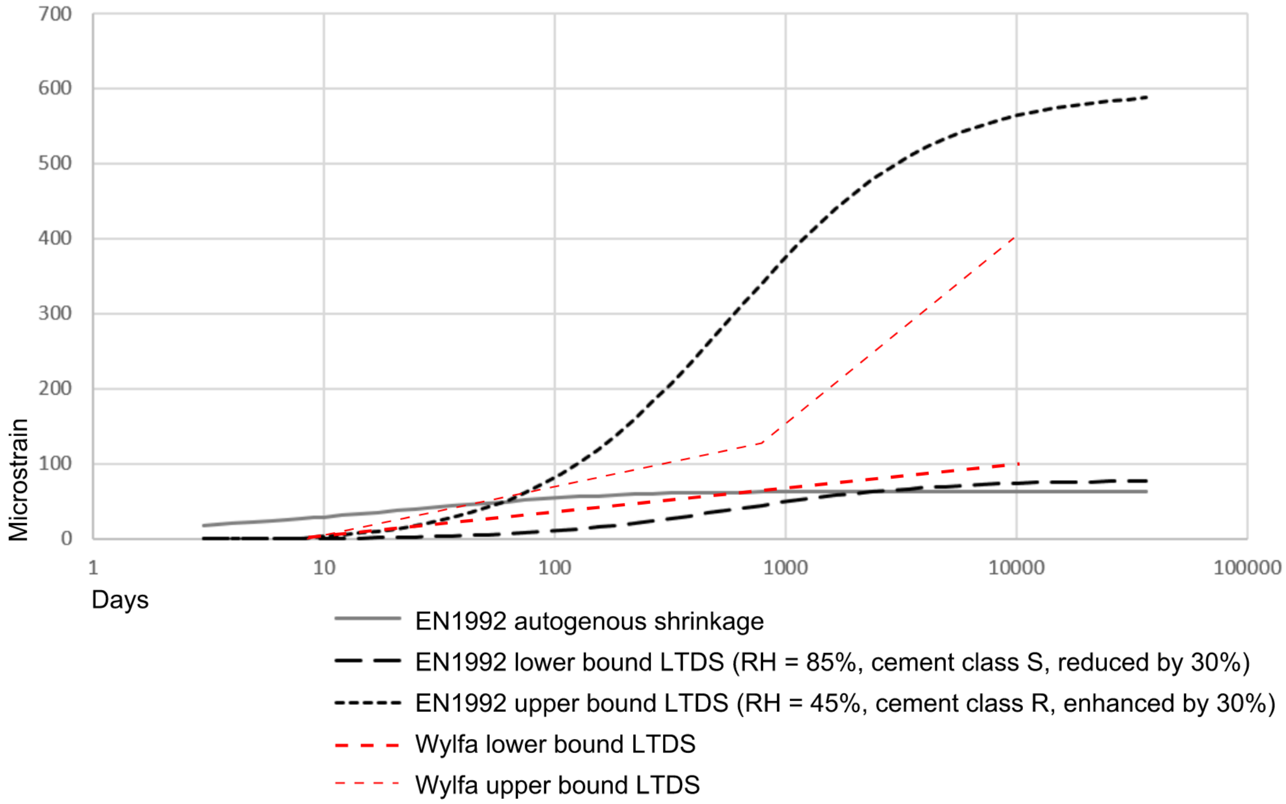
[6] A material constituent model is the numerical encapsulation of selected real-world behaviour(s) in a format that can be simulated within analyses.

[7] Note that there is not consensus in the current day on how best to simulate these effects within constituent models and therefore it is not at all surprising that models in the 1960s differ.



Note, EN1992 notes that any calculation of LTDS may vary by 30% and this has been included in the graph. Relative humidities (RH) of 45% and 85% have been used based on contemporary guidance in Ciria C766 [8] for interior and exterior UK conditions.

Figure 7. Illustrative comparison of long term cumulative drying shrinkage (LTDS) and autogenous shrinkage derived using EN1992 [7] with data reported for the design of Wylfa [5.13]

While the accessible records have given insights into the material constituent models, we have greater uncertainty on how these models were applied within analyses. We expect that each plant's design would have been based on simplified application of the material constituent models that may or may not hold up against current day RGP.

As an example, we anticipate that only the global effects of concrete creep and shrinkage on pre-stressing may have been predicted, and not the local effects of creep and shrinkage on concrete confinement, which affects concrete strength and ductility[8]. To this day, the application of these behaviour in analyses has not been explicitly codified and they remain characteristics of concrete that are troublesome to simulate.

Results from the historic analyses could be directly benchmarked against current day equivalents, provided the original parameters can be retrieved from the design record. However, more valuable than this purely theoretical comparison could be to:

1. Compare the originally predicted behaviour (if retrievable from archives) against the measured behaviours (from instrumentation).
2. Compare the originally assumed time-dependent parameters[9] against actual measured time-dependent parameters recorded during the plant's existence to date (e.g. relative humidity, temperature, pre-stressing load - including re-stressing history - and internal pressure).

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[8] Confinement is particularly important to prestressing anchorages. It was also a topic of focus in the recent review of the shear key crenulations at the base of the PCPVs for Heysham 1 and Hartlepool where three contemporary models gave differing results. Meanwhile historic creep and shrinkage under pre-stress could lead to concrete cracking when PCPVs are de-stressed.

[9] Time-dependent parameters are parameters that change as a function of time. Constituent models for simulating the long-term behaviour of pre-stressed concrete are likely to be defined, in part, by time-dependent parameters.

3. Re-simulate the behaviour using actual measured time-dependent parameters and modern numerical simulation capability, using original and current day constituent models and compare these against: (a) the measured behaviour and, (b) the originally predicted behaviour.

3(a) would yield the most useful basis upon which to determine the current design margin and to simulate future behaviours. However, differences between the simulated and measured behaviours may only be understandable and, hence, reliably predicted into the future with insights gathered from 1, 2 and 3b.

Note that such a study would be a substantial analytical undertaking, necessary if aiming to reliably understand the state of a PCPV, but potentially not needed if behaviours of the PCPV can be shown to have little sensitivity across a range of plausible future states / load cases. It is therefore important licensees develop considered plans for how they will use analyses to substantiate the post-operational phases, and that inspectors are open to a range of approaches.

The ICE Papers [5] report how analytical predictions were benchmarked during each plants' designs against physical tests on scaled models. This is a good practice despite being far less common at the current time. Should any of the scaled models still exist in a serviceable condition, they could be useful for validating stages of the post-operation.

Papers outlining design considerations associated with instrumentation

- ICE Proceeding Papers 52 to 55 [5.52 to 5.55] discuss the instrumentation embedded into the concrete, giving insights into the predicted and realised success of this instrumentation.

Over 50 years has passed since the conference was held and determining the serviceability of the instrumentation at any particular plant is outside the scope of this desk study. However, we consider that it would be prudent that any parties responsible for post-operational plant management schedule out, and understand the potential to make use of, existing monitoring. This is discussed further in Section 6.

BS 4975

Only the more recent BS 4975:1990 has been reviewed in this study. It is generally quite limited on detail, providing expectations for the matters to be considered by designers. It contains:

- Requirements for the testing and surveillance of completed PCPVs which specifically includes regular tendon load checks and anchorage examinations.
- Limits on the concrete compressive stresses, with separate limits defined for during construction and in service.
- Limits on reinforcement stresses.
- A list of actions to be considered.
- Ageing effects to be considered.
- References to the complementary design and material standards that were current at the time.

In some cases, BS 4975 reads as being quite prescriptive (e.g. limits on reinforcement and concrete stresses) and it is foreseeable that licensees may need and/or be motivated to try and dismiss it as not relevant or current. Officially, according to the BSI website[10], BS 4975:1990 remains current, neither withdrawn nor superseded. This is not to say, however, that it presents RGP on all matters that it discusses, or that it is altogether applicable to decommissioning. We judge it is best treated as useful guidance, to be supplemented by more contemporary international counterparts, e.g. ACI 349 [9].

We trust that PCPVs will have been assessed as against more contemporary codes and standards as part of periodic safety reviews, conducted in accordance with LC 15 and TAG 50 [10].

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[10] https://knowledge.bsigroup.com/products/specification-for-prestressed-concrete-pressure-vessels-for-nuclear-engineering/standard

Heysham 1 and Hartlepool

The Heysham 1 and Hartlepool are sister NPPs with AGR technology. Neither is discussed in the ICE Proceeding Papers [5] as these sites were constructed in 1968 and 1970, after the papers were presented.

The PCPVs at these plants have pre-stressing that comprises relatively traditional vertical strands in ducts in combination with horizontal cables wound externally around the concrete in a series of horizontal channels. In total, each PCPV has 20 horizontal channels (Figure 8), each containing multiple cables (layered over each other) that are themselves wound multiple times around the PCPV with anchors only at their ends.

Cable[11] winding pre-stressing systems are introduced at high level in CIRIA Report 106 [11].

Detailed plant-specific design information would need to be accessed to understand how the number of cables and windings was arrived at, and to understand the detail of the anchorages. Having been informed that the number of windings varies between channels, we judge it likely that active monitoring, of the concrete and/or the cable, during the winding operation helped inform the number of windings at each channel.

The installation and stressing of these cables was completed simultaneously using machines that travelled around the circumference of the PCPV. It is reasonable to expect that similar machines could remove the pre-stress by reversing this construction method (see Section 5.2).

Cable friction on this kind of system would make it very difficult (likely impossible) to restress below the outermost windings without unwinding and reapplying the cable. This may have been done at times during each plant’s operation, as is required by BS 4975. However, we also expect the designers would have foreseen this difficulty associated with restressing. They may have made the plants’ designs more resilient to pre-stress losses so as to reduce the need for and/or frequency of restressing. These matters could impact the level of pre-stressing to assume in any analyses and/or the ease of cable removal.

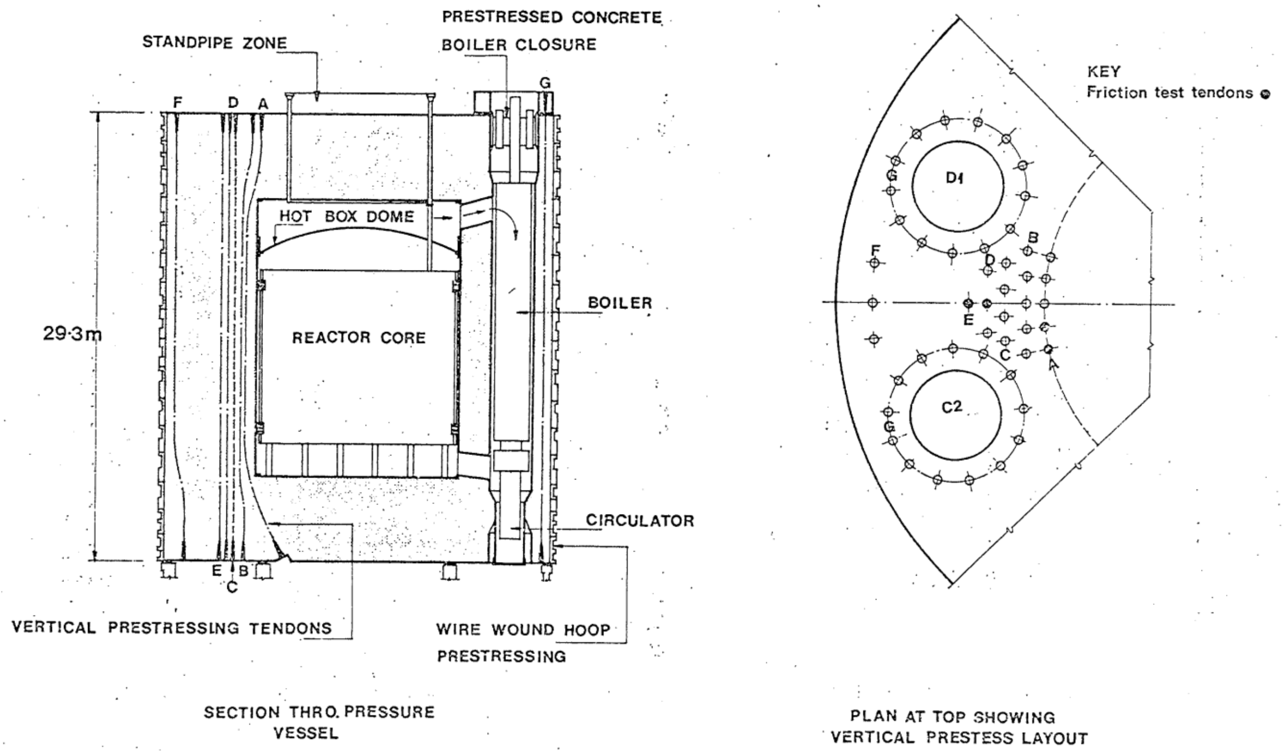

Figure 8. Heysham 1 and Hartlepool PCPV pre-stressing layout (reproduced with permission of EDF)

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[11] CIRIA Report 106 describes the system as “wire winding”, which is the more commonly used terminology. However, in the case of these power plants, this is inconsistent with the common definitions for wire and strand, as given in Section 1.1.

3.2 Post-tensioning in other non-PCPV applications

Four common applications of post-tensioning have been identified and investigated as part of this research: post-tensioning in bridges, offshore oil and gas structures, silos and other non-nuclear pressure vessels and societal building structures. These are discussed below, but common to all:

- Grouted post-tensioning is the norm.
- There are no radiological containment or shielding requirements dictating an equivalent to the 'care and maintenance' stage.
- With grouted tendons and without the radiological hazard, the main effect of pre-stress on decommissioning is to potentially constrain the demolition sequence, to ensure that the unloading of pre-stressed members does not result in their failure due to unbalanced pre-stress.

As consequence of the differences between these characteristics and those of PCPVs, it will be important that Engineers and Contractors who are suitably qualified and experienced (SQEP) for the design and decommissioning of non-nuclear pre-stressed structures acknowledge and adapt to the relatively unique requirements of PCPVs.

Post-tensioning in non-PCPV applications	
PfC 3.4	We would expect Engineers and Contractors who are experienced with pre-stressed structures in other civil engineering sectors to need to familiarise themselves with the pre-stressing systems and the post-operational requirements of PCPVs.

3.2.1 Post-tensioning in bridge structures

One of the most common uses of post-tensioned concrete is in the construction of bridges. Many forms of bridge exist but they are all characterised by a common need to carry gravity loads between supports.

In most cases, a bridge deck can be regarded as a one-dimensional (1-D) beam acting in bending. A bridge's self-weight is usually a very substantial component of the total load to be resisted. This will vary during construction but is then stable in service. Live loads are much more variable in magnitude and, unlike the pressure load cases governing a PCPV, will not dwarf the structure's self-weight. The pre-stressing is therefore working at a relatively high utilisation throughout a bridge's life, and it is often the case that a pre-stressed bridge could not be serviceable under normal loading without the pre-stress being effective.

Straight post-tensioning along the length of a bridge deck can increase the deck's flexural resistance in the manner described in Section 2.2, by creating compression. However, by profiling the post-tensioning, it is also possible to create vertical actions within the deck that counteract the gravity load, reducing the peak bending stresses. Balancing the self-weight in this way is common and, in bridges that are constructed segmentally, the pre-stress is often built up during construction to continuously balance the growing self-weight.

The axial force from the post-tensioning also enhances a bridges resistance to shearing forces and provides a clamping force across any segment to segment 'cold' joints.

The majority of bridges have primary structural elements that are exposed to external environmental conditions throughout their service life including frequent wet and dry cycles. Most bridge decks are also subject to both abrasive loads and direct solar radiation, both of which degrade waterproofing systems. In order to protect tendons from water ingress and associated corrosion, it is standard practice in the UK that post-tensioning ducts within bridges are grouted (even if the tendons have a grease protective layer or are inside an HDPE duct).

Once grouted, the tendons cannot be replaced or re-stressed. Where there is an up-front requirement to accommodate changes to pre-stress, it is common practice to include provision in the initial construction by way of empty ducts which can have tendons added at a later date. In cases where such a provision was not made, different methods have been used to add pre-stressing, typically in a manner quite different to the original installation.

Testing tendons for corrosion is typically by intrusive investigation techniques (e.g. coring through the concrete to expose a short lengths of the tendon) or by non-destructive methods such as acoustic monitoring (listening for wire breaks). Both these techniques are suitable for grouted and ungrouted tendons.

End of life for most bridges is driven by a change of basic requirements (e.g. road widening) or irreparable safety concerns linked to severe deterioration. When there are such safety concerns, the substantial self-weight of bridges mean they become liabilities if not demolished and demolition will often occur relatively quickly. The inconvenience of prolonged road and or rail closures and disruptions are further drivers for demolition to occur quickly and speed is often prioritised over material, labour, process or equipment efficiency.

In instances where the pre-stressing is built up during construction, it is often necessary to stage the demolition so that the pre-stressed components do not fail as loads are removed and/or the support conditions change.

To reduce disruption to online infrastructure and improve safety, it is often preferable to lift and relocate individual bridge spans (or components thereof) so that they can be demolished at ground level [12]. Owing to movement joints that are present in bridges, this is often possible without cutting major structural components insitu.

While most bridges have grouted post-tensioning, the performance and extent of grouting cannot always be guaranteed during decommissioning. It is therefore common to take precautionary measures assuming tendons are ungrouted. A typical precautionary measure is to place a steel shield plate beyond the pre-stress tendon ends, held in position by a hardcore or earth bund.

Mechanical breakers are most commonly used to break up pre-stressed bridge structures. The concrete will tend to be broken into rubble that can be reused as hardcore, ideally with minimal transportation. Steel is typically removed for recycling.

In summary the application of pre-stress in bridges is quite different to that in PCPVs. However, relevant experiences and knowledge that may be transferable from the bridges sector includes:

- Detailing, supply and handling of large multi-strand tendons, anchorages and jacks.
- Undertaking synchronised multi-tendon jacking operations with live monitoring.
- Undertaking intrusive ‘keyhole’ corrosion surveys.
- Ongoing acoustic monitoring for wire breaks.
- Temporary works solutions for containing severed ungrouted tendons.

UK highway moratorium

In December 1985 the Ynys-y-Gwas bridge over the river Afan in South Wales collapsed without warning. This was a multi-beam single span structure where each beam was composed of a number of segments held together by longitudinal pre-stressing strands. Transverse pre-stressing stands also held the individual beams together. All the strands were in grouted ducts.

Examination of the failed structure revealed that the grouting of the ducts had not eradicated voids and that water leakage into the ducts at the segment joints had corroded the pre-stressing strands where locally ungrouted, causing failure of the strands which triggered the ultimate failure of the overall structure. The cause of failure was identified as chloride induced corrosion due to inadequate protection of the strands at segment joints.

The collapse triggered a series of examinations of other post-tensioned bridges, revealing multiple bridges with systematic grouting defects.

In September 1992 the Department of Transport placed a country wide moratorium on the use of grouted post-tensioned concrete bridges[12]. In practice, this moratorium led to a pause on all post-tensioned concrete bridges in the UK (grouted or ungrouted). The moratorium triggered research that was brought together in the publication of Technical Report (TR) 47 by the Concrete Society in 1996 [13]. This set out new, more stringent RGP procedures for site operations and testing with key features being:

- Requirements for pressure testing ducts to reveal leaks prior to grouting.
- Recommendations for using HDPE or similar ducts that do not corrode and can be glued together to make a seal, in preference to metal ducts.
- Refinements to grouting procedures, including stages at which pressure of the grout is held for a period of time to ensure all voids are filled.
- Introduction of guidance on the location of grout vent tubes at key points along ducts where air would likely accumulate and could otherwise become trapped.

TR 47 has since been withdrawn and superseded by TR 72 [14]. Not seemingly within the scope of either TR 47 or TR 72 is discussion on how to manage existing non-compliant structures. TR 72 does describe retrospective void grouting (to eradicate flaws in grouted systems) and tendon replacement in external ungrouted systems. We would expect a licensee to refer to and, where appropriate, conform to or justify deviation from TR 72 guidance, identifying the limitations of this guidance when being applied to PCPVs.

Noting that PCPVs have steel ducts, the change to HDPE ducts promoted by TR 47 is significant because it has led to various non-intrusive monitoring techniques becoming preferred RGP methods (e.g. ground-penetrating radar) that can inspect through HDPE but not through steel. These methods would not be suitable for PCPVs.

3.2.2 Post-tensioning in offshore oil and gas structures

Post-tensioning has been used extensively in offshore oil and gas concrete gravity structures (CGS), a number of which in the North Sea have recently commenced decommissioning following end of extraction. The post-tensioning is typically vertical within cylindrical legs[13], with local vertical post-tensioning also forming the connection to the steel topside structure. A mixture of tendons and solid Dywidag threadbars[14] are known to have been used for this post-tensioning across different structures, in all instances being grouted.

fib Bulletin 18 [15] discusses the topic of post-operational decommissioning. However, on the topic of de-stressing, it simply states, "*Post-tensioned reinforcement will require detailed analysis of the reinforcement system and condition. The cables are normally well grouted and the risk of large concentrated energy*

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[12] https://hansard.parliament.uk/Commons/1993-02-09/debates/bef52b30-f73e-4da7-9ef5-5459139fab66/Bridges(GroutedDuctTendons)

[13] A state of hoop precompression is maintained in the cylindrical legs while in service without hoop pre-stressing by hydraulic drawdown of the internal water level.

[14] Solid steel bar, with surface deformations creating a coarse thread and yield strength higher than historical reinforcement, suited to post-tensioning with screw-on jack.

release [when dismantling, cutting or breaking] is low." Disposal and recycling of contaminated materials is considered at length, but without the specific hazard of radioactivity, and with no specific concern reported with regards to dust.

Not reported on in *fib* Bulletin 18, Brent Delta is an example platform that has recently undergone decommissioning. It had Dywidag threadbars bars extending out of the CGS and through the baseplate of the steel topside to form a pre-stressed bolted CGS to topside connection. The decommissioning could have attempted to untighten the locking nuts on the Dywidag threadbars that held the topside (i.e. reverse the construction) as was likely intended by the station's designers. However, the preferred and adopted approach was to cut the Dywidag bars concurrently with the surrounding concrete immediately below the topside baseplate using a diamond wire (see Section 5.3.2.2). This caused localised loss of pre-stress, but the stress was maintained away from the cut via the grout. Cutting was favoured over untightening the locking nuts due primarily to the relative time and cost of each operation and the relative predictability of wire cutting; the condition of the locking nuts being highly variable with many corroded and feared fused. This case study demonstrates the feasibility of diamond wire cutting through thick-walled concrete with embedded grouted pre-stressing. It also gives precedent for making an ALARP decision not to reverse the construction, departing from the designers' expectations and provisions.

3.2.3 Post-tensioning in silos, tanks and non-nuclear pressure vessel structures

There is precedent for post-tensioning to be used in silos, tanks and other non-nuclear pressure vessels including liquid nitrogen gas tanks. In these applications, the pre-stressing shares similarities with PCPVs in so far that its primary function is to resist outward uniform pressure. However, key differences are:

- The structural concrete wall thickness is typically much less in silos and tanks, not required to provide anything equivalent to biological shielding. These structures are therefore much more like thin-walled shells with matters such as through-thickness crack widths under applied loads, concrete buckling and over-stress under the pre-stress compression more dominant considerations.
- Pre-stressing is typically grouted when confined to ducts. Instances with ungrouted systems exist, but these often have pre-stressing applied via externally-located windings (similar to Heysham 1 and Hartlepool AGRs – see Section 3.1).
- The structures are often external, or subject to external environmental conditions throughout their operation.
- Without radioactivity, clean up, decommissioning and demolition can be via relatively traditional methods, often without any motivation to prolong or delay these activities or heightened concern about concrete dust or slurry being generated.

A CROSS Safety report from 2009 [20] provides an account of a collapsed ungrouted post-tensioned precast concrete sewage water treatment tank, caused by emulsified duct grease that led to corrosion of the hoop tendons. The critical tendon failure that led to the tank's collapse occurred while the tank was in service and subject to hydrostatic pressure. Had the tank been empty, the initiating tendon failure may still have occurred, but this failure would have been less likely to trigger further tendon failures and collapse. Similar is true in a PCPV; under the high internal pressure experienced during a fault scenario, a single tendon failure has the potential to overload and trigger failures of other tendons. However, during decommissioning, when there is little or no internal pressure, there is much lower risk that an isolated tendon failure would lead to progressive failures.

3.2.4 Post-tensioning in societal buildings

By 'societal buildings', we mean an array of non-industrial building types including: office buildings, multi-occupancy residential buildings, hospitals, retail buildings, leisure and faith building, etc. All of these are designed primarily to accommodate people, with protected, often controlled, internal environments.

While most societal buildings have a shorter design life than infrastructure, long design life examples include the Sydney Opera House [16], Coventry Cathedral [17], St Catherine's College Oxford [18], Scottish Parliament Assembly Building [19] and La Grande Arche de La Défense. The opulence of these examples should not be seen as a prerequisite for post-tensioning and there are many thousands of inconspicuous buildings with post-tensioning systems. Indeed, regular orthogonal buildings dominate the post-tensioning building market.

Within societal buildings, post-tensioning is most commonly implemented within multi-span concrete floor slabs, making these slabs more efficient in bending (under gravity loads) and therefore able to be thinner. The floors are often two-way spanning onto discrete column supports and the pre-stress is provided orthogonally.

Post-tensioning systems are also used in transfer structures, these being horizontal structural systems at specific non-standard floors that transfer loads from columns above onto offset columns below.

Post-tensioning practices in societal buildings has varied between countries and also evolved over the last 60 years. Contrary to the UK building examples named above that are all grouted, early pioneers in the UK and US tended to use ungrouted systems. Meanwhile, Australian contractors were quick to develop grouted systems. The latter gained international popularity in the 1980s and grouted systems have gone on to dominate UK practice.

Today, normal practice for post-tensioning floor slabs is to have multi-strand flat ducts whereby circa 5 strands run parallel to one another. It is also common practice to have the strand inside the duct when the concrete is cast, and to have a cast-in fixed anchorage at one end of the strand (known as a ‘dead’ end).

Anchors are typically in small, recessed pockets along slab edges or, where this is not possible, in pans set just inside the slab edge (Figure 9). After stressing and grouting, tendon tails at the jacked (‘live’) end are always cut short, within a few centimetres of the anchorage and it is typical to grout the anchor pockets or pans to protect the tendons and anchorages against fire and corrosion. Cutting the tendon tails so short is often essential to allow insulation and the façade to be continuous past the concrete slab edge (where the tendon terminates in pockets) or to allow smooth uninterrupted floor finishes (where the tendon terminates in a pan). It does, however, prevent the tendons from being restressed or de-stressed via the use of jacks. Therefore, when these buildings are demolished, other destruction techniques (e.g. sawing and/or breaking) are used.

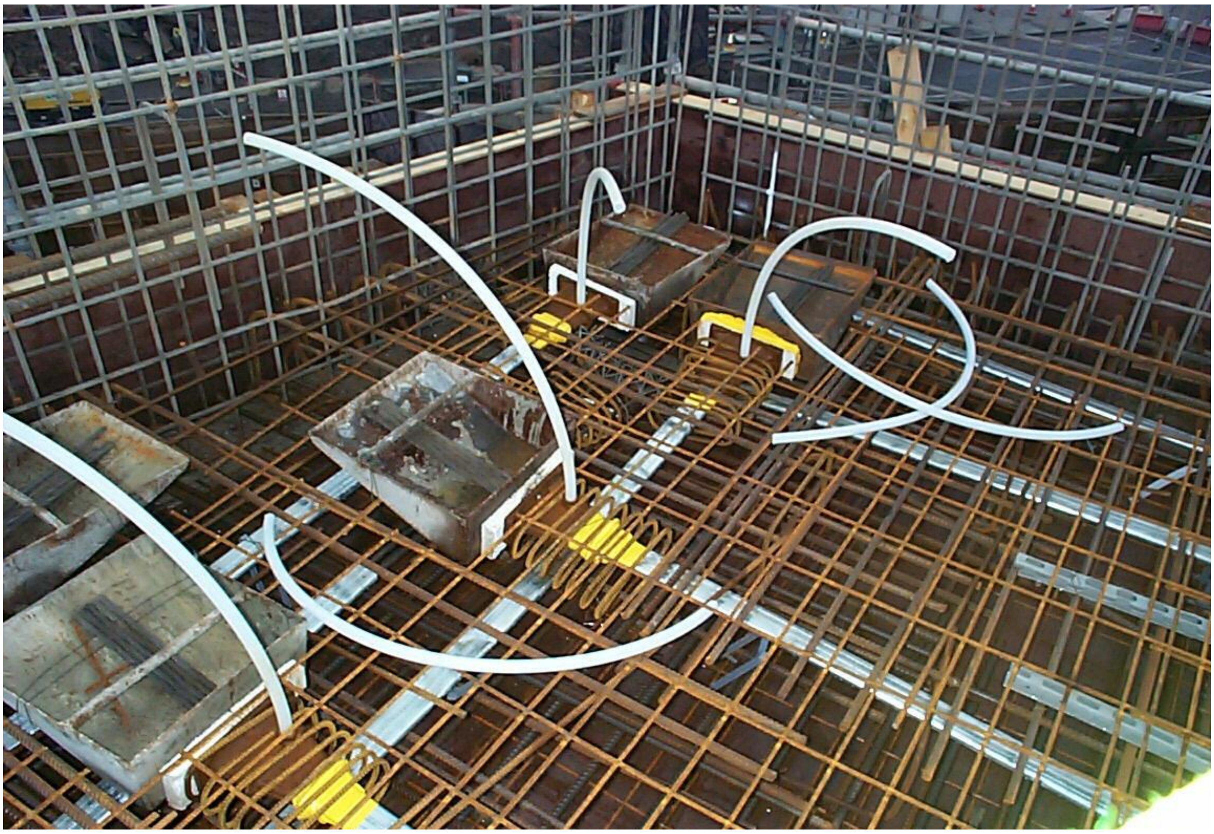

Figure 9. Post-tensioned floor slab system prior to casting concrete with flat tendons (white) and live end anchorages in pans set in from the slab edge. Also visible are white grout tubes and yellow seals joining the ducts to the anchorages. The unstressed strand tails can be seen projecting from each duct within the pans.

The environmental conditions within societal buildings are relatively benign and stable and the combination of this environment plus grouting means that corrosion of tendons in carefully constructed and well managed buildings would not normally be expected to be a problem.

There is relatively modern and detailed literature to support design, specification and management of post-tensioning in buildings – e.g. Concrete Centre CCIP-0059 [21] and Concrete Society TR 43 [22]. While these are intended for common building applications of post-tensioning systems, they are useful in defining ‘normal practices’ that UK contractors will be most familiar with.

In addition to these guides, there have been technical papers written on the demolition of specific buildings. These tend to focus on the acute challenge facing demolition contractors when demolishing buildings with grouted post-tensioning in transfer structures (e.g. [23] and [24]). In these undertakings, the challenge is to remove the gravity loads from the transfer structures without being able to stage the de-stressing of the grouted tendons; this is not dissimilar to the challenge when demolishing post-tensioned segmental bridges. Apparent from these case studies, it is normal practice to develop bespoke demolition sequences with bespoke temporary works provisions as needed.

4. Activities and stages post-operation

We understand that the post-operational management strategies are not consistent across existing sites, and that the maturity of these strategies also varies. In this section we set out the activities that may be enacted and their characteristics, acknowledging the changing actions and environmental conditions that the PCPV structure could be subject to.

While some of the following activities can only occur in a certain order, the order of others could be more flexible. Likewise, some activities can only occur sequentially while others could overlap. The duration of each exposure during each activity can also vary, depending on the totality of the post-operational management strategy.

A key difference between the post-operational decommissioning and the pre-operational construction is the radiological risk post-operation, which is posed by the content and, in part, the material of a PCPV. This can mean that aspects of a PCPV's deconstruction cannot be the reverse of the construction. It also differentiates the demolition of a PCPV from other civil structures.

Across the post-operational stages, it will be the licensees' duty to comply with the Construction Design and Management (CDM) Regulations, and to meet the requirements of TAG 05 [25] when assessing risks associated with conventional health and safety. Many hazards continue across post-operational stages, while others are specific to certain activities and the techniques adopted (e.g. for de-stressing and EIMT). Conventional health and safety is discussed further in Section 8.

The following PfCs apply irrespective of the post-operational strategy adopted. They align with the SAPs (see Appendix A) and TAG 17 Annex 6.

Activities and stage post-operation	
PfC 4.1	We would expect the licensee's reactor building decommissioning plan (SAP DC.4) to be comprehensively developed, acknowledging the specific activities relating to the PCPV, and to be coordinated with the overall site decommissioning strategy (SAP DC.2) before commencing the reactor building decommissioning phase.
PfC 4.2	We would expect the plant's safety case to be suitably updated prior to the decommissioning phase (SAP DC.9), in order that it defines the requirements on the PCPV during decommissioning. For the PCPV, we would expect these requirements to be dependent on stage of the decommissioning.
PfC 4.3	We would expect the substantiation of the safety case to accommodate changes in the PCPV's withstand capacity resulting from staged works on the PCPV or surrounding structures, and/or time-dependent material changes including but not limited to creep, corrosion, and fatigue (as applicable).
PfC 4.4	While accepting that a plant's decommissioning plan may be subject to review and changes, we would expect sufficient foreplaning at all stages to avoid scenarios whereby safer, more favourable options transition from viable to unviable as consequence of delayed activities or inadequate planning.

End of energy operation milestone

For the purpose of this study, it is assumed the PCPV has survived all actions that it has been exposed to up until this milestone.

We would expect the licensee to be able to quantify upper and lower bounds on the pre-stressing load at this point in time. Creep of the concrete will have continuously contributed to pre-stress losses during operation, but tendon restressing and replacement may have counteracted these losses. Corrosion of the pre-stressing system (i.e. tendons and anchorages) may also have been endured, causing some loss in strength and stiffness that may be derived via monitoring, extrapolated from known parameters or predicted based on assumptions.

The PCPV concrete is assumed to have a peak level of irradiation and possible contamination at this stage, most severe on the inner surface and diminishing through the concrete thickness. Embedded pre-stressing tendons may also have radiological effects (irradiation and/or contamination). The level of radiological effects is outside the scope of this study but we raise it as a significant factor that will influence the demolition methodology and will differ at each site.

Defueling

Defueling is expected to occur in two phases: defueling of the reactor and defueling the site. These may be in series or in parallel. Defueling the site does not directly impact the PCPV but may influence the overall decommissioning strategy, impacting the timing of other activities that will have influence on the PCPV works. It may also impact the amount of attention afforded to the PCPV.

Defueling the reactor removes the potential for a loss of cooling accident (LOCA) within the PCPV. This removes the need for the PCPV to sustain high temperatures and/or pressures, which are the conditions that put greatest demand on the pre-stress. With this in mind, it is conceivable that less onerous requirements on the pre-stress (such as allowing greater number of individual wire or strand breakages) could be acceptable and the licensee may pursue an easement of previous safety claims.

The end of energy production and subsequent defueling will initiate a cool down period when the PCPV will cool from the normal operating temperature (with temperature gradient through the thickness of the concrete) down to a more uniform ambient temperature. This cooling will cause the PCPV to contract. We expect this to happen relatively freely, noting that PCPVs are typically isolated from surrounding structures with minimal points of restraint.

Steel and concrete have similar coefficients of thermal expansion and therefore a temperature change will not automatically mean a dramatic change in pre-stress. However, the change in temperature gradient through the thickness will cause differential straining which will manifest as curvatures and may interact with the pre-stressing, increasing and/or decreasing pre-stress near opposite faces of the concrete. In cases where the pre-stress has never been re-tensioned, it is likely that any change on pre-stress during cooling would only be the reverse of changes that occurred during the early power generation and heat-up, scaled down by any pre-stress losses sustained during operation. However, in cases where the PCPV was re-tensioned during short-term power-outages, it is possible the current pre-stress load has never been applied with the PCPV in a prolonged cool state.

The cool down is also likely to bring about an increase in relative humidity in the vicinity of the PCPV, potentially leading to condensation and heightened risk of corrosion of exposed steel including the pre-stressing anchors and strand tails.

The rate of heat loss, the thermal gradient through the PCPV, and the level of atmospheric humidity will depend on: the continued operation or decommissioning of the cooling water system; the continued operation or decommissioning on any building heating, ventilation and air conditioning (HVAC) systems; the weather-tightness of the reactor building envelope; air movement; human activity; any other sources of water/moisture and heat.

Structural analyses and corrosion models should use appropriate thermal and humidity design values based on the post-operational environment.

Cooling of the PCPV to a steady state, and stabilisation of the surrounding relative humidity could take many months, extending well beyond the end of the defueling stage. It is therefore possible that subsequent activities (e.g. de-stressing) could commence before a steady state is reached. In this eventuality, we would expect the effects of the transient states to be considered as the structure is modified.

Aside from these environmental conditions there are some other salient key changes during this stage:

- Up until a time (to be confirmed via a modification to the PCPV safety case, most likely to be after the end of defueling), the PCPV will remain classified as a pressure vessel, subject to Pressure Systems Safety Regulations (PSSR) and be subject to periodic EIMT. We expect that compliance with the PSSR would continue to be a requirement of the safety case until such a time that the licensee has reasonable certainty that there will be no future need to re-pressurise the PCPV.

- Prior to losing pressure vessel classification, the licensee may seek to reduce the pressure withstand claim within their safety case. We would expect such a proposal to be assessed and to be accompanied by a physical change to the pressure safety relief valve. A reduced peak pressure would broaden the envelope for acceptable pre-stress loss and change the criteria for EIMT.

- Following a site being certified as free of fuel, responsibility of the site and its safety case will transfer from the plant's operator to the Nuclear Decommissioning Authority (NDA). Note that, as this handover concerns the defueling of the site rather than the PCPV, it could be some time after defueling the PCPV.

Modification of the reactor building

A sub-stage of a plant's decommissioning stage could be to undertake deconstruction or a controlled demolition to part of the reactor building.[15]

Any major works on the reactor building could temporarily or permanently breach the environmental enclosure that surrounds the PCPV. A loss of environmental protection may expose the PCPV to direct or wind-driven wet-dry rain cycles, snow, freeze-thaw or sea spray. These are not anticipated to be significant loads on the PCPV but each may cause a change to the extents and/or rates of corrosion. Even short-term exposure to rain, snow or sea spray, if causing moisture and/or salts to become trapped, could irreversibly raise the rate of corrosion, leading to an acceleration in the loss of capacity of the pre-stressing system.

If the PCPV is exposed to wetness, drying the pre-stressing by blowing heated dry air through the ducts may be possible remedial technique. This has been used on bridges (typically as a short term measure during construction, prior to grouting). If the anchorages have low permeability, it would require new penetrations to be formed through the duct walls to create the necessary air passages.

Removal of structures surrounding the PCPV could render the PCPV more vulnerable to hostile or accidental/wind-borne missile impacts. It could also cause a change to the reactor building's fire compartmentalisation, fire ventilation and fire fuel load (e.g. hydrocarbons).

A significant reduction in building mass and/or stiffness could impact the seismic response of the reactor building, however we expect the PCPV is structurally isolated from the surrounding building and, thus, this change may not significantly affect the seismic response of the PCPV. It may, however, impact any services (e.g. pipes) bridging this isolation gap.

Any change to an existing crane above the PCPV could impact the extent to which this crane could be relied upon for subsequent maintenance and/or deconstruction of the PCPV. This includes changes to the crane's EIMT requirements. Changes to the crane's environmental exposure could, over time, lead to the crane becoming corroded or otherwise unfit for use.

Should a decision be made to remove an existing crane as part of a partial deconstruction programme, we would expect the short term risk of the crane falling and striking the roof of the PCPV, during the crane's disassembly and removal, to be assessed as part of the modification works.

Any temporary cranes brought onto site to facilitate demolition works that are within strike distance of the PCPV could also pose a strike risk, either from dropped load or crane overturning. We would expect the safety claims to be managed accordingly. This is discussed further in Section 7.

De-stressing the PCPV

Ungrouted post-tension strands can be de-stressed by tendon cutting or by releasing their anchorages. Various techniques exist that we discuss in Section 5, with discussion on monitoring in Section 6 and analyses in Section 9.

As explained in Section 5, de-stressing may be via uncontrolled deterioration or controlled interventions. Thus de-stressing could take place, at least in part, at any time in the lifetime of the PCPV.

De-stressing would ideally be carried out in a sequence that avoids an unfavourable interim imbalance in stresses. If an imbalance cannot be avoided, it needs to be within the withstand capacity of the structure; if

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[15] A likely future precedent for this is the reactor building height reduction works planned at Trawsfynydd (a non-pre-stressed Magnox plant).

excessive, it could present itself as either an overstress in the concrete (potentially leading to concrete crushing) and/or an overstrain in tendons that are yet to be released (potentially leading to tendon breaks).

Various de-stressing sequences will be conceivable (especially when the number of tendons runs into the thousands) but an obvious sequence to consider first is a sequence that is based on the reverse of the original stressing sequence.

Practical matters such as the provisions of temporary access platforms, the availability of jacks, coordination with other site activities and programme targets can impact the viability of any de-stressing sequence. We would therefore anticipate that a preferred sequence is decided based on a risk-based assessment following ALARP criteria set out in TAG 05. ONR inspectors may wish to seek evidence of the licensee’s reasoning for selecting a de-stressing sequence. Within this, they may wish to explore the sensitivity of the sequence to uncontrolled tendon failures, and seek evidence that the chosen sequence results in adequate stress states at all stages.

PCPVs that required partial stressing during construction (e.g. Wylfa – see Section 3.1) may be unable to withstand their own self-weight or modest loading post de-stressing without some pre-stress being retained, or additional propping, restraints or other support structures being added. These support structures may be classified as either temporary works or permanent works, depending on their requirement and the risk associated with their failure[16].

Access to detailed historic design and construction information will provide useful information regarding the structural withstand and inform decision making. By comparison, structures that were only stressed once completed should be able to support their self-weight with pre-stress removed. However, we would not advise that this is automatically assumed without verification. It may be that the factor of safety on the unstressed structure might have been knowingly sub-standard (accepting this as a short term condition during construction, without a radiological hazard) or unknowingly sub-standard relative current RGP (e.g. if the seismic hazard was not considered).

By removing the anchorages and pre-stress, ungrouted tendons cease to fulfil a structural function having relatively very low flexural stiffness and no load path to be loaded in tension. Therefore, if left insitu and ungrouted within the ducts, the tendons would not be reliable as passive reinforcement to the concrete.

In a de-stressed state, the PCPVs will be lightly reinforced[17] structures with significantly reduced withstand capacity. This reduced withstand capacity would need to be assessed and demonstrated to meet the loads applicable.

Should a PCPV have below minimum reinforcement[18], the licensee may need to determine and implement measures to ensure cliff-edge failures are avoided. A postulated cliff-edge scenario that is directly linked to minimum reinforcement would be the formation of an uncontrolled crack, leading to an associated strain concentration in the liner that causes a tear and loss of containment.

The reliability of the steel liner to supplement the bar reinforcement (as is common on modern Inner Containments) is unclear, with few details given in the available literature about the liners’ anchorages or welds. Even if not originally designed and claimed to fulfil such a function, it may be possible to utilise the liner in this way and licensees may look to do so via an update of the safety case.

Left insitu, the de-stressed pre-stressing system is likely to continue to corrode unless protected. However, corrosion of the de-stressed pre-stressing system is unlikely to pose any significant risk to the structure; the ducts are expected to be generous in size relative to the tendons meaning ongoing corrosion and expansion of de-stressed tendons should not exert pressure on the concrete.

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[16] Temporary works structures normally have lower reliability requirements, owing to reduced consequences of failure and/or probability of a failure event occurring. The design of temporary works is typically in accordance with temporary works standards, e.g. BS 5975 [26].

[17] The terminology “lightly reinforced” relates to the cross section area of reinforcing steel as a percentage of the concrete’s cross section area, and not the absolute volume or mass of reinforcement.

[18] “Minimum reinforcement” is the amount of reinforcement (by cross section area) that provides tension capacity greater than the tensile capacity of the concrete. The amount is dependent on the relative strengths of the reinforcement and concrete.

More concerning could be corrosion of the passive reinforcement. Without pre-compression, the concrete will be more prone to cracking and, should any cracks open, corrosion of the passive reinforcement could accelerate. The relationship between crack widths, the rate of corrosion initiation and corrosion rates is not an accurate science, but there is general consensus that crack widths larger than 0.2mm have an impact on the rate of corrosion initiation [27] [28] [29].

Left insitu, the de-stressed pre-stressing system could create a conventional safety hazard with heavy metallic objects at risk of falling if not suitably secured. Corrosion could change the risk profile over time.

Grouting the pre-stressing

Instead of, or in combination with de-stressing the PCPV, the tendons may be grouted so that they become bonded to the concrete and less dependent on the performance of the exposed anchorages.

We would expect grout to be cementitious, mixed, installed and tested in accordance with codes and standards and supplementary guidance, such as that published in Concrete Society TR 72 [14] and *fib* Bulletin 20 [30].

The reliability of retrospectively installed grout would depend on the cleanliness of the tendons and ducts prior to grouting. Any tendon grease or other material that cannot be flushed out of the ducts could compromise the performance. Mock up exercises or trials may be necessary to demonstrate this is possible, achieving an adequate result.

Relative to ungrouted de-stressing, successful grouting with pre-stress will preserve the withstand capacity of the structure, maintain a greater degree of ductility, and maintain a greater degree of crack suppression.

Grout will also provide a level of protection against corrosion. However, adding grout will add to the total material to be disposed of and it would also make separation of the steel tendons and concrete much more onerous (if indeed it is necessary). The latter might not be a major drawback, noting that there will be other steel (the ducts and passive reinforcement) that is also bonded to the concrete and equally hard to separate. If material separation is needed, further mock up trials may be necessary to demonstrate this is possible, achieving an adequate result.

Another common advantage of grout is that it will ordinarily make tendons safe to be cut, meaning they can be cut (using a diamond-encrusted saw or drill – see Section 5.3) along with the concrete, passive reinforcement and metal ducts as part of the PCPV's deconstruction. This could remove the need for a standalone de-stressing operation. However, noting the large size and quantity of tendons and general low level of passive reinforcement, grouted cut segments of PCPV could be susceptible to concrete splitting, initiated by stress concentrations at the cut tendons[19]. We would expect this risk to be checked when deciding whether to pursue grouting. The risk of concrete splitting could be combatted by partially de-stressing the tendons prior to grouting, but this would reduce the benefit of using grout. A different approach could be to add external strapping around the concrete prior to cutting. Alternatively, it may be acceptable and manageable to allow concrete to split during cutting.

Removing the pre-stressing tendons

Removing the pre-stressing tendons (while keeping the PCPV intact) is only possible if they are not grouted, as is the case for UK PCPVs. Assuming they can be removed, a decision on whether and when to remove them should be based on an ALARP assessment.

Removal would need to follow the de-stressing, but would not need to form part of, or follow directly on from, the de-stressing operation. Indeed, it could form part of the PCPV's deconstruction. However, if left too long, it may be that the tendons become so severely corroded that they cannot be pulled from their ducts. It may also be the case that the knowledge and/or equipment to do this operation is lost, recognising that the operation of removing individual tendons is currently an activity undertaken by the licensees at each site periodically as part of the operational EIMT requirements.

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[19] Concrete splitting in this way during demolition may not be problematic.

Leaving the tendons insitu would maintain the mass of the PCPV structure as it has been during operation, while their removal would bring about a mass reduction, reducing the load on the PCPV and its support structures. Analyses of individual PCPVs would need to be performed to show which condition is more favourable for the array of applicable applied loads.

If left insitu, the presence of slack tendons is unlikely to aid but could hamper the deconstruction of the PCPV concrete. We have not found any literature on this topic but note:

- Unlike reinforcement which is spliced at regular intervals and often need not be cut when concrete is broken, tendons are continuous and potentially very long. We would expect they would need to be cut during the concrete's deconstruction if left insitu.
- The tendons are made from steel that is much stronger than the passive reinforcement and ducts, meaning they will be less easy to break or cut.
- Saws and core drills are more prone to snag or struggle to bite when trying to cut through material that is slack, has no rigidity and/or is not firmly held in position (as would be the case for ungrouted, de-stressed tendons).

Deconstruction of the PCPV

The PCPV can be deconstructed once:

- de-stressed (potentially with tendons removed), or
- tendons are grouted, or
- other measures are introduced to safely contain tendons as they are ruptured.

If safety claims remain imposed on the PCPV during its deconstruction, then at all times the structures (including any structures introduced as permanent or temporary works) must be demonstrably capable of achieving these.

Once the deconstruction programme and 'time at risk' are confirmed, it may be possible to redefine the design basis events for certain hazards (e.g. the seismic hazard) based on probabilistic analyses.

We would expect the chosen sequence and technology for the deconstruction to be sympathetic to the evolving withstand capacity of the structure as it is broken down, which will vary depending on whether the structure was fully or partially de-stressed or grouted locking in pre-stress.

5. De-stressing

This section describes the methodologies by which a PCPV may be de-stressed, splitting these into three groups:

- Uncontrolled de-stressing methods
- Controlled de-stressing via reversal of the construction
- Controlled de-stressing via other methods

These are discussed in turn under separate subheadings (Sections 5.1 to 5.3), followed by a section that summarises the foreseeable consequences of de-stressing (Section 5.4).

5.1 Uncontrolled de-stressing

5.1.1 Acceptability and desirability

Uncontrolled de-stressing can be subdivided using acceptability and desirability as two metrics:

- It will be **acceptable** when the process and/or outcome is manageable and does not warrant preventative measures that are deemed more onerous or risky than the de-stressing event.
- It will be **desirable** when leading to a more favourable (e.g. less hazardous) end-state than the start state.

Unacceptable uncontrolled de-stressing, by definition, will be undesirable in terms of instantaneous hazard created and/or impact on the structure's performance Such de-stressing events will typically result from shortcomings in the design, construction or maintenance, omissions or miscalculations in analyses, and/or an extreme scenario (or set of scenarios) outside the design envelope.

The failure of the Ynys-y-Gwas bridge pre-stress that led to the bridge's collapse and the moratorium on post-tensioning (see Section 3.2) is an example of unacceptable uncontrolled de-stressing. In this instance, the failure was due to shortcomings in the grouting during construction.

For PCPVs, the peak design basis demand on the pre-stress reduces post-operation, when the risk of a loss of cooling accident (LOCA) event is removed. This means that there is greater potential (than during operation) for uncontrolled de-stressing mechanisms to be acceptable, while certain mechanisms are expected to remain unacceptable. For example:

- Failure of an anchorage may be unacceptable, leading to a sudden and violent release of the energy stored in multiple strands.
- Failure of individual strands within the ducts may be acceptable provided critical stress limits are maintained, leading to a steady loss of stored energy and concrete precompression. This would be desirable if loss of pre-stress is an objective, but undesirable if pre-stress needs to be maintained.

5.1.2 Management

Managing uncontrolled de-stressing to ensure that it is acceptable will often rely on:

1. Analysis of the structure subject to different incremental permutations of pre-stress, in combination with other coincident loads, to determine the envelope of acceptable pre-stress states.
2. Analysis of the risks to humans and surrounding systems resulting from de-stressing events.
3. Robust monitoring and/or inspection of the de-stressing sustained, necessary to determine the rate and distribution of stress loss.

The third of these is not needed in the rare scenarios when total de-stressing, arrived at via any sequence of individual tendon de-stressing, is permissible.

By definition, unacceptable uncontrolled de-stressing must be prevented. However, it may be possible to change an unacceptable scenario into one that is acceptable, for example:

- The structure can be made more tolerant to stress loss by controlling other coincident loads or adding structural strengthening.
- Humans and surrounding systems can be protected by adding barriers[20] to safely contain tendons when they rupture.

5.1.3 Cause

Industry specific discussion on the causes of system degradation is contained in IAEA document NP-T-3.5 *Ageing management of concrete structures in nuclear power plants* [31].

The single greatest cause of uncontrolled de-stressing is corrosion. Aligned with the two bullet point examples given in 5.1.1, corrosion-induced de-stressing can come about via different modes: corrosion of the strands and corrosion of the anchorages.

While corrosion can be relatively widespread, a wire failure is likely the result of local corrosion due to either pitting, stress corrosion cracking or hydrogen embrittlement.

- Pitting is a local intense loss of section area in otherwise uniform material, often due to a localised concentration of an anion such as chloride.
- Stress corrosion cracking occurs in fractures of normally ductile metals when subject to corrosive environments.
- Hydrogen embrittlement is frequently associated with hydrogen sulphide exposure and occurs when hydrogen atoms enter the metal lattice causing a reduction in ductility.

Other causes of uncontrolled de-stressing are less common. They can include:

- Accidental damage to a strand or anchorage, e.g. caused by impact or severing.
- Strand and/or anchorage embrittlement, including irradiation and fatigue.
- Severe loading causing plastic extension, followed by relaxation when the loading recedes.
- Severe elevated thermal exposure (e.g. fire), leading to softening and elongation of the strand.
- Elevated thermal exposure impacting the microstructure of previously heat-treated and drawn metals.
- Mismanagement (erroneous prediction and/or poor execution) of controlled de-stressing.
- Loss of integrity of the concrete (e.g. due to fire- or corrosion-induced spalling).

Irradiation can both strengthen and reduce ductility of pre-stressing steels and the overall effect is impacted by thermal exposure.

5.1.4 Measures to increase control and predictability of corrosion

Corrosion can be accelerated or decelerated and, in the context of decommissioning, either of these may be viewed as desirable. Corrosion control can be achieved via barriers (e.g. oils, greases), humidity control, chemicals/catalysts (e.g. anodic metals, alkalis, acids and salt solutions), and with use of electric currents.

It is highly unlikely that individual tendons in PCPVs are electrically isolated from one another; instead, we would expect there to be conduction paths inside the concrete via reinforcement, tie wires and other miscellaneous metal that was used to hold the ducts in position during concreting[21]. As a consequence of this, it is unlikely to be possible to use currents to accelerate and decelerate corrosion of specific tendons in isolation to the point that corrosion could be used as a highly tuneable controlled de-stressing technique. It may, however, be tuneable to the point that groups of tendons can be forced to corrode at different rates.

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[20] Barriers to withstand the energy from the large tendons used in PCPVs would need to be substantial structures.

[21] Intentionally electrically isolated tendons (EIT) are a relatively new development, pioneered to improve tendon monitoring using electromagnetic non-destructive techniques.

5.1.5 PfCs

The following summarise the PfCs associated with uncontrolled de-stressing:

Un-controlled destressing	
PfC 5.1	We would expect the causes and likelihoods of uncontrolled de-stressing to be identified and managed, including any contributing factors which could accelerate or decelerate corrosion.
PfC 5.2	Any uncontrolled de-stressing mechanism that is deemed unacceptable must be prevented, or else other measures introduced to make the de-stressing mechanism acceptable.
PfC 5.3	In order to define an uncontrolled de-stressing mechanism as acceptable, we would expect it to be underpinned by sufficient evidence that defines the envelope for acceptability and sets the monitoring and recourse to ensure this envelope is not breached.

5.2 Controlled de-stressing via reversal of the construction sequence

Controlled de-stressing via reversal of the construction sequence is to perform the same (or similar) operations that were used to stress the tendons, but in reverse. The major steps for the types of tendons and anchorages used at Oldbury[22] would be:

1. Remove any protective covers from the strand tails and anchorages.
2. Attach a multi-strand stressing jack to the protruding strand tails. Mark at-least one strand, typically with paint, to show extension of the strand under load.
3. Apply the jacking force until the anchor head is no longer in contact with the anchor body.
4. Release the conical wedges around each strand from the anchorage head. This may require hammering to dislodge the wedges.
5. Progressively release the load in the multi-strand jack until the strands are unloaded (at which point the paint marks on the strand should have been drawn into the duct). During jack release it would be useful to measure the amount that the strand pulls in for comparison with original records of strand extension (if available). This will confirm that there is no unrecorded residual tension in the strand (perhaps due to the strand being locked/snagged at some remote location in the duct).
6. Remove the muti-strand jack and move to the next anchorage.
7. Repeat steps 1 to 5 following a premeditated de-stressing plan, most likely needing to work across all the tendon groups to avoid intermediate stages with out-of-balance pre-stress.

Where viable, reversing the construction process will often be the simplest method for de-stressing and we anticipate it being the preferred approach – potentially the only approach seriously considered – for PCPVs in the UK.

Note that, there could potentially be greater freedom in the de-stressing operation than there was in the stressing operation as it is not necessary for the PCPV to maintain operational viability. For example, where the original stressing operation may have been required to work within limited space, the de-stressing could include a prior phase of demolition of surrounding structures.

5.2.1 Viability

The viability of this method, using current technology, is dependent on certain attributes of the structure:

- For systems with wedge anchors, such as those used at Oldbury and Wylfa, tendons need to have been left with projecting strand tails long enough to be gripped, otherwise jacking is not viable. A tail length of approximately 1m is needed for standard jacks. If the projecting tail is less than this, a custom-

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[22] The type of tendons and anchorages used at Oldbury are the most conventional.

designed jack may be useable, or else it may be possible to splice the strand tails to make them longer. However, if the strands have been cut off flush with the ends of the conical wedges (which is considered normal in other sectors such as bridges and buildings), then attaching a multi-strand jack is unlikely to be feasible and an alternative de-stressing approach would need to be pursued.

The PCPVs with this type of anchor that we are aware of all have sufficient length of projecting strand tails for jacking to be feasible, and we anticipate the same being true of other PCPVs noting the requirement in BS 4975 for tendons to be able to be restressed and/or replaced.

- The anchorage must not be fused (with release force greater than the tendon tail breaking strength), and the tendon tail must not be severely weakened as a result of corrosion; otherwise a tendon breakage within the length of the tail could occur when jacked.

- Suitable jacks need to be available to be deployed. We understand that some power plants retained their original stressing jacks and these may still be serviceable (or capable of being refurbished) for the de-stressing operation.

  Where existing jacks are not available, new or repurposed ones would need to be arranged. The development of stressing technology has continued throughout the time that the reactors have been in service and so currently available jacks are unlikely to fit the older anchorages. Nonetheless, many of the pre-stressing companies operating today are the same as, or successors to the ones that supplied the construction of PCPVs, and it is expected that they are likely to be able to adapt or custom-manufacture equipment to fit the older patterns.

- There needs to be enough space around the stressing anchorage to accommodate the jack and the equipment required to lift it into place. Typically, multi-strand jacks are approximately 1m diameter and 1.5 to 2m long and weigh of the order of 1,000kg.

  Custom-designed jacks, as used for stressing the vertical tendons during the construction of Dungeness due to geometric constraints beneath the PCPV[23], may be smaller but this will likely result in a shorter stroke length.

  If the gallery that houses the anchorages had additional walls, slabs, ducts or pipework added after the tendons were stressed, these may obstruct access for the jacks and may need to be removed or relocated to give unfettered access for jacking.

- Historic space and/or access provisions within the stressing gallery may not be sufficient to satisfy current health and safety practices and regulations. We would expect each worksite be re-evaluated to ascertain whether the proposed methodology can facilitate works in accordance with current CDM Regulations.

  Undertaking the works safely may require temporary working platforms, traditional lifting equipment and/or other machinery/robotics (see Section 7). Alternatively, it may now (or in the future) be possible and favourable to carry out activities using autonomous or remotely operated machines that reduce or eliminate the need for operatives to undertake hazardous work – see Section 7.

5.2.2 Tendon breakage

The process of re-applying tension to old tendons (which is necessary to release the anchorages) can cause breakage of wires, strands or tendons, either within the length of the tail (between the anchorage head and the body of the jack), or within the duct. The risk of a breakage will ordinarily increase with level of corrosion, meaning a de-stressing solution that is currently viable/safe could become unviable/unsafe at a future time. This could be a major concern were de-stressing to be delayed until the latter stages of a lengthy care and maintenance period. However, even relatively limited exposure and corrosion has been known to cause embrittlement of certain pre-stressing strands. The risk of embrittlement is linked to the strand’s manufacture: cold or hard drawn strands are less susceptible than heat treated strands.

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[23] We understand the original design intention for Dungeness was to stress the vertical tendons from above the top cap but, owing to conflicting site operations, a decision was made to stress from below.

Any breakage will cause the release of built-up strain energy. Breakages of individual wires will often go almost unnoticed[24] and breakages of strands will often self-stabilise as a result of friction and strand entanglement within the ducts. However, a breakage of an entire tendon (possibly after successive non-critical strand breaks that each add force to the unbroken strands) would be explosive, causing the tendon and jack to become missiles that will likely cause significant damage or harm to anything or any person they strike. Whether a ruptured tendon will completely exit its duct (from either or both ends) or not will depend on the location of the break, the lengths of the two severed sections of tendon, and the energy dissipation mechanisms (e.g. friction within the duct).

The target when installing multi-strand cables is to ensure the strands do not cross one another, and that they are located in the same relative position through the anchorage at each end. However, it is not uncommon that this is not achieved. For this reason, normal practice is for all strands sharing a single duct to be stressed / de-stressed simultaneously.

5.2.3 PfCs

The following summarise the PfCs associated with de-stressing via reversal of the construction:

De-stressing via reversal of the construction	
PfC 5.4	Should de-stressing via reversal of the construction be proposed/pursued, we would expect the impact of corrosion on the method’s current and future viability to be taken into consideration.
PfC 5.5	We would expect the sequence of de-stressing to be planned, cognisant of the impacts of the sequence on the structure (e.g. the levels of asymmetric stress and/or cracking sustained)

5.3 Other controlled de-stressing methods

There are several alternative techniques for initiating and/or carrying out controlled de-stressing.

Many of these incur some level of damage to the concrete, creating planes of weakness and generating particulate dust and/or concrete slurry (the latter being formed when using water for cooling). These waste products can add significantly to the volume of contaminated unbound material needing capture, treatment and/or storage. Drilling or cutting through the anchorages or tendons will also generate a relatively small volume of metal swarf.

With unbonded tendons, each of these methods is potentially explosive causing a sudden release of elastic strain energy that can result in tendons, anchorages, and/or fragments of concrete becoming missiles. This is extremely hazardous for operatives, with these missiles also likely to damage any SSCs impacted.

Barriers can be used to contain missiles, controlling the hazard they present.

In theory, targeted grouting could be used to prevent missiles from forming, while still allowing de-stressing. There are, however, no known precedents for this and it is difficult to envisage how it would be implemented. (In contrast, full grouting is more common and proven, but this removes the opportunity to de-stress the structure. Therefore, while it may be a valid - and even favoured - solution, it is not a method for enabling de-stressing.).

The level of control varies across the methods listed and we would expect any unpredictability associated with any lack of control to be identified and managed via a risk-based management plan.

De-stressing via other controlled methods	
PfC 5.6	We would expect that the consequences of explosive releases of stain energy as tendons are severed, and any consequences, to be mitigated via practical controls.

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[24] Detectable via acoustic instrumentation but not otherwise apparent.

PfC 5.7	For options that involve drilling, cutting or splitting the concrete, we would expect the maximum acceptable depth of through-thickness fissure through the PCPV to be determined.
PfC 5.8	For options that create concrete dust or slurry (e.g. drilling, cutting or splitting), we would expect appropriate measures to be developed and implemented that capture, store and/or process the dust and or slurry.
PfC 5.9	*(Same as 5.5)* We would expect the sequence of de-stressing to be planned, cognisant of the level of asymmetric stress that can be sustained.

5.3.1 Drilling

Drilling techniques are well developed and used extensively when reversal of the construction sequence is not feasible. There are two approaches to drilling:

- Drilling through the concrete, approximately perpendicular to the pre-stressed strand to intersect and sever the strand.
- Drilling through the anchorage to induce a fracture and initiate failure of the anchorage.

In situations where the pre-stress duct runs generally parallel to a surface, as is common in PCPVs, it is relatively easy to use a diamond-tipped core cutter to drill through pre-stress strands. However, this drilling becomes progressively more costly in time and volume of drilling waste (kerf) with depth of hole needed and is therefore not ideal for large wall thicknesses.

Drilling concrete generates relatively low volumes of concrete dust or slurry (if the core is water cooled). The drilled holes could be retrospectively grouted if it is deemed `necessary to reinstate the full bioshield thickness.

Depending on the drill bit and rig controls, a drilling operation could aim to cut one strand at a time or a whole tendon. As each strand is cut into, a point is reached where the stress in the strand reaches its yield and strand failure occurs, releasing any residual strain energy that the strand is carrying.

5.3.2 Combined concrete and tendon cutting

There is a family of techniques for cutting reinforced and pre-stressed concrete that cut through the through-thickness of the structure. Such techniques will simultaneously de-stress and deconstruct an ungrouted PCPV, or else deconstruct a grouted PCPV while maintaining locked-in stresses.

5.3.2.1 Circular saw cutting

Saw cutting using circular saws has become an established technique for dismantling structures. Circular saw cuts work best when there is a large planar area that needs to be sub divided for disposal. The blades commonly available can be up to 3m in diameter which limits the maximum cut depth to around 1.0 to 1.3m. Larger blades are logistically problematic, being difficult to transport and manoeuvre. The larger saws available tend to be mounted on hydraulic arms that give a high degree of control over orientation of the cut.

Saw cutting concrete generates dust and also heat from friction on the cutting blade. Water is normally used to suppress the dust and simultaneously cool to the blade.

While the practical limits on saw blades may mean this technique cannot be used to through the full thickness of PCPVs, circular saws can be used effectively to cut partially through the thickness meaning it may be possible to cut only to the depth needed to intersect the pre-stressing tendons. This can preserve leak tightness, reduce the amount of dust being generated from the most highly irradiated concrete, and prevent cooling water entering the PCPV during cutting. However, it will inevitably create a plane of weakness simultaneously cutting through any unstressed reinforcement along the cutting path.

Damage to the PCPV’s integrity may be able to be limited, while still achieving de-stressing, if cuts can be positioned within projecting anchor blocks.

5.3.2.2 Wire saw cutting

Wire saws use a steel cable encrusted with industrial diamond dust. The technique involves pulling the wire through a series of pulleys that place the wire in contact with the element to be cut and the pulleys are advanced such that the wire is progressively moved through the element under tension, cutting as it goes.

One of the common uses of wire saws in industry is in dismantling of ships, where the saw can be used to literally slice a ship up into more manageable pieces for further dismantling.

Unlike circular saws, the depth of cut achievable with wire saws is not limited by the blade diameter and, therefore, is also less directly restricted by the space provisions. However, wire saws work best when cutting through an element's entire through-thickness, and when the element being cut can be accessed from both sides allowing the wire to be set up. Because of these limitations, we envisage wire cutting to be more suited to PVPC deconstruction than de-stressing alone.

At the current time, wire saws typically require the set up to be completed by operatives handling the wire but, once set, cuts can be remotely controlled.

Similar to saw cutting, wire cutting generates dust and also heat from friction. In normal circumstances no cooling is used, but the heat build-up needs to be assessed on a case by case basis.

5.3.2.3 High pressure water cutting

High pressure water jetting has become a common technique for the removal of concrete from around reinforcement – a technique referred to as 'hydro demolition'. Typically, the water pressure used to demolish concrete in this way is between 2000psi and 5000psi. At these pressures concrete is disrupted but steel is only mildly ablated, meaning this method could be used to expose the ducts in order for duct and tendon to be cut using another cutting technique.

At higher pressures, even steel can be cut and it is theoretically possible that a high pressure water jet could be used to expose and cut the pre-stressing strand and/or cut the anchorages.

Water jets can be mounted on robotic arms for remote control and to increase precision. There is recent precedent for this in the shipbuilding/demolition industry.

Water jetting generates very high volumes of waste water, many times the volume of the concrete being cut. This waste water has high fines content and is highly alkaline.

5.3.2.4 Thermic lance or other heat based methods

Thermic lances generate very high temperatures (3800° C to 4400° C), capable of cutting steel and concrete in a localised and therefore controllable way.

A thermic lance is effectively an iron tube approximately 3m in length filled with iron-aluminium alloy rods leaving gaps through which oxygen is forced under pressure. When ignited, typically using a welding torch, the iron is oxidised (combusted) at the tip of the lance generating a molten iron slag which is driven out by the pressure of the oxygen supply. The iron rods and tube burned to form the slag are consumed, so the residual waste from the cutting process includes the volume of the rods.

Similar to water jets, a thermic lance can be mounted on robotic arms for remote control and to increase precision. It could be used to expose and cut the pre-stressing strand and/or cut the anchorages.

Being a very high temperature process, thermic lances will tend to produce a large volume of gaseous effluvia which is potentially contaminated, and which must be properly captured by the ventilation system and either treated or stored in some way.

5.3.3 Pressure bursting

Pressure bursting is a term used to cover methods where the concrete is disrupted or fragmented. As a by-product, any stressed post-tensioning in the concrete will be de-stressed by the fragmentation process.

5.3.3.1 Hydraulic splitters

This technique introduces hydraulically controlled wedges into pre-drilled holes. Applying hydraulic pressure expands the wedges causing splitting of the concrete around the hole.

5.3.3.2 Expansive chemicals

With this method holes are drilled into the concrete sections into which the expansive material as a liquid is introduced. Typically, this slurry initiates an expansive chemical reaction during setting and once complete (usually within 24 hours) the concrete mass around the hole has been subjected to a pressure which is sufficient to crack the concrete.

5.3.3.3 Issues to be considered when using bursting methods

These methods take advantage of concrete's low tensile strength and work best in lightly reinforced concrete. In heavily reinforced sections it is possible that the pressure applied by the expansion method (typically about 30MPa) may not be sufficient to overcome the resistance of the reinforcement. PCPVs are generally lightly reinforced, but the zones around the pre-stress anchorages – where such a method may be targeted – tend to be more heavily reinforced with reinforcement purposefully arranged to prevent concrete splitting [32].

When using a chemical in liquid form it is best if the holes drilled are inclined downward rather than horizontal or inclined upward. Where the latter is unavoidable, capsules can be used to contain the liquid.

The control that can be achieved with expansive methods is less acute than other cutting and drilling methods. The placement, spacing and quantity of holes for chemicals or wedges allows the level of control to be tailored, however there will be a trade-off between the number of holes created and the reliability with which the desired outcome is achieved. We would expect a licensee to carry out research to determine an optimum hole pattern and spacing.

5.3.4 Explosives

Although a number of references [33] refer to the use of explosives for demolition of reactor containment structures, we assume that such methods are not suitable in the UK context and have not considered these further.

5.3.5 Use of demolition robots

Demolition robots come in various forms, most relying on hydraulic power driving a hardened metal hammer breaker or shears. Use of such a robot could relieve pre-stress by damaging the concrete. This is a common technique used in bridge demolition.

5.4 Consequences of de-stressing and grouting

The previous sections identify several consequences of de-stressing and grouting. These are summarised here.

During de-stressing

- (Dependent on de-stressing methodology) increased risk of explosive (hazardous) tendon failure, leading to:
    - increased risk of injury for operatives.
    - increased risk of damage to surrounding SSCs.
- (Dependent on de-stressing methodology) release of concrete dust, concrete slurry and/or metal swarf.
- Increased risk that the de-stressing method fails (e.g. if the projecting tendon tails fail during jacking).
- Increased risk of crack initiation, including:
    - uncontrolled cracking (where minimum reinforcement is not provided)

- Interim stress states, most likely including some degree of stress asymmetry.

Once fully de-stressed

- Reduced risk of uncontrolled consequences of corrosion, including:
  - elimination of the risk of explosive tendon failure.
- Removed concrete precompression, leading to:
  - reduced ultimate shear resistances.
  - potential stress reversals (relative to stresses during construction, manifesting from creep sustained under pre-stress).
  - greater likelihood of cracks across the concrete:
    - increasing risk of corrosion to embedded reinforcement.
    - reducing radioactive shielding.
    - reducing structural stiffness.
    - modifying the dynamic response.
- Reduced tensile capacity (due to removal of active steel), leading to:
  - reduced ultimate flexural and pure tension resistances.
- Potentially weakened planes in in the structure if cutting methods were used for the de-stressing.
- Increased susceptibility to cliff-edge failure, especially if less than minimum reinforcement.

Consequences of de-stressing	
PfC 5.10	We would expect the licensee to identify and evaluate the relevant consequences of de-stressing.
PfC 5.11	We would expect the locked in energy associated with pre-stressing to be viewed as a hazard, and managed via a risk-based hierarchical management approach (e.g. eliminate, reduce, isolate, control)

Grouting

Grouting the pre-stressing tendons has been identified in previous sections as an alternative to de-stressing. The consequences of grouting are:

- Addition of new material, impacting the mass and volume of eventual waste.
- Risk that the grout has voids and/or has been ineffective.
- Loss of ability to re-tension or de-stress the tendons.
- Stabilises the structure in the existing stress state, including crack suppression.
- Protection of tendons within ducts against ongoing corrosion.
- Removed dependency on the exposed tendon anchors and tails to remain serviceable.
- Significantly reduced risk of explosive tendon failure and the associated consequences.
- Allows/restricts the PCPV concrete to being cut or broken down while remaining under pre-stress.

Consequences of grouting	
PfC 5.12	As part of the overall post-operational / decommissioning plan for the PCPV, we would expect the licensee to compare the risks and merits of grouting (to lock in pre-stress) against the alternative viable de-stressing method(s).

6. Structural monitoring

Monitoring is a widely used term that is similar to EIMT. It is synonymous with examination, inspection, and testing and a common precursor for non-scheduled maintenance.

Structural monitoring can be extremely useful to verify and/or calibrate analyses. It can also be used to forewarn of scenarios that have not been investigated within the analytical programme. However, care is needed not to place too great a reliance on monitoring and/or provide redundancy in the monitoring system, being wary that false readings and instrumentation malfunctions can occur.

Monitoring is also only as reliable as the procedures that are in place to process and react to the data collected. Heathrow (1994) [34] and Gerrards Cross (2005) tunnel collapses are two examples where structural monitoring was in place but the chain of decision making it should have informed did not prevent failures occurring.

Structural monitoring	
PfC 6.1	We would expect continuous and/or periodic monitoring to form part of the post-operational management.
PfC 6.2	We would expect the methods by which any monitoring data will be interpreted to be determined as part of the arrangements, to ensure the adequacy and usefulness of the monitoring.
PfC 6.3	We would expect all aspects of the arrangements to be determined and tested for their reliability, to ensure the monitoring (including any chain of events that the monitoring data trigger) fulfils the intended purpose, i.e. to provide confidence in and/or a control on the structural performance.
PfC 6.4	We would expect the requirements for monitoring to be cognisant of any changes in the post-operational phase, and to be adapted as appropriate. Changes may include changes to the PCPV structure, the environmental conditions and loading it is exposed to, the safety claims and withstand requirements, etc).

6.1 Metrics to monitor

It is important that those physical characteristics that are monitored yield a manageable quantum of useful information, explored further herein:

6.1.1 Usefulness

The usefulness of the information will typically depend on:

- The forewarning or delay between the measurable response(s) being recorded and a critical failure event occurring, which is dependent on:
  - The correlation between the failure sequence and measurable response(s).
  - The availability of baseline data.
  - The abruptness of a critical failure and relevance of trend data.
  - The instrumentation (precision, recording frequency, etc).
  - The time to post-process
- The reliability that a measurable response is associated with a defect and not an innocuous cause:
  - The combining of coincident metrics (e.g. temperature and strain) may help improve this, but increases the post processing and will alter the error profile.
  - The degrees of separation between the characteristic measured and the characteristic defining failure reduces reliability. (e.g. if release of radioactivity is a failure criterion, measuring radioactive activity

    on the outside of PCPV has fewer degrees of separation than measuring concrete strain as proxy for crack monitoring and structure permeability),

- The instrumentation:
  - The coverage of the monitoring relative to the potential sources of initiating events / defects.
  - The precision and frequency of readings.
  - The amplitude of noise / routine fluctuations relative to the amplitude of concerning triggers.
  - The availability, maintenance and calibration of equipment required.
- The statistical reliability of the structural response and failure criterion, including:
  - The reliability of the analyses used to determine the metrics that define the measurable failure criterion / criteria.
  - The correlation between variability in measurable variables and variability in variables that govern failure.

These statements are not specific to pre-stressing, concrete or PCPVs.

6.1.2 Metrics

Metrics of relevance to PCPVs that could realistically be measured include:

- Insitu atmospheric conditions:
  - Temperature
  - Relative humidity
- Insitu concrete external surface measurements:
  - Positions in space (to determine absolute movements and relative deformations)
  - Local strains
  - Discrete crack widths
  - Surface temperature and moisture content
- Insitu concrete through-thickness monitoring:
  - Strains (via embedded strain gauges)
  - Temperature and moisture (via embedded thermometers and moisture meters)
  - Presence of contaminates (e.g. chlorides) and radiation
- Insitu tendon and anchorage monitoring:
  - Acoustic (for wire breaks and stress changes)
  - Stress checks (via jacks, provided the tendons are ungrouted)
  - Corrosion of tails and anchorages (via visual checks)
- Non-insitu tendon and anchorage monitoring (requiring tendon/anchor removal):
  - Corrosion
  - Strength and brittleness testing
- Non-insitu concrete monitoring (requiring material samples):
  - Strength testing (via concrete coring and load testing)
  - Stiffness testing (via concrete coring and load testing)
  - Laboratory testing for constituent chemicals

We have excluded from this list more challenging insitu testing, such as exposing a length of tendon (while under stress) to attach a strain gauge. While technically plausible, this is one of many monitoring techniques that is theoretically and potentially useful but less likely to be justifiable or viable in practice. In the context of PCPVs, any localised intrusive test would need to be quite extensively implemented to give data that is statistically representative of the large volume of concrete and/or large number of tendons.

6.1.3 Non-destructive testing

When an existing structure needs to maintain a function throughout a course of monitoring and testing, it is generally preferrable to adopt non-destructive testing (NDT) methods that have no direct impact on a structure's condition. Table 2 lists families of NDT methods, stating the principles of use, common applications and associated technologies and techniques. All of these are well established, with detailed guidance on the applicability of each method in IAEA NP-T-3.5 [31] and CIRIA C798 [35].

The capabilities of these techniques to 'see through' concrete from an instrumentation stand-off distance is presented graphically in Figure 10. Note, however, that none of the techniques reported can see through steel meaning that they would not be able to survey tendons within steel ducts. This will significantly limit their application to PCPVs. Equivalent NDT methods for inspecting materials within the steel ducts are likely to require endoscopic equipment inserted into the ducts..

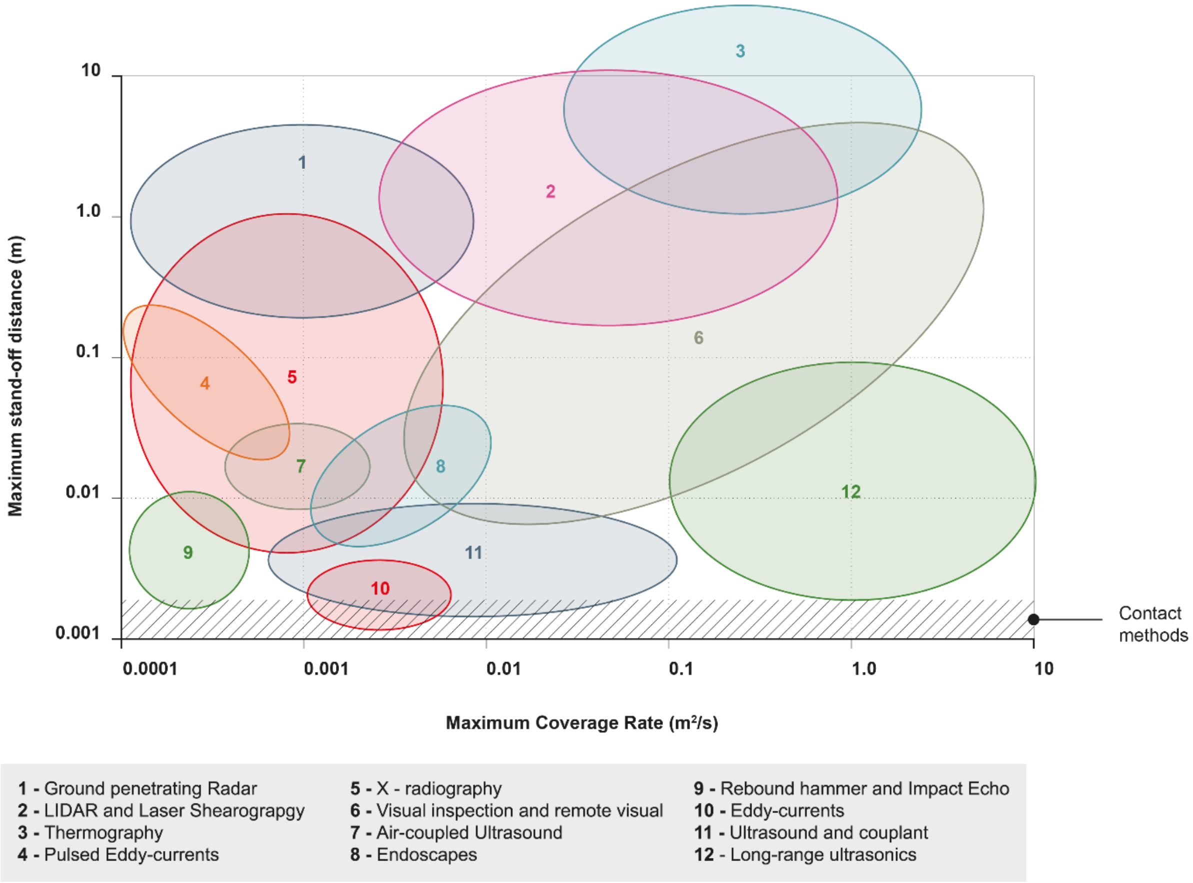

Figure 10: Representation of the typical range of instrumentation stand-off distances and rates of coverage for a variety of NDT inspection methods

Among the techniques listed in Table 2, load testing has the potential to be non-destructive or destructive. Care is therefore needed not to cause damage that cannot be managed. *fib* Bulletin 17 [36] defines three sub-categories of load tests:

- Acceptance testing
- Proof testing
- Testing aimed at investigating structural behaviour

The first two are not dissimilar: acceptance testing being to confirm behaviour under a prescribed condition and proof testing being a check of the withstand capacity. Both are quite simple in nature, but both can risk a structural failure if it is not guaranteed that the pass criterion will be achieved. By contrast, the third test type can be undertaken with greater margin to failure, but is less prescriptive and yields less definitive results, requiring greater planning, interpretation, and uncertainty management.

Load tests can fulfil more than one of the three sub-categories simultaneously. For example, the load tests undertaken to comply with PSSR will be acceptance tests but, with adequate instrumentation, might also provide useful insights into the structural behaviour.

Table 2. Non-destructive testing methods

NDT Family	Principle	Applications	Technologies
Visual/ Optical	Imaging or taking measurements by utilising filtering, distortion or other manipulation of the visible light spectrum	Inspection of exposed and/or accessible surfaces. Detection of varying scale flaws, down to microscopic details.	- Borescopes/ endoscopes - Liquid penetrant inspection - Fibre optic strain measurement - Laser scanning
Physical	Measuring various physical properties of structures	Determination of various material and/or system characteristics, such as hardness and distortion.	- Hardness tests - In situ stress and strain measurements - Load testing
Thermal	Analysis of infrared emission from a structure.	To indicate surface and/or internal variations in materials or construction.	- Passive thermography - Active thermography
Acoustic	Use of sound waves to detect variations in structure.	By using a controlled impact, this can detect subsurface cracks, voids, delamination, lack of bonding and changes in stiffness, density and microstructure. Continuous monitoring for uncontrolled sounds can detect changes in condition (e.g. cable breaks).	- Hammer/ coin tapping - Impact echo - Acoustic emission
Electromagnetic	Measurement of the effects arising from the interaction of electricity and magnetism.	Information about substructure interfaces and construction features including flaw detection, material characterisation and dimensional measurement	- Cover meter testing - Eddy Current measurement - Ground penetrating radar - Alternating current field measurement
Ultrasonic	Measurements are made as the ultrasound is transmitted, scattered and reflected by variations and irregularities in the material.	Information about substructure interfaces and construction features including flaw detection, material characterisation and dimensional measurement	- Pulse echo - Ultrasonic pulse velocity - Ultrasonic tomography - Guided wave ultrasonics
Electrochemical	Interactions between electrical and chemical effects. Good for assessing corrosion in reinforced concrete.	Systems can provide a way of surveying reinforced concrete elements at risk of corrosion and can give an indication of its potential rate.	- Resistivity - Half – cell measurements - Linear polarisation resistance - Electrical resistance Probes - Electrochemical noise
Radiation	Interaction between the structure and various types of radiation part of the EM spectrum.	Material thickness and density changes are visible.	- X-ray radiography - Gamma-ray radiography - Muon imaging - Neutron radiography

6.1.4 Destructive testing

It may be possible and valuable to carry out a limited amount of destructive (or intrusive) testing without jeopardising the overall structural integrity or performance. Such testing might include:

- Extracting concrete cylindrical cores for strength and/or stiffness testing.
- Extracting dust (from pilot holes) for contamination (e.g. chlorides) tests, to assess the risk of reinforcement corrosion.
- Extracting concrete samples for laboratory testing for common deterioration mechanisms such as alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).
- Extracting individual tendons and anchors for inspection, strength and brittleness testing.

Given the scale of the PCPV structures, each of the above should be possible for a limited number of samples with negligible impact on the overall performance of the PCPV.

Extracting individual tendons could also prove or disprove the viability of controlled de-stressing via reversal of the construction (see Section 5.2).

Many of these tests are standardised and we would expect the relevant British, European or international standard to be followed.

6.2 Provision of monitoring equipment

6.2.1 Existing provisions

BS 4975 states that "*Monitoring and periodic inspection of a PCPV shall be undertaken from the installation of pre-stressing and continued throughout its working life*."

While existing monitoring may be worthwhile to continue through the post-operational phase, we would not recommend that it is simply assumed to be adequate or even useful without a review undertaken.

Where monitoring equipment is relatively dispensable, the requirements for monitoring and instrumentation can be determined first. The usefulness/adequacy of any existing provisions can then be assessed against these requirements and a 'gap analysis' completed to determine the limitations.

However, where existing instrumentation is installed/embedded in places that would not be convenient to install, it will often be appropriate to put more emphasis on determining how it can be used most usefully. We would not expect instrumentation that is performing reliably, that cannot be readily replaced, to be decommissioned without reasonable confidence that it will not be required at any stage in the future.

6.2.2 New provisions

We would expect new monitoring provisions to be devised and implemented to meet monitoring needs that are not satisfied by existing systems.

6.3 Baseline data and trigger levels

Most monitoring is only useful when comparable to baseline data and trigger levels.

Trigger levels may be based on different interpretations of data. However, three of the most relevant for post-operational management of a PCPV will be:

- absolute values (e.g. a stress or strain limit).
- change in values relative a datum (e.g. change in stress or strain)
- time dependent relative measures (e.g. rate of change in stress or strain, with respect to time).

The first of these is likely the most informative, but also the hardest to measure accurately and, depending on monitoring records, may be impossible to obtain. Accepting practical limitations, the latter two are often utilised especially when managing changes to existing structures.

6.4 Code requirements

The most directly relevant code requirements for monitoring PCPVs are those listed in BS 4975. Clause 9.4.1 prescribes the following minimum surveillance:

a. Tendon load checks to measure residual force at the anchorage.
b. Tendon anchorage examinations to detect signs of deterioration.
c. Tendon corrosion examinations to detect signs of deterioration.
d. Concrete surface examinations to monitor and assess the significance of any cracking and the general condition of concrete.
e. Foundation settlement surveys.

BS 4975 also recommends the following:

f. Survey of readings of vibrating wire strain gauge embedded in the concrete and their correlation with theoretical predictions
g. Survey of vessel concrete and liner temperature readings and their compliance with the operating rules for the vessel
h. Main reactor coolant leakage summaries
i. PCPV deflection surveys
j. A review of operating history for the period under consideration

With reference to (a) to (j) above:

- (j) is important, if available, for informing any detailed staged analyses of the reactor load history.
- (a) to (i) can be relevant post end of energy production, throughout defueling, prior to de-stressing, however:
  - (h) may become irrelevant once the cooling system is decommissioned, although historical records of leaks could be useful information when reviewing tendon corrosion risks.
  - (f) is only possible using embedded sensors that may or may not be functioning. If not functioning, externally mounted strain gauges could be fitted but these will give non-comparable readings.
  - (g) should produce output demonstrating a declining temperature, departing from the baseline operational state.
- As the PCPV cools and/or external environment condition changes, inspections (b), (c) and (d) may need to increase in frequency. (i) may also return results that depart from the baseline operational state.
- (a), (b) and (c) only apply while there are tendons insitu. After de-stressing, inspection (a) would become irrelevant, while (b) and (c) would only be required for conventional health and safety (to safeguard against these items falling).
- (d) would be more significant after de-stressing, especially during and in the short term.

Beyond BS 4975, other relevant codes and standards include EN 13445-5 [37], PD 5500 [38] and ASME BPVC [39].

7. Machines and robots in construction

While it is common outside civil engineering to differentiate robots and machines based on the degree of intelligence and/or autonomy, the boundary is blurred and is best not deliberated on within this context.

Machines have been a part of manufacturing, construction and demolition since the industrial revolution, with almost continuous evolution in their design and application. In recent decades, even the most traditional machines have become increasingly digitised with varying levels of pre-programming and real-time control (from full autonomation, through autonomous- and user-overrides, to full manual control). An everyday example is a crane that will not operate if overloaded.

The use of machines in civil engineering has been driven by various factors including:

- Reducing or removing human activities from hazardous environments
- Increasing physical ability (e.g. power, force, speed, etc)
- Reducing variability and/or error
- Reducing cost.

Alongside incremental evolution, there have been various step changes in the development and/or deployment of machines driven and/or made possible by: the needs arising from new applications, new legislation (e.g. CDM Regulations), digital, sensing, control and data-logging technologies, and power-source (e.g. battery) technologies. Some of the development has been led in the nuclear sector [40] [41].

Revolutionary deployments of machines can also come about via new combinations of existing established technologies [44].

Applications and viability

While it seems desirable to identify specific applications best suited to robots/machines, the reality is that they could be used in almost any physical on site or laboratory task relevant to the post-operational management of a PCPV.

Based on the current technology readiness for machines, and the timeframes for UK plant decommissioning, we consider it appropriate that machines are considered for any of monitoring, de-stressing and/or deconstruction operation relating to PCPV structures. Their application will always come with some cost and/or performance differential relative more manual methods and a comparative judgement would be needed to ascertain the favoured approach.

The development and application of customised machines will often be more viable when used for repetitive tasks. It may therefore be that an EIMT ‘sampling’ operation during the care and maintenance period might not justify a machine, but the same operation needing to be extensively repeated during decommissioning may do. In an alternative instance, conventional safety requirements might make it prohibitive to carry out an operation with anything other than an autonomous or remotely controlled machine (e.g. works inside the PCPV), in which case a machine becomes more intrinsic to the viability of an option and the decision on using it is less about relative performance and, instead, more binary.

Where a matter relating to the management of the PCPV is irreversible (e.g. corrosion of pre-stressing tendon tails, leading to the loss of ability to use jacks to de-stress tendons), we would not expect corresponding aspects of the decommissioning plan/strategy to be reliant on unproven future capabilities of machines without reasonable quantification and comparison of risks. Put another way, at no time would we expect the decommissioning to become conditional on uncertain technological developments.

The effect of radioactivity and concrete shielding on electronics and electromagnetic signals is outside the scope of civil engineering, but crucial to the deployment of machines inside the PCPV.

Safety claims

When being considered for an application, we would expect robots/machines to be treated as other SSCs, with appropriate safety claims and quality control arrangements assigned to them, based on their application and the associated dependencies. There is existing precedent for this safety management of machines within civil engineering (e.g. the management of gantry cranes).

Machines and robots	
PfC 7.1	We would expect the opportunities for using remote machines/robots to be considered.
PfC 7.2	Should machines/robots be deployed, we would expect the performance, control and/or fail-safe requirements to be defined to ensure all aspects of safety are controlled.

8. Conventional health and safety

It is the licensee's duty under CDM2015 to consider the whole life of the PCPV to final deconstruction when making decisions about the forward strategy, reducing risks at all stages to meet the requirement of ALARP in line with TAG 05.

Some key hazards associated with the foreseeable post-operational activities and stages include:

- Release of stored elastic energy, occurring when a stressed tendon or anchor fails.
- Drop from height of an object of significant mass. Such objects might include:
  - an anchor or part of an anchor
  - a length of de-stressed tendon
  - a block of cracked/spalled concrete
  - a machine or piece of equipment (e.g. a destressing jack or monitoring instrument).
- Work at height or in confined spaces (e.g. while accessing tendon anchorages up the walls of the PCPVs)
- Inhalation of dust (e.g. produced during drilling or sawing, or disturbed during an inspection)
- Hazards associated with machinery, including:
  - Release of high pressure gas or fluid (e.g. from a hydraulic jack, pressurised grout system or hydro demolition)
  - Muscular strains
  - Electrocution
  - Tissue injuries (e.g. from cutting blades)
  - Vibration

    Noise

The risk of these hazards occurring and/or causing harm will vary as a function of the activities undertaken, the condition of the structure and the mitigating measures.

Useful generic guidance on the identification and management of hazards associated with pre-stressing is contained in design guides (e.g. [13] [14]) and in temporary works and demolition guides, such as those prepared by the Institute of Civil Engineers [42] and the National Federation of Demolition Contractors [43]. We would expect this guidance to prompt and support, but not be a substitute for, site specific risk identification and management activities.

Corrosion of pre-stressing components and/or passive reinforcing steel will tend to make certain failures (e.g. release of stored elastic energy) more prone to occur and/or less predictable.

In meeting CDM2015, the licensee will need to appoint/assign the duty holders as defined by the Regulation. We consider that de-stressing/deconstruction activities are design activities and their planning/design will require a Principal Designer to be appointed. This appointment should be ahead of work commencing under the supervision of a Principal Contractor.

Conventional health and safety	
PfC 8.1	We would expect the licensee to manage and mitigate against conventional health and safety hazards, meeting the requirement of ALARP in line with TAG 05 and the obligations under CDM2015.

9. Modelling and analysis

Despite many advances in computer hardware and software, analytical modelling of PCPVs is not straightforward and there will be a number of considerations and decisions that we would expect the licensee to make when simulating stages of a PCPV's decommissioning.

TAG 17 Annex 1 'Design' Section 4.12 is generally applicable for the design/engineering activities that are associated with decommissioning, with the majority of paragraphs relevant to PCPVs. (Only those paragraphs that are explicitly related to other structures are not relevant.)

In addition to the statements in TAG 17, we would expect the following to be considered when planning and undertaking analyses of a PCPV for decommissioning:

- Being either cylindrical or spherical, PCPVs will typically have macro symmetry about a vertical axis promoting the use of part-models. However, not all features of the PCPV will adhere to this symmetry. For example, the pre-stressing in the base and top slabs of cylindrical PCPVs is typically orthogonal, and major penetrations are also not repeated uniformly around the walls.
- PCPVs are thick walled and not readily suited to being modelled using 2-dimensional (2-D) shell elements, especially if trying to determine material stresses, strains and cracking. 3-D solid elements are more appropriate, but are more demanding in terms of computational processing.
- We would expect any 3-D modelling of a PCPV's thick walls (including local regions such as around anchorages) to simulate concrete confinement generated by any pre-stressing and/or passive reinforcement. Confinement has the effect to increase the compressive stress and strain capacity of the concrete, but significant care is needed to ensure the material constituent model is suitably calibrated. This calibration will be made more complicated by the effects of creep and shrinkage that are likely to counteract confinement.
- There is not a single standard method for modelling pre-stressing in concrete, especially when modelling ungrouted tendons in curved ducts. To model the effects of creep, shrinkage, tendon relaxation, re-stressing and de-stressing, the tendons need to be restrained to follow the correct profile and act on the concrete along their length where curved, but would ideally also be free to slip axially relative to the concrete.
- There will be many permutations for de-stressing and it may be impractical to model all or even a significant proportion. If the decommissioning strategy is such that there is a risk of unplanned de-stressing (e.g. due to corrosion) we would expect a practical number of scenarios/sequences of de-stressing events to be analysed, with justification for why analysing these sequences has been prioritised.
- The quantum of tendons means it may not be practical to model each tendon individually. Instead, the licensee might choose to model elements that represent groups of tendons, or choose not to model the tendons at all, favouring an alternative method for applying the pre-stress. Any such approximation introduces new challenges and we would expect the licensee to justify the decisions made and to demonstrate the adequacy and accuracy of the analyses undertaken.
- The mesh element size and number of elements through the concrete wall thickness may be dependent on and/or influence the approach for modelling the pre-stressing effect/components, liner, reinforcement, penetrations and/or other geometric features.
- Applying (or removing) a desired level of pre-stress in a model can be iterative, noting that the concrete will contract in reaction to the pre-stress (tendon strain) being applied. Contraction of the concrete leads to a loss of strain, and hence stress, in the tendon.
- The PCPV concrete may have been subject to varying creep through the wall thickness, and at different locations, as a consequence of the pre-stressing action, thermal action and pressure, as well as the influence of the liner and unstressed reinforcement. We would expect the licensee to justify their decision regarding the level to which this variability (including time-dependency) is attempted to be simulated.

- Non-linear shear resistance of cracked concrete is notoriously hard to model reliably. This may be an issue if trying to simulate a seismic load on an de-stressed PCPV.
- Information pertaining to existing structures can be obtained from multiple sources including: historical project records (e.g, drawings, specifications, calculations, test and monitoring records, etc), historical codes and standards, modern codes and standards, and present-day physical measurements and testing. It is important that appropriate information is combined, and that the information that is selected is suitably reliable and representative of the structur.

Modelling and analysis	
PfC 9.1	Where numerical analysis is utilised, we recommend reference is made to TAG 17 Annex 1 Section 4.12 ‘Finite element modelling and numerical analysis’, supplemented by specific considerations included here for analysing thick-walled concrete, ungrouted post tensioning and time-dependent material change.
PfC 9.2	We would not expect analyses of the future performance of an existing structure to rely solely on theoretical constituent models. Instead, we would expect models to utilise measured data to inform the model calibration.

10. Miscellaneous matters

10.1 Changing licensees and information exchanges

We understand responsibility for a plant and its safety case transfers between licensees, from the plant's operator to NDA following defueling activities. It is important at this stage that no important information or knowledge relevant to the ongoing management of the PCPV is lost.

Within this information exchange, we would expect attention to be paid specifically towards the monitoring systems, ensuring that each of historic data, data-processing methodologies and all calibrated equipment is transferred.

We consider it essential that the consideration of intellectual property (IP) does not prohibit or interfere with the disclosure or sharing of relevant information at the transfer of duties between licensees.

Information management	
PfC 10.1	Accompanying the requirement of SAP DC.6, we would expect all data underpinning a safety case, including analytically-derived and measured records, to be transferred between licensees following defueling, and at any other stage that the licensee may change.

10.2 Learning and feedback

While the form of the PCPVs varies between plants, we would expect that their staggered decommissioning activities will allow lessons to be shared allowing latter decommissioning programmes to benefit from the accumulation of knowledge.

Mindful of the long timeframe for post-operational care and maintenance, we recommend that windows of opportunity are facilitated to review and update decommissioning plans as and when new knowledge and technologies comes available.

Learning and feedback	
PfC 10.2	We would expect there to be opportunities to review and update a PCPV's decommissioning plan as and when new knowledge and technologies come available.

10.3 Other structures

In most cases, the stability of the PCPV will be dependent, in part, on supporting structures. These structures, are mostly reinforced concrete (e.g. PCPV pedestals and raft slabs) but may include other materials (e.g. polymeric bearings). All original components will be of similar age to the PCPV and likely nearing (or beyond) the end of their original design life, increasingly susceptible to accelerating and/or critical deterioration.

The supporting structures are unlikely to be subject to the acute change in temperature and pressure envelope that the PCPV is subject to during post-operation. They may, nonetheless, be subject to changes (e.g. resulting from the changing mass and/or stiffness of the PCPV and/or changing environmental condition within the reactor building).

Among the changes, the watertightness of basement slabs could become less reliable, especially if dependent on an external tanking membrane.

Other structures	
PfC 10.3	We would expect the post-operational plan for the PCPV to be developed with consideration for the structures supporting the PCPV and any other adjacent structures that have potential to be impacted by, or impact on the works on the PCPV.

11. Summary

This study has sought to provide guidance to ONR inspectors within civil engineering on the post-operational management of AGR and Magnox PCPVs at existing UK NPPs. It has comprised a horizon-scan of international information from across industry sectors.

We have found limited directly relevant knowledge and precedent from other industries. Moreover, the substantial variation in the design and management of the different PCPVs means that the specific detailed requirements are unlikely to be universally applicable. Instead, general regulatory, management and engineering principles would be best followed and developed into plant-specific plans and evidence.

The ongoing radiological risk associated with the content of the PCPVs, and the potential activation of the PCPV concrete make the decommissioning of PCPVs distinctly different from other civil engineering structures. With these hazards being present, and safety requirements (claims) needed on the structure beyond the end of energy generation, it is appropriate that the safety case is managed, evolved and substantiated so as to remain relevant throughout the post-operation phase, just as is normal during operation. This is in accordance with the expectations of ONR SAPs.

Without the need to withstand extreme fault scenario pressures once defueled, it is conceivable that the pre-stressed tendons could be allowed to corrode, triggering gradual loss of stress as wires individually break; this is assuming an enveloping condition can be justified via analyses. Much more concerning would be corrosion of an anchorage leading to anchor failure and the sudden release of elastic energy from an entire tendon. This would be hazardous for anyone within the vicinity and could cause significant damage to nearby SSCs.

The original CEGB requirement for tendons to be restressed means that tendon end conditions should allow jacks to be reattached at most, if not all, plants. This not only allows tendons to be restressed but also for the stress to be relaxed or removed through the use and control of the jacks. A significant risk for the decommissioning is that, should the de-stressing be delayed, the exposed tendon ends (the tails and/or anchorages) could corrode to the state that they cannot be de-stressed in the intended and well-practiced manner. This would mean an alternative, less familiar de-stressing method is required. Alternative options may generate other hazards, such as increasing the concrete dust and/or slurry. Any such method would likely require mock up exercises or trials to demonstrate the method’s efficacy.

Our study has revealed that all known cylindrical PCPVs were only stressed once fully constructed. It is therefore highly probably that these can support their self-weight without pre-stress. This does not, however, mean that these PCPVs can withstand all post-operational design basis actions that they might be subject to (e.g. seismic), and we would expect the evolving post-operational requirements to be defined and checked using analyses and captured in safety case claims.

In contrast, the spherical PCPVs at Wylfa had temporary supports and were partially stressed during construction, meaning it is possible they cannot withstand their self-weight with total removal of pre-stress. This highlights the importance of site-specific considerations at each site, as the PCPV designs differ. It is also important the licensee has access to detailed design, construction and in service EIMT data, as far as this is available. The usefulness of detailed historical records for the PCPVs cannot be overstated, but all records should be reviewed for their reliability and completeness.

Machinery will almost certainly be used in the decommissioning, perhaps with some level of automation or remote control. We would expect the degree to which machines (and/or their controls) are developed to carry out specific functions is decided based on an ALARP assessments. We would not expect decommissioning operations to be delayed based on unverified future technological developments to the extent that the delays risk irreversible detrimental consequences.

We recommend that EIMT is continued not least to meet safety case claims, but also to the extent that it is useful for managing current and future hazards and risks, or useful for informing or validating analyses. Some EIMT activities from the PCPV’s operational phase will be no longer necessary to be claimed in the post-operational safety case and can be removed, whereas others may still be needed to demonstrate the safety case claims continue to be met. EIMT activities that are (or were) used in the operational phase may also be regarded as onerous and alternatives may be suitable to demonstrate the post-operational safety case claims are met. Non-destructive EIMT would be preferred to destructive EIMT while the PCPV is relied upon to meet safety claims, especially when this EIMT needs to be repeated periodically. Notwithstanding this preference, some limited destructive testing might be necessary or worthwhile if the benefits of acquiring the information outweigh the impacts that the destructive EIMT has on the structure. However, we would not expect insitu destructive EIMT (e.g. load tests) to be so severe or onerous that they heighten the overall failure risk profile.

The management of PCPVs post-operational will change the conventional hazards and the risk profile for operatives working in the vicinity of the PCPV structures. Notable foreseeable hazards include the release of stored elastic energy that would result from a tendon or anchorage failure, masses including prestressing components and machinery falling from height, work at height and/or in confined spaces, inhalation of dust, and operating hazardous machinery. Our expectation is that the licensee meets the requirement of ALARP in line with TAG 05 and fulfils their obligations under CDM2015.

Following cessation of operation and through to site transfer to NDA, there will likely be changes in personnel. In this situation, there are recognised risks associated with knowledge management, equipment availability and EIMT amongst other aspects.

We also recommend that opportunities are created for knowledge to be shared across plants as they undergo staggered decommissioning programmes.

Table 3 collates the ‘points for consideration’ that are dispersed throughout the sections of this report.

Table 3. Collated points for consideration

Post-tensioning in PCPVs	
PfC 3.1	Based on the level of variability across PCPVs, we would expect the post-operational management plan for each PCPV to be tailored to the characteristics of the PCPV and its surroundings.
PfC 3.2	We consider it necessary that the relevant characteristics of each PCPV structure are understood in advance of developing a plant-specific post-operational management plan.
PfC 3.3	We would expect licensees to have access to and make appropriate use of all relevant retained historical information relating to a plant as they develop and implement the post-operational management plans. Relevant historical information may include: drawings, specifications, calculations, design commentaries, test records, in service monitoring records, etc.)
Post-tensioning in non-PCPV applications	
PfC 3.4	We would expect Engineers and Contractors who are experienced with pre-stressed structures in other civil engineering sectors to need to familiarise themselves with the pre-stressing systems and the post-operational requirements of PCPVs.
Activities and stage post-operation	
PfC 4.1	We would expect the licensee’s reactor building decommissioning plan (SAP DC.4) to be comprehensively developed, acknowledging the specific activities relating to the PCPV, and to be coordinated with the overall site decommissioning strategy (SAP DC.2) before commencing the reactor building decommissioning phase.
PfC 4.2	We would expect the plant’s safety case to be suitably updated prior to the decommissioning phase (SAP DC.9), in order that it defines the requirements on the PCPV during decommissioning. For the PCPV, we would expect these requirements to be dependent on stage of the decommissioning.
PfC 4.3	We would expect the substantiation of the safety case to accommodate changes in the PCPV’s withstand capacity resulting from staged works on the PCPV or surrounding structures, and/or time-dependent material changes including but not limited to creep, corrosion, and fatigue (as applicable).

PfC 4.4	While accepting that a plant's decommissioning plan may be subject to review and changes, we would expect sufficient foreplaning at all stages to avoid scenarios whereby safer, more favourable options transition from viable to unviable as consequence of delayed activities or inadequate planning.
Un-controlled destressing	
PfC 5.1	We would expect the causes and likelihoods of uncontrolled de-stressing to be identified and managed, including any contributing factors which could accelerate or decelerate corrosion.
PfC 5.2	Any uncontrolled de-stressing mechanism that is deemed unacceptable must be prevented, or else other measures introduced to make the de-stressing mechanism acceptable.
PfC 5.3	In order to define an uncontrolled de-stressing mechanism as acceptable, we would expect it to be underpinned by sufficient evidence that defines the envelope for acceptability and sets the monitoring and recourse to ensure this envelope is not breached.
De-stressing via reversal of the construction	
PfC 5.4	Should de-stressing via reversal of the construction be proposed/pursued, we would expect the impact of corrosion on the method's current and future viability to be taken into consideration.
PfC 5.5	We would expect the sequence of de-stressing to be planned, cognisant of the impacts of the sequence on the structure (e.g. the levels of asymmetric stress and/or cracking sustained)
De-stressing via other controlled methods	
PfC 5.6	We would expect that the consequences of explosive releases of stain energy as tendons are severed, and any consequences, to be mitigated via practical controls.
PfC 5.7	For options that involve drilling, cutting or splitting the concrete, we would expect the maximum acceptable depth of through-thickness fissure through the PCPV to be determined.
PfC 5.8	For options that create concrete dust or slurry (e.g. drilling, cutting or splitting), we would expect appropriate measures to be developed and implemented that capture, store and/or process the dust and or slurry.
PfC 5.9	*(Same as 5.5)* We would expect the sequence of de-stressing to be planned, cognisant of the level of asymmetric stress that can be sustained.
Consequences of de-stressing	
PfC 5.10	We would expect the licensee to identify and evaluate the relevant consequences of de-stressing.
PfC 5.11	We would expect the locked in energy associated with pre-stressing to be viewed as a hazard, and managed via a risk-based hierarchical management approach (e.g. eliminate, reduce, isolate, control)
Consequences of grouting	
PfC 5.12	As part of the overall post-operational / decommissioning plan for the PCPV, we would expect the licensee to compare the risks and merits of grouting (to lock in pre-stress) against the alternative viable de-stressing method(s).
Structural monitoring	
PfC 6.1	We would expect continuous and/or periodic monitoring to form part of the post-operational management.

PfC 6.2	We would expect the methods by which any monitoring data will be interpreted to be determined as part of the arrangements, to ensure the adequacy and usefulness of the monitoring.
PfC 6.3	We would expect all aspects of the arrangements to be determined and tested for their reliability, to ensure the monitoring (including any chain of events that the monitoring data trigger) fulfils the intended purpose, i.e. to provide confidence in and/or a control on the structural performance.
PfC 6.4	We would expect the requirements for monitoring to be cognisant of any changes in the post-operational phase, and to be adapted as appropriate. Changes may include changes to the PCPV structure, the environmental conditions and loading it is exposed to, the safety claims and withstand requirements, etc).
Machines and robots	
PfC 7.1	We would expect the opportunities for using remote machines/robots to be considered.
PfC 7.2	Should machines/robots be deployed, we would expect the performance, control and/or fail-safe requirements to be defined to ensure all aspects of safety are controlled.
Conventional health and safety	
PfC 8.1	We would expect the licensee to manage and mitigate against conventional health and safety hazards, meeting the requirement of ALARP in line with TAG 05 and the obligations under CDM2015.
Modelling and analysis	
PfC 9.1	Where numerical analysis is utilised, we recommend reference is made to TAG 17 Annex 1 Section 4.12 ‘Finite element modelling and numerical analysis’, supplemented by specific considerations included here for analysing thick-walled concrete, ungrouted post tensioning and time-dependent material change.
PfC 9.2	We would not expect analyses of the future performance of an existing structure to rely solely on theoretical constituent models. Instead, we would expect models to utilise measured data to inform the model calibration.
Information management	
PfC 10.1	Accompanying the requirement of SAP DC.6, we would expect all data underpinning a safety case, including analytically-derived and measured records, to be transferred between licensees following defueling, and at any other stage that the licensee may change.
Learning and feedback	
PfC 10.2	We would expect there to be opportunities to review and update a PCPV’s decommissioning plan as and when new knowledge and technologies come available.
Other structures	
PfC 10.3	We would expect the post-operational plan for the PCPV to be developed with consideration for the structures supporting the PCPV and any other adjacent structures that have potential to be impacted by, or impact on the works on the PCPV.

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Appendix A

Safety Assessment Principles

All safety assessments principles (SAPs) should be considered by ONR inspectors for their applicability to the PCPV during a NPP's post-operational phase. The following principles are a subset of the full SAPs with commentary added specific to the Civil Engineering management of PCPVs post-operation.

Key engineering principles and structural classification

All shall apply, with specific focus on:

EKP.4 The safety function(s) to be delivered within the facility should be identified by a structured analysis.

EKP.5 Safety measures should be identified to deliver the required safety functions(s).

ECS.2 Structures, systems and components (SSCs) that have to deliver safety functions should be identified and classified on the basis of those functions and their significance to safety.

The evolving safety function(s) attributed to the PCPV at stages post-operational should be defined in order to establish the equivalent structural performance requirements and structural safety classifications.

Safety function(s) should also be assigned to any other SSCs associated with the post-operational stages and/or activities. These may include monitoring equipment, jacks, hoists and/or other construction machinery that is relied upon to fulfil or uphold one or more safety functions.

Codes and Standards

ECS.3 Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards.

ECS.4 Where there are no appropriate established codes or standards, an approach derived from existing codes or standards for similar equipment, in applications with similar safety significance, should be adopted.

ECS.5 In the absence of applicable or relevant codes and standards, the results of experience, tests, analysis, or a combination thereof, should be applied to demonstrate that the structure, system or component will perform its safety function(s) to a level commensurate with its classification.

The maintenance, testing and inspection described in ECS.3 extends to the post-operational phase. So to, the 'design' and 'constructed' aspects do not only apply to the building of the PCPV, but they also apply to structural modifications and deconstruction activities.

Considering the age of PCPV structures, there may be aspects of their design and construction that do not conform with current codes and standards. ONR inspector may wish to consider justification given in periodic safety reviews to understand how any gaps in the current codes and standards have been addressed by the licensee during the latter stages of the operational phase.

There may also be stages and/or activities within the post-operational phase that do not marry with the assumptions inherent of codes and standards, for example BS 4975 assumes the PCPV is acting as a pressurised structure and this is likely to cease to be the case.

Equipment qualification

EQU.1 Qualification procedures should be applied to confirm that structures, systems and components will perform their allocated safety function(s) in all normal operational, fault and accident conditions identified in the safety case and for the duration of their operational lives.

Monitoring equipment and/or construction equipment should be qualified where relied upon to fulfil or uphold one or more current or future safety functions.

Design and reliability

EDR.1 Due account should be taken of the need for structures, systems and components to be designed to be inherently safe, or to fail in a safe manner, and potential failure modes should be identified, using a formal analysis where appropriate.

This is a fundamental requirement of safety-classified structures making up a NPP. Specific to a de-stressed PCPV, the structure may be brittle with little passive reinforcement and the licensee may need to determine and implement measures to ensure cliff-edge failures are avoided.

EDR.2 Redundancy, diversity and segregation should be incorporated as appropriate within the designs of structures, systems and components.

EDR.3 Common cause failure (CCF) should be addressed explicitly where a structure, system or component employs redundant or diverse components, measurements or actions to provide high reliability.

The structure's safety functions should be insensitive to the loss of individual pre-stressing tendons.

Throughout the post-operational phase, there be should be suitable provisions to nullify CCF of multiple pre-stressing tendons if CCF could put the safety functions at risk.

EDR.4 During any normally permissible state of plant availability, no single random failure, assumed to occur anywhere within the systems provided to secure a safety function, should prevent the performance of that safety function

The PCPV is a system made up of many SSCs. A single random failure could apply to a component of the pre-stressing system (e.g. a tendon, anchorage or jack) or to any instrumentation fulfilling a monitoring function.

ERL.1 The reliability claimed for any structure, system or component should take into account its novelty, experience relevant to its proposed environment, and uncertainties in operating and fault conditions, physical data and design methods.

The reliability of the stressed tendons, their anchorages, and of de-stressing techniques may evolve over time (e.g. as a result of increasing corrosion).

The reliability of EIMT will depend on the extent of coverage, on the accuracy of the equipment, on the level of background noise and on the repeatability and overall quantum of measurements.

Maintenance, inspection and testing

EMT.1 Safety requirements for in-service testing, inspection and other maintenance procedures and frequencies should be identified in the safety case.

The requirements for (including format and frequency of) examination, inspection, maintenance and testing may vary at different stages post-operation.

EMT.4 The continuing validity of equipment qualification of structures, systems and components should not be unacceptably degraded by any modification or by the carrying out of any maintenance, inspection or testing activity.

De-stressing and the removal of individual tendons may be necessary to fulfil the inspection and testing regime. During such an activity, it may not be necessary to uphold the operational condition post-operation; in such a scenario, new criteria defining the bounds on the stress state should be established and included within the modification proposal and safety case. The safety case should be supported by evidence demonstrating the plant remains in a safe condition prior to, during and following the proposed changes.

EMT.6 Provision should be made for testing, maintaining, monitoring and inspecting structures, systems and components (including portable equipment) in service or at intervals throughout their life, commensurate with the reliability required of each item.

ECE.20 Provision should be made for inspection, testing and monitoring during normal operations aimed at demonstrating that the structure continues to meet its safety functional requirements. Due account should be taken of the periodicity of the activities.

Provisions (e.g. in terms of conventional health and safety) that are deemed necessary at present and in the future may deviate from those assumed when plants were designed and manufactured.

The wider decommissioning activities (e.g. removal of ventilation, lighting and/or alarm systems) may impact activities relating to the PCPV.

EMT.8 Structures, systems and components should be inspected and/or re-validated after any event that might have challenged their continuing reliability.

Such events may include earthquake events, plant fires, crane drops, etc.

Note, within the format of the SAP, corrosion is more conveniently considered through the ageing and degradation principles, rather than as an ‘event’.

Ageing and degradation

Each of **EAD.1** to **EAD.5** apply, with focus on the corrosion of the steel post-tensioning cables and their anchorages. In particular:

EAD.2 Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components.

In the context of pre-stress de-stressing, “*allowing for the effect of material ageing*” should be considered within the framing of the PCPV’s ability to perform its function, and also the ability to execute the desired de-stressing technique, noting that corrosion can impact the viability and/or reliability of certain de-stressing techniques.

It should also be noted:

- Some ageing mechanisms (e.g. tendon relaxation, concrete creep and shrinkage) decelerate over time, while others (e.g. tendon corrosion) tend to accelerate.
- Some post-operational phases will bring about step changes in demands that will bring about similar step changes in the margins; see EHA.3 below.

EAD.3 Where material properties could change with time and affect safety, provision should be made for periodic measurement of the properties.

EAD.4 Where parameters relevant to the design of plant could change with time and affect safety, provision should be made for their periodic measurement.

In the context of the post-operational decommissioning, it is foreseeable that material property and/or parameter changes may not affect safety margins to the degree that they did during plant operation and, therefore, may need less rigorous measurement than previously needed. Where this is the case, it is expected that the arguments and evidence are included in the safety case modification proposals.

Hazards

Generally speaking, this next set of SAPS interface with disciplines outside Civil Engineering. However:

EHA.3 For each internal or external hazard which cannot be excluded on the basis of either low frequency or insignificant consequence (see Principle EHA.19), a design basis event should be derived.

ECE.21 Pre-stressed concrete pressure vessels and containment structures should be subjected to a proof pressure test, which may be repeated during the life of the facility.

ECE.22 Civil engineering structures that retain or prevent leakage should be tested for leak tightness prior to operation.

Internal and external hazards are likely to evolve during the post-operational phase, leading to different Civil Engineering demands on the PCPV structure, with or without pre-stress. This evolution is likely to be affected by changes to both the PCPV and its surroundings. We would anticipate that a comprehensive set of design basis events / criteria would form the basis for the assessment of the PCPV's performance analyses for stages through the post-operational phase.

As the structure is modified and/or corrodes, there may be a requirement for pressure and/or leak tests to be repeated during stages of the post-operational phase.

Civil Engineering

ECE.1 The required safety functions and structural performance of the civil engineering structures under normal operating, fault and accident conditions should be specified.

This is intrinsically linked to key engineering principles EKP.4 and EKP.5, safety classification principles ECS.1 and ECS.2 and hazard principle EHA.3. The required safety functions may evolve through the different stages of the post-operational phase.

ECE.3 It should be demonstrated that structures important to safety are sufficiently free of defects so that their safety functions are not compromised, that identified defects can be tolerated, and that the existence of defects that could compromise safety functions can be established through their lifecycle.

ECE.6 Load development and a schedule of load combinations, together with their frequencies, should be used as the basis for structural design. Loadings during normal operating, testing, design basis fault and accident conditions should be included

In each of the above, the subject (be it defects or loads) is likely to evolve during the post-operational phase.

ECE.26 Special consideration should be given at the design stage to the incorporation of features to facilitate radioactive waste management and the future decommissioning and dismantling of the facility.

This is unlikely to have been considered in any detail during the design of the UK's AGRs and Magnox fleet but should, nonetheless, be considered as part of the decommissioning design.

ECE.12 Structural analysis and/or model testing should be carried out to support the design and should demonstrate that the structure can fulfil its safety functional requirements over the full range of loading for the lifetime of the facility.

ECE.13 The data used in structural analysis should be selected or applied so that the analysis is demonstrably conservative.

ECE.14 Studies should be carried out to determine the sensitivity of analytical results to the assumptions made, the data used, and the methods of calculation.

It is anticipated that additional analyses will be necessary to support the decommissioning plan, covering the envelope of design basis scenarios, material and parameter changes, and structural configuration changes.

The analyses should cater for uncertainties associated with the decommissioning activities and scenarios.

ECE.15 Where analyses have been carried out on civil structures to derive static and dynamic structural loadings for the design, the methods used should be adequately validated and the data verified.

Methods adopted in the decommissioning may differ to those adopted historically in the design and require verification and validation (V&V).

It is anticipated that claims based on modern methods of analyses may be supplemented through references to historic or modern analyses. It should not be assumed that all historic analyses, or their application to current and future scenarios are reliable without appropriate V&V.

ECE.17 The construction should use appropriate materials, proven techniques and a quality management system to minimise defects that might affect the required integrity of structures

Historic materials may not comply with modern quality management systems.

ECE.24 There should be arrangements to monitor civil engineering structures during and after construction to check the validity of predictions of performance made during the design and for feedback into design reviews.

The supports of PCPVs, which typically comprise elastomeric bearings, are relatively tolerant of deformations of the supporting structure, deformations during decommissioning due to the demolition (or partial demolition) of surrounding structures may have influence and can be monitored to record movements. Once de-stressed, the PCPV is likely to be significantly less tolerant to deformations and the licensee can use analyses to demonstrate the anticipated impacts of the changes.

Decommissioning

DC.1 Facilities should be designed and operated so that they can be safely decommissioned.

DC.6 Documents and records that may be required for decommissioning purposes should be identified, prepared, updated, retained and owned so that they will be available when needed.

We note that existing plants with PCPVs were designed prior to the development of the SAPs and it cannot be assumed that equivalent SAPs were enforced at the time of their design and/or throughout operation.

Specifically in relation to DC.1, methods that might have been considered ‘safe’ in the past may no longer meet current expectations. Conversely, improved (safer) methods, technologies and techniques are available, and others may become available in the future that would not have been foreseen during design.

DC.2 A decommissioning strategy should be prepared and maintained for each site and should be integrated with other relevant strategies.

DC.4 A decommissioning plan should be prepared for each facility that sets out how the facility will be safely decommissioned.

The sub-clauses associated with DC.2 identify that the ‘decommissioning strategy’ should:

- describe the planned end-state
- identify the decommissioning options, their timescales, and reasons for selection decisions.
- demonstrate that, if it is proposed to defer the decommissioning, the options for implementing earlier decommissioning will remain available and not become technically foreclosed.

The latter point is subtly different to an additional matter of particular concern for PCPVs, relating to the timing of decommissioning, the corrosion of the pre-stressing, the availability of functioning jacking equipment and workforce familiarity with de-stressing operations. This additional matter can be summarised as:

- [The ‘decommissioning strategy’ for the PCPV should] demonstrate that, if it is proposed to defer the decommissioning, the methodologies for undertaking the decommissioning that are currently available will remain available and not become technically foreclosed.

Not acknowledged in the above sub-clauses to DC.2 are intermediate (or interim) states. A sub-clause to DC.4 acknowledges these, stating that plans should:

- address any changes to existing SSCs
- be supported by appropriate evidence to demonstrate that decommissioning can be undertaken safely and that the planned end-state (and any interim states) can be achieved.

This is important for decommissioning PCPVs as there will undoubtedly be interim states that may last considerable time; each required to fulfil certain safety functions. CDM2015 requires the licensee to demonstrate consideration and reduction of the risks associated with design for all states including interim states of any duration.

DC.9 A safety case should be provided to demonstrate the safety of the decommissioning plan and its associated decommissioning activities and then kept up to date as the work progresses.

DC.3 The safety case should justify the continuing safety of the facility for the period prior to its decommissioning. Where adequate levels of safety cannot be demonstrated, prompt decommissioning should be carried out and, where necessary, prompt remedial and operational measures should be implemented to reduce the risk.

DC.9 and the first part of principal DC.3 are consistent with Safety Case SAPs (SC.#) not reproduced here as all apply post-operational phase without need for PCPV-specific interpretation.

The latter statement, "*prompt remedial and operational measures*", implies some level of scenario forecasting and pre-emptive planning may be required. In the context of the PCPV and active monitoring, this might mean setting trigger levels on monitoring and planning the response(s) should any triggers be exceeded. "*Prompt*" should also be proportionate to the rate of change of condition and urgency of the intervention, noting the rate of change may be quite slow during the care and maintenance period.