3. INSTRUMENTATION

3.1 Background

The instrumentation suite installed on the PCCV model was designed to support the test program objectives, i.e., to provide data on the response of model to internal pressure loading well into the inelastic regime, for comparison with analytical models; and to provide insight and information into response and failure mechanisms that may be representative of actual nuclear power plant containment structures.

Since most types of instrumentation are only capable of measuring a single response parameter at a discrete location, the task of designing the instrumentation suite consisted of identifying critical response parameters and locations from which the overall and local response of the model could be inferred, selecting transducers with the requisite accuracy and range, meeting other operating constraints (pressure, temperature, size, etc.) and integrating them with the other transducers and the data acquisition system. The design of the instrumentation suite also required the specification of quality control procedures to ensure the transducers would perform as designed and that the output could be reliably interpreted in terms of the response parameters of interest.

This chapter describes the considerations given in the design of the instrumentation, gives specifications for the transducers selected, and provides a list of all the transducers installed on the model, along with details of the location, installation, and quality control procedures.

3.1.1 Design Considerations

The basic instrumentation plan was outlined by NUPEC in early 1992 during the initial planning for the PCCV model test [29]. After extensive discussions between NUPEC, its subcontractors, the NRC, and SNL, the details of the instrumentation were agreed upon and documented [30, 31]. Preliminary analyses of the PCCV model guided the selection and location of the final suite of measurements [32]. The detailed PCCV Instrumentation Plan provides a complete description of the instrumentation system and was updated throughout the model design and construction, finally reflecting the 'as-built' configuration employed during the pressure tests.

Considering the basic design philosophy, described in Section 2.1, the basic instrumentation plan identified the following measurements to be taken during the PCCV pressure tests:

1. load (internal pressure),
2. displacement,
3. rebar strain,
4. concrete strain,
5. concrete crack width,
6. liner and liner anchor strain,
7. tendon force, and
8. temperature.

These parameters would be measured at a number of locations to characterize both the global and local response of the model. The basic plan also called for the instrumentation to provide information regarding the potential failure modes identified in Section 2.1. Table 3.1 shows the relationship between instrument location, instrument type, measurement type, and measurement objective. The measurement objectives are either to capture global or local response at specified locations in the PCCV or to measure the behavior of potential failure modes, as shown above. The measurement types and the various instrument types to be specified are discussed in Section 3.2. Installation and locations of the instruments are discussed in Section 3.3.

The basic instrumentation plan also specified a grid of azimuths and elevations which would form the basis for the instrumentation layout and provide a scheme for incorporating the nominal gage locations in the individual gage IDs. This basic grid of cardinal lines is shown in Figure 3.1.

Thirteen cardinal elevations were established, from 1 at the top of the basemat (elev. 0.00) to 13 at the dome apex. Twelve cardinal azimuths, spaced roughly 30 degrees apart, were established with A at 0 degrees (or 360 degrees) to L at 324 degrees. A thirteenth cardinal azimuth was established at 135 degrees and designated Z. This azimuth was selected to represent the global axisymmetric response of the containment based on preliminary analysis results. While the PCCV model is not axisymmetric in terms of geometry and stiffness, Azimuth Z is reasonably distant from any major structural discontinuities and the net hoop prestressing force is close to the average.

The cardinal lines of the model were selected because they correspond to the measurement locations for the prototype Structural Integrity Test (SIT). The SITs were carried out on the containments of the Ohi Nuclear Power Station (Units 3 and 4) in 1991 and 1992. Comparison of the SIT results from the prototype with the model SIT results might be useful for investigating the similarity between the structures. The SIT for both the Ohi containment and the model were performed at 1.125 times design pressure.

Table 3.1 Instrumentation Objectives

Location	Material	Measurement Type	Instrument Type	Measurement Objective
Free-Field Cylinder and	Liner	Strain	Strain gage	Response and Liner failure
Dome	Liner anchor	Strain	Strain gage	Response
	Rebar	Strain	Strain gage	Response
	Tendon	Strain	Tensmeg & Strain gage	Response and Tendon failure
		Force	Load cells	Response
	Concrete	Strain	Strain gage	Response
		Cracking	Video	Response
	All	Displacement	CPOT and TLDT	Response
Wall-Basemat	Liner	Strain	Strain gage	Liner failure
Juncture	Liner anchor	Strain	Strain gage	Liner failure
	Rebar	Strain	Strain gage	Shear failure
	Concrete	Strain	Gage bars	Shear failure
		Cracking	Video	Shear failure
On E/H or A/L	Steel hatch	Strain	Strain Gage	E/H or A/L failure
		Displacement	LVDT	Response
Around E/H or	Plate and Liner	Strain	Strain gage	Liner failure
A/L	Liner anchor	Strain	Strain gage	Liner failure
	Concrete	Cracking	Video	Response
Other	Steel Plate	Strain	Strain gage	Penetration failure
Penetrations	Liner	Strain	Strain gage	Liner failure
	Liner anchor	Strain	Strain gage	Liner failure
Basemat/ Tendon	Tendons	Force	Load cell	Response and Tendon failure
Gallery	Rebar	Strain	Strain gage	Shear failure
	Concrete	Uplift Displacement	LVDT	Response
Buttress	Liner	Strain	Strain gage	Response and Liner failure
	Rebar	Strain	Strain gage	Response
	Tendon	Force	Load cell	Response and Tendon failure

CPOT - Cable Potentiometer
LVDT - Linear Variable Differential Transformer
TLDT – Temposonics Linear Displacement Transducer

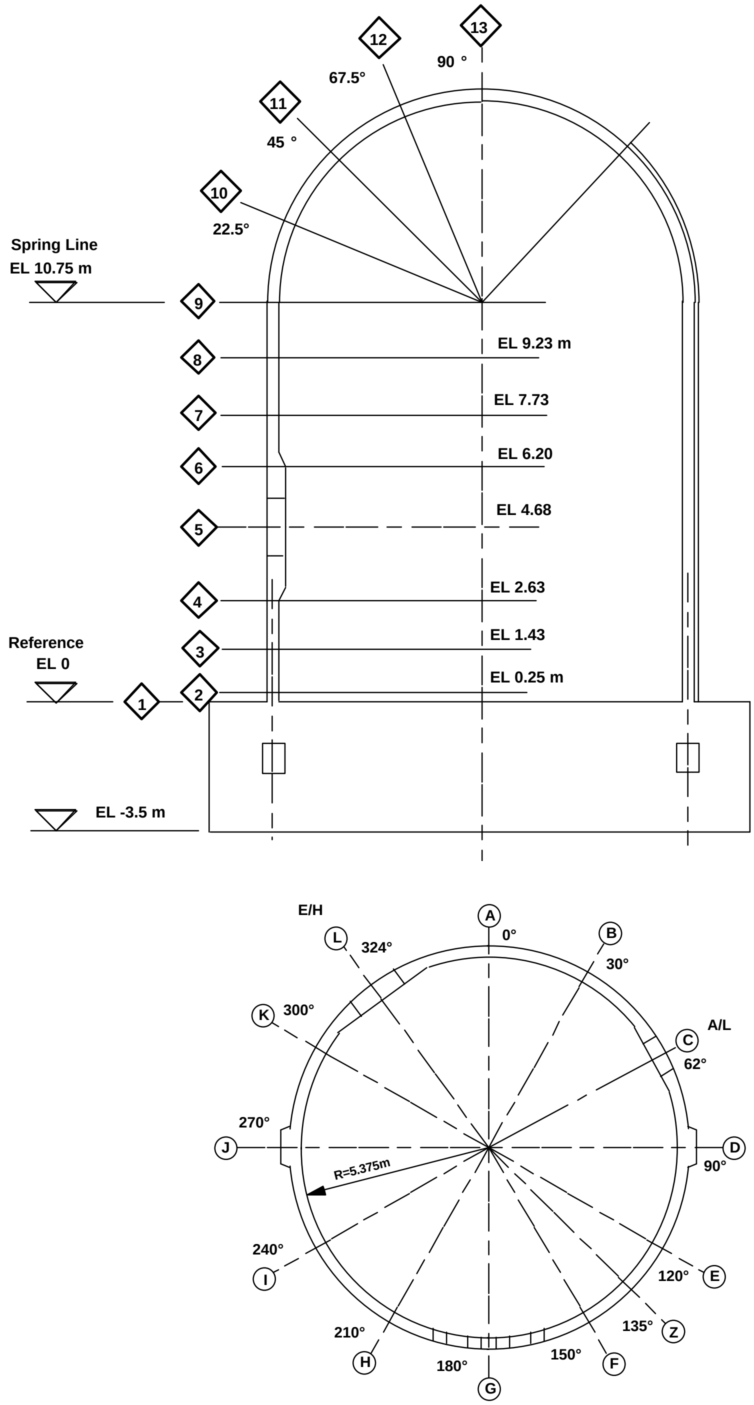

Figure 3.1 Cardinal Instrumentation Layout Lines

3.2 Types of Measurements

This section summarizes the types of measurements required to meet the PCCV test objectives. Details of what and why measurements were taken are included. These measurement types correspond to those shown previously in Table 3.1.

3.2.1 Pressure

Accurate measurement of the internal gas pressure in the PCCV during pressure tests was necessary for several reasons. First, the pressurization of the vessel for the test needed to be carefully controlled and accurately recorded to allow comparison of model response with pre- and posttest analytical results as a function of pressure. Next, accurate calculation of the integrated gross leak rate of the vessel during low pressure testing and detection of leaks and leak rate estimation during high pressure testing dictated the need for accurate pressure and temperature data. These data, along with knowledge of the gas properties in the vessel, allow calculation of leak rates during the tests.

The specifications for the pressure sensors are presented in Table 3.2. The accuracy requirements dictate voltage output devices (rather than millivolt output) with integrated signal conditioning electronics included.

Table 3.2 Pressure Transducer Specifications

Specification Item	Data
Type of measurement required	Gage pressure inside PCCV model
Anticipated exposure conditions	Non-purified nitrogen gas at pressures from ambient to approx. 2.1 Mpa-g (300 psig) for durations no more than 20 days (500 hours)
Operational range	1% of full scale < P_{op} < 2.4 Mpa-g (350 psig) (125% of anticipated rupture pressure)
Desired output	Amplified voltage
Total desired accuracy (i.e., linearity, repeatability, hysteresis, sensitivity)	Less than or equal to 0.1% of span
Temperature effect	< 0.05% full scale per /F over temperature compensated range
Logistics (electrical connection, cabling requirements, etc.)	Pressure taps from vessel will be installed so the transducer housing will represent part of the pressure boundary, typical four wire connection with independent power supply required (i.e., not provided by VXI mainframes), specifications for power supply dependent on type of pressure transducer (i.e., input voltage needs)

Two high-accuracy pressure transducers, Mensor Model 4040 high-accuracy digital units[18], were installed in the vessel to provide redundancy in the measurements. Although the predicted failure pressure of the model was not known with certainty, preliminary calculations indicated it would be in the range of 1.6MPa-g (230 psig). The pressurization system and all equipment was designed for an upper-bound capacity estimate of 2.1MPa-g (300 psig). Applying an overpressure margin of 15%, the specified range for the pressure transducers was 2.4 MPa-g (350 psig).

[18] Mensor Corporation, 201 Barnes Drive, San Marcos, Texas, 78666. (http://www.mensor.com/Digital_Pressure_Transducer_4000.htm)

(An independent pressure transducer was supplied with the pressurization system to control test operations. This transducer was independently calibrated; however, all test results are reported against the 'official' pressure transducers.)

3.2.2 Temperature

Both model material and internal gas temperatures were measured. Material temperature measurements were made to provide data for thermal compensation of all strain gages within the PCCV model and to provide data to correlate the response of the model to changes in ambient thermal conditions and the effects of direct radiant heating. Two types of T/Cs were used: Omega Model SA1-T T/Cs were placed on the inside surface of the PCCV liner, while Omega Model TQSS-116 were embedded within the concrete[19]. Due to the low sensitivity of the strain gages to temperatures around 23/C and the anticipated low temperature gradients along the inside surface of the model, low cost thermocouples were installed so that one T/C compensated several gages. Therefore, only a relatively small number of T/Cs were required to fulfill the temperature compensation requirements for the entire suite of strain gages. These were uniformly distributed, along with additional liner T/Cs near the E/H and A/L.

Internal gas temperature measurements were required to evaluate the integrated leak rate from the vessel prior to and during the pressure tests. High accuracy transducers were required for this purpose due to the small magnitude of the overall leak rate compared to the large volume of the vessel. Resistance temperature detectors (RTDs), Omega Model RD 805 precision gas temperature monitoring units[19], were used for this purpose. The RTDs were distributed fairly uniformly throughout the model so that the tributary volumes associated with each sensor were approximately equal. These temperature measurements, in conjunction with the pressure measurements, provided data to detect leaks and estimate leak rates. Fans were available to circulate the gas inside the model in order to minimize thermal stratification during testing. A single RTD was also located outside the model (on the north side, i.e., in the shade) to provide ambient air temperature data.

The requirements for each of the two temperature monitoring instruments are provided in Tables 3.3 and 3.4 For the PCCV tests, three wire, lead-resistance-compensation-type sensors with low self-heating errors were used.

Table 3.3 Thermocouple Specifications

Specification Item	Data
Type of measurement required	Temperature measurements of inside surface of PCCV model
Anticipated exposure conditions	Nitrogen, from ambient to 2.1 MPa-g (300 psig), expected maximum temp. range from -5 to 50/C
Operational range	-10 to 100 /C
Desired accuracy	< 2% of total input range
Temporal response times	Unspecified, not critical
Junction characteristics	Ungrounded, sheathed
Logistics (electrical connection, cabling requirements, etc.)	Two-wire twisted, insulated leads of same material as thermoelement junction pair, junctions at pin-type pressure feedthroughs (requires pins of same materials as conductors)

[19] Omega Engineering, Inc., One Omega Drive, Stamford, Conn. 06907-0047. (http://www.omega.com/temperature/tsc.html)

Table 3.4 RTD Specifications

Specification Item	Data
Type of measurement required	PCCV internal gas temperature measurements
Anticipated exposure conditions	Nitrogen, ambient to 2.1 MPa-g (300 psig)
Operational range	-10 to 100/C
Desired accuracy	< 2% of total input range
Desired sensitivity	N/A
Logistics (electrical connection, cabling requirements, etc.)	Four-wire twisted, insulated leads. Requires constant current source (typically 1ma).

3.2.3 Displacement

Displacements were measured at discrete locations to compare with analysis and allow construction of the global response of the model. The types of displacement measured included:

1. radial displacements of the cylinder wall at regular azimuths and elevations relative to a reference point on the instrumentation frame,
2. vertical displacements at the springline at regular azimuths relative to the top of the basemat liner,
3. horizontal and vertical displacements in the dome at regular azimuths and elevations relative to the instrumentation frame,
4. vertical displacements at the apex of the dome relative to the instrumentation frame,
5. changes in internal diameter (i.e. ovalization) of the E/H and A/L barrels,
6. vertical displacement or uplift of the basemat relative to the mudmat.

The range of displacements to be measured included small, elastic deformations during prestressing and subsequent changes due to ambient temperature variation, creep, etc., through large inelastic deformations during pressure testing.

For the PCCV model test, three types of displacement transducers allowed a wide range of expected displacement to be measured. Overall global deformations at the cardinal points were typically measured using CPOT Celesco Model PT 101[20] (Figure 3.2). Where deformations were expected to be small, such as at the wall-junction or where higher precision was desirable, such as measuring local deformations at penetrations, Schaevitz HCD series[21] LVDTs with ranges on the order of 4" or less were used (Figure 3.3). In some locations where both high accuracy and long range were required, Temposonics® magnetostrictive high-accuracy TLDTs[22] were used (Figure 3.4). The specifications for each of these displacement transducers are provided in Tables 3.5, 3.6, and 3.7.

Note that all displacement data represents the relative motion between the point of interest and a reference point. Ideally, the reference point is fixed and not influenced by the loads applied to the test structure; however, in most cases, this is impractical. For the case of the PCCV model, most displacements were measured internally and referenced to the instrumentation frame or the top of the basemat. Since the basemat was judged to be, essentially, a rigid mass, the only consideration required for the instrumentation frame was its response to variations in internal temperature. A set of transducers were mounted on the instrumentation frame to measure changes in height and plan dimensions and determine if there was any effect on the cylinder or dome displacements. These frame displacement transducers consisted of

[20] Celesco Transducer Products, Inc., 20630 Plummer St., Chatsworth, CA, 91311. (http://www.celesco.com/cet/index.html)

[21] Measurement Specialties, Inc., Sensor Products Division, 950 Forge Ave. Bldg B, Norristown, PA 19403. (http://www.msiusa.com/schaevitz/products/LVDT/index.html)

[22] MTS Systems Corp., Sensors Group, 3001 Sheldon Drive, Cary, NC 27513. (http://www.mtssensors.com/)

CPOTs and two Spectron Model SSY0140 dual-axis inclinometers[23] to monitor tilt of the frame due to possible basemat curvature.

In addition, the internal displacement transducers were attached to the liner surface, assuming that the liner was 'perfectly' bonded to the concrete. This assumption, while valid in most cases, was incorrect in a number of cases (which will be discussed in Chapter 5) and it is worth remembering that all internal displacement data represents the position or motion of the liner, not necessarily the concrete wall.

Similarly, uplift of the basemat was measured relative to the mudmat (Figure 3.5) and, as was previously identified, any motion of the mudmat would affect the uplift data.

Table 3.5 Displacement Transducer Specifications (CPOT)

Specification Item	Data
Type of measurement required	Radial or vertical displacement of internal surface of the PCCV model
Anticipated exposure conditions	Nitrogen, from ambient to 2.1 MPa-g (300 psig)
Operational range	5 cm, 12.5 cm, 25 cm, and 38 cm (2", 5", 10" and 15")
Desired accuracy (linearity and repeatability)	0.15 to 0.25% full scale
Logistics (electrical connection, cabling requirements, etc.)	Power supply required (not included on VXI card), multi-pin cable connector needed

Figure 3.2 CPOT Mounted on Instrumentation Frame and Attachment to PCCV Liner

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[23] Spectron Systems Technology, Inc., 595 Old Willets Path, Hauppage, NY 11788. (http://www.spectronsensors.com/inclinomter.htm)

Table 3.6 LVDT Specifications

Specification Item	Data
Type of measurement required	Radial or vertical displacement of internal surface of the PCCV model Ovalization of equipment hatch and personnel airlock, basemat uplift
Anticipated exposure conditions	Nitrogen, from ambient to approx. 2.1 MPa-g (300 psig)
Operational range	2.5 and 10 cm (1" and 4")
Desired sensitivity	< 1% total input range
Deviation from linearity	0.25% full scale
Logistics (electrical connection, cabling requirements, etc.)	Same as CPOT requirements

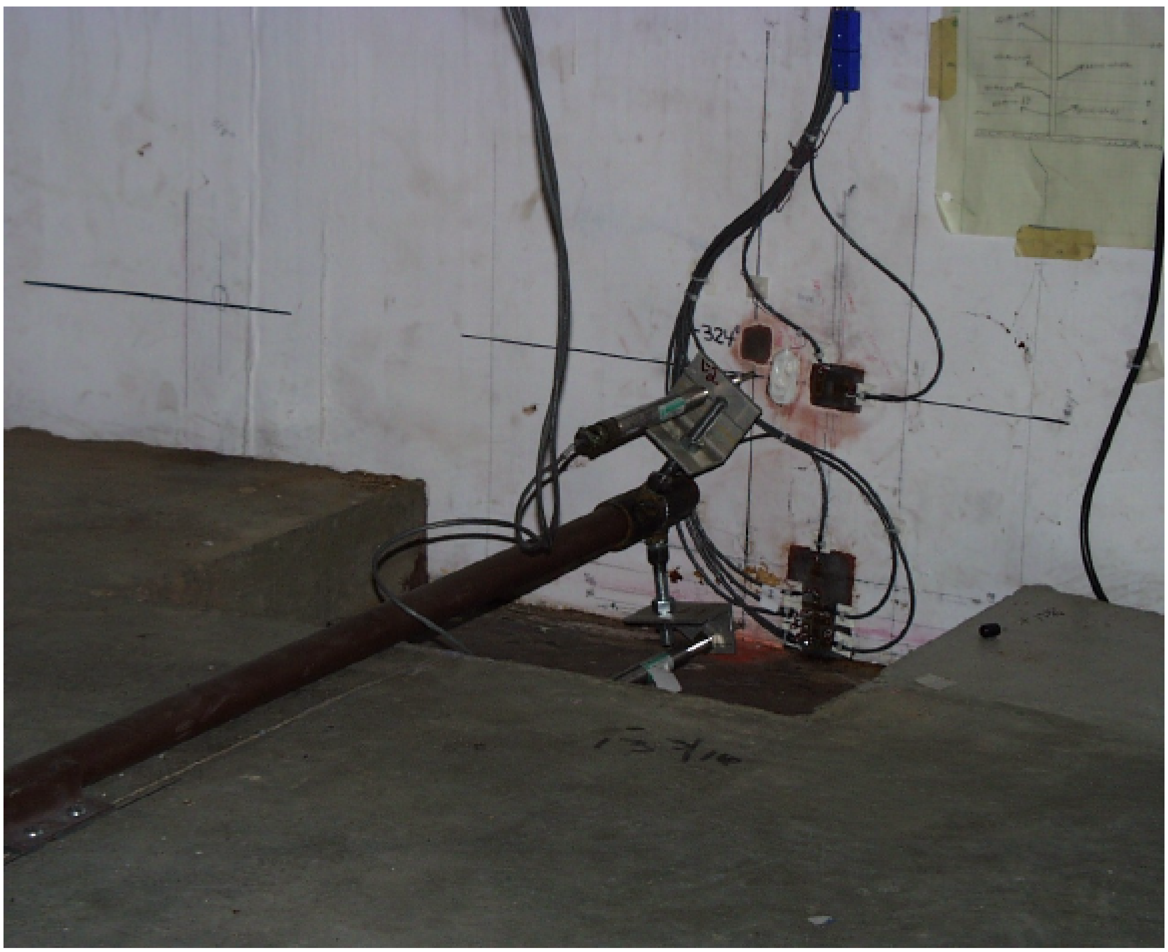

Figure 3.3 LVDTs at Wall-Base Junction (Azimuth 324 degrees, Elev. 0.0 and 250.0)

Table 3.7 Temposonics Linear Displacement Transducer Specifications (TLDT)

Specification Item	Data
Type of measurement required	Accurate and high range measurements of linear displacement of internal surface of PCCV model
Anticipated exposure conditions	Nitrogen, from ambient to approx. 2.1 MPa-g (300 psig)
Operational range	38 cm (15")
Desired sensitivity	< 1% total input range
Deviation from linearity	0.02% full scale (min 13 mm)
Logistics (electrical connection, cabling requirements, etc.)	Same as CPOT requirements

Figure 3.4 TLDT Mounted on Instrumentation Frame and Attachment to PCCV Liner

3.2.4 Concrete Cracking

The basic instrumentation plan identified the relationship between concrete cracking and load or pressure as one of the response mechanisms to observe during the PCCV test. In order to thoroughly model and understand concrete cracking mechanisms, several parameters to measure were identified:

1. the strain in the concrete,
2. when and where a crack first occurs,
3. crack propagation, and
4. crack width.

Measurement of discrete concrete crack width is, however, difficult to perform in practice. A discrete crack must be identified prior to placing a gage at the crack location. However, since most cracks of interest will not form until the test pressure exceeds the design pressure (and the prestressing load), safety constraints prohibit the installation of gages during testing. Several schemes for measuring concrete crack width were considered, including pre-cracking the model, placing crack width gages at a number of shrinkage cracks, or using high resolution video monitoring. However, none of these schemes was considered to be practical or cost-effective. The decision was made to abandon requirements to measure concrete crack width and focus on crack detection and crack propagation.

Figure 3.5 External LVDT Measuring Displacement between Basemat and Mudmat

Crack initiation and propagation were monitored by performing detailed visual inspection to construct crack maps in areas of interest following critical load steps. These crack maps are supported by photographic records of all the areas inspected. Detection of crack initiation during pressure testing was also attempted via acoustic monitoring, described in Section 3.2.8.

Concrete strain measurements are discussed in Section 3.2.5.2.

3.2.5 Strain Measurements

Strain gages applied to individual structural elements provide information on the discrete strain in the element being interrogated and are also capable, when used in groups, of providing insight into local and global strain fields in the structure. Extensive experience through the previous history of containment testing at SNL and elsewhere formed the basis for the specification of strain gage requirements for the PCCV experiment. Standard electrical-resistance type, bonded strain gages were chosen for their simplicity and accuracy, as well as low relative cost. All foil-type strain gages used on the PCCV model were high-elongation-type EP Micro-Measurements gages constructed of annealed constantan on a polyimide backing.[24] These gages were used to measure strains in the rebar, concrete, liner, liner anchor, hatches and penetrations, and tendons. In some cases, noted below, special types of strain gages were used in addition to the bonded foil gages to provide additional response information.

Care must be exercised, however, when interpreting strain gage output, since very small gage length strain gages are highly susceptible to the influence of local structural discontinuities or as-built conditions and positioning of the gage in areas with high strain gradients can significantly affect the results. These factors should be considered when comparing strain data with analysis results at discrete points in a structure. Furthermore, the application of the strain gage to the structural element may perturb the strain fields in the vicinity of the gage and these effects should, if present, also be considered.

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[24] Micro-Measurements Division, Vishay Measurements Group, Inc., Raleigh, NC 27611. (http://www.vishay.com/brands/measurements_group/strain_gages/mm.htm)

3.2.5.1 Reinforcing Bar Strain

Strain gages, mounted to meridional, hoop, and transverse reinforcing steel, were used to measure the global 'free-field' or local membrane, bending and shearing strains in the model as a function of pressure. Reinforcing strain measurements were generally not made in areas where the reinforcing was highly congested, such as around penetrations, or to determine local strain concentrations. Exceptions to the latter case included the wall-basemat intersection and around the tendon gallery. In areas of highly congested reinforcing, rebar strains were measured at the perimeter of the reinforcing grid to confirm boundary conditions for comparison with pretest analyses. Typical reinforcing strain measurements included:

1. Free-field strain measurements of meridional and hoop reinforcing steel at regular azimuths and elevations in the cylinder wall and dome for comparison with pretest axisymmetric and global 3D analyses and to determine the global strains at which local failures were expected to occur. Typically, both inner and outer reinforcing strains were measured to resolve membrane and bending behavior.
2. Near-field strain measurements of meridional and hoop reinforcing steel at the boundaries of local reinforcing areas, e.g. E/H, A/L, etc., were acquired for confirm boundary conditions for local submodels in pretest and posttest analyses.
3. Near-field strain measurements of radial ties in the vicinity of structural discontinuities where large shears or large bending moments were predicted to occur, and to measure triaxial state of strain (stress) for evaluating failure models. In addition, inclined gage bars were used, based on the predicted orientation of principal tensile stresses.

The specifications for the rebar (and tendon wire) strain gages are summarized in Table 3.8. Figures 3.6 and 3.7 show a typical rebar strain gage after mounting on the bar and in place in the model, with protective epoxy cover.

Understanding the method of mounting the strain gages on the rebar is important to interpreting the rebar strain data. One of the first considerations is that the surface of the rebar to which the gage is to be bonded must be ground smooth. This typically removes a portion of the bar's cross-section, which can result in a local strain concentration in the bar. This phenomenon is described in more detail in Section 5.3.2.1.5. Second, requirements to protect the strain gages during erection and concrete placement locally debond the rebar from the concrete, so that local strains between the rebar and concrete may not be compatible. Finally, strain gages on rebar are located away from the ends of bars or mechanical splices to ensure the bars are fully developed and to avoid end effects. However, in some cases, end effects may be a factor and the location of the gage relative to the bar end should be known.

Table 3.8 Strain Gage Specifications (Rebar & Tendon wire)

Specification Item	Data
Type of measurement required	Point strain (approx.) in the "hoop," "meridional," and "radial" directions attached to the reinforcing steel and the prestressing tendon strand wires.
Anticipated exposure conditions	Concrete placement, curing, long term exposure, temperatures from -5 to 50/C
Operational range	Wire gages: 4 - 6% Rebar gages: 5 - 10%
Desired strain sensitivity (gage factor, k)	$1 < k < 2$ (all gages)
Transverse sensitivity, k_t	$k_t < 2\%$ (all gages)
Mounting configuration	Strain gages will be adhesively bonded to the reinforcing steel and tendon wire strands
Logistics (installation, electrical connection, cabling requirements, etc.)	Three wire twisted, insulated cables

Figure 3.6 Rebar Strain Gage

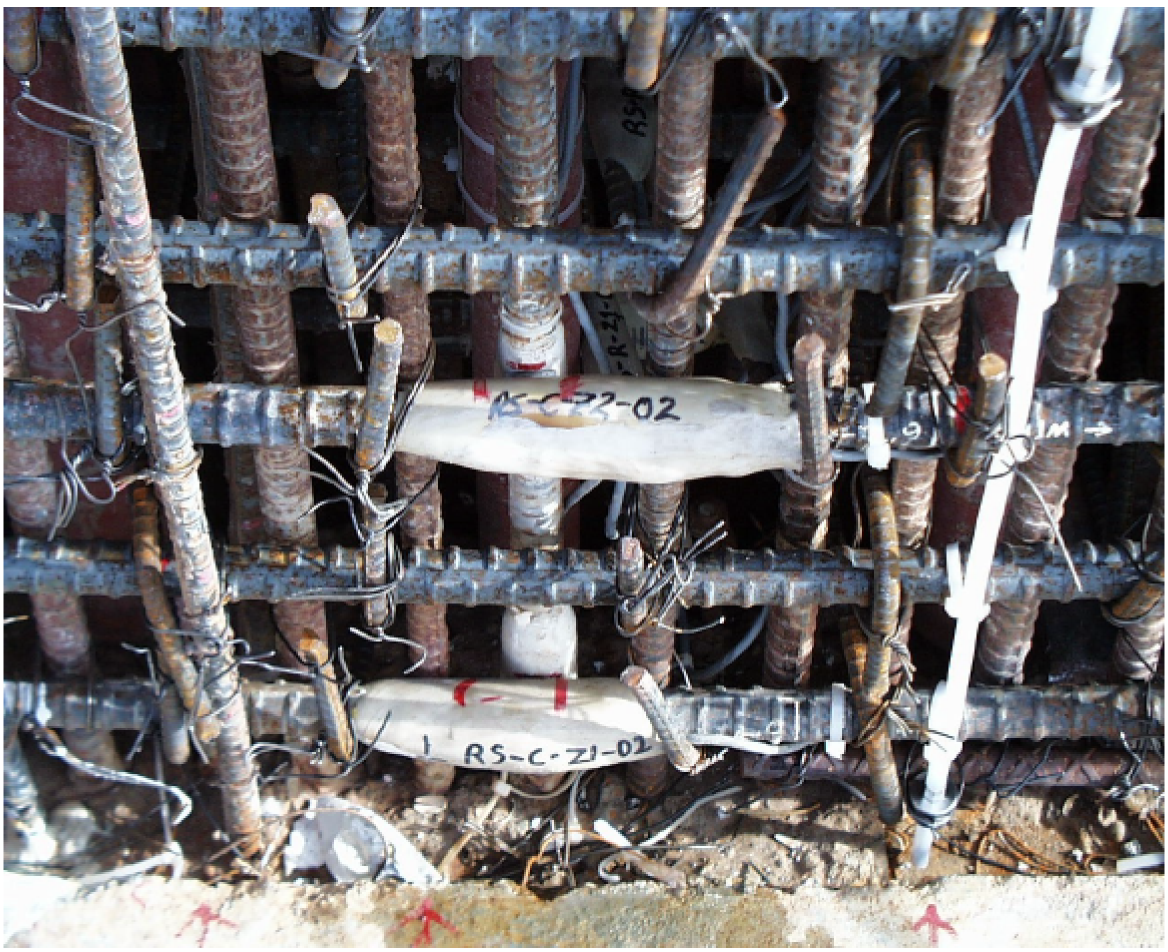


Figure 3.7 Rebar Strain Gages Installed in PCCV Model
(Note SOFO Fiber Optic Concrete Strain Gage at right)

3.2.5.2 Concrete Strain

As noted above, since rebar gages are susceptible to local strain concentration and may be debonded from the concrete, rebar strains may not provide an accurate indication of the concrete strain. Measurement of concrete strains, therefore, may require the use of independent gages designed specifically for this purpose. Based on experience during previous model tests, commercially-available concrete strain gages were not judged reliable or cost-effective. Measurement of global concrete strain can be most accurately and reliably be determined from displacement data using the kinematic relationship $\varepsilon = \Delta r/R$. Specially fabricated bars, or gage bars, which are not part of the normal reinforcing, along with long-gage length fiber-optic gages, were installed to help measure local concrete strains, such as where significant bending occurs (e.g. at the wall base junction, adjacent to the buttresses and near penetrations) and for comparison with rebar strain measurements.

Specifications for the gage bar strain gages are summarized in Tables 3.9. The configuration of the gage bars is illustrated in Figure 3.8. Sample rebar and gage bar strain gages are compared in Figure 3.9.

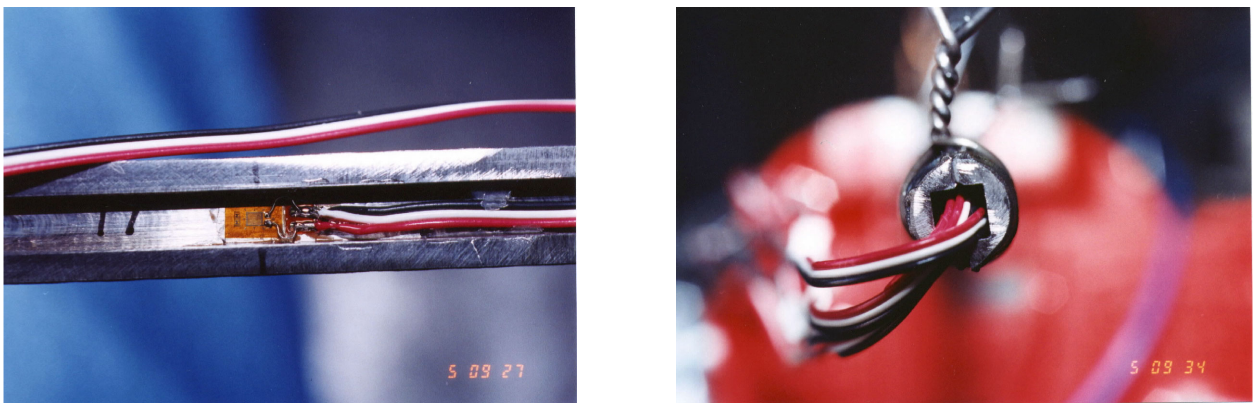


Figure 3.8 Concrete Strain Gage Bars

Figure 3.9 Sample Rebar and Gage Bar Strain Gages

Table 3.9 Strain Gage Specifications (Concrete Gage Bars)

Specification Item	Data
Type of measurement required	Point strain (approx.) in the "hoop" and "meridional" directions, embedded in the concrete.
Anticipated exposure conditions	Concrete placement, curing, long term exposure, temperatures from -5 to 50/C
Operational range	5 – 10%
Desired strain sensitivity (gage factor, k)	$1 < k < 2$ (all gages)
Transverse sensitivity, k_t	$k_t < 2\%$ (all gages)
Mounting configuration	Attached to the reinforcing steel prior to concrete placement
Logistics (installation, electrical connection, cabling requirements, etc.)	Three wire twisted, insulated cables

Specifications for the fiber optic gages SOFO Model 500[25] are summarized in Table 3.10. The SOFO gage, prior to installation, is shown in Figure 3.10. The active gage length is between the two 'anchors,' shown at the bottom, and the remainder is the fiber optic transmission cable. The installed SOFO gage was shown in Figure 3.7.

Table 3.10 Strain Gage Specifications (Fiber Optic Gages)

Specification Item	Data
Type of measurement required	Global or 'near-field' strain in the "hoop" and "meridional" directions in the concrete
Anticipated exposure conditions	Concrete placement, curing, long term exposure, temperatures from -5 to 50/C
Operational range	50 cm (20") gage length, 1 – 2%
Desired strain sensitivity (gage factor, k)	NA
Transverse sensitivity, k_t	NA
Mounting configuration	Place between reinforcing steel prior to concrete placement
Logistics (installation, electrical connection, cabling requirements, etc.)	Fiber optic leads running to 10 channel SOFO DAS reader

3.2.5.3 Liner and Liner Anchor Strain

Both the membrane and bending strains in the liner, as well as strains in the liner anchors, were measured. Strain gages were used to measure both free-field and local strains near liner discontinuities where strain concentrations might occur. Liner anchor strain measurements were included to investigate shear transfer across anchor, pullout force on anchor, and reinforcement contribution in the axial direction of the liner anchor. The specifications for the liner and liner anchor strain gages are summarized in Table 3.11.

At particular details and locations, arrays of gages were applied to allow characterization of the local strain fields and provide insight into the mechanism that tears the liner. Note that gages located adjacent to tears often exhibit much lower strains than expected since the tear acts as a strain relief mechanism on the surrounding structure. In areas where bending strains were likely to occur, strain gages were applied to both sides of the liner to allow them to be resolved into bending and membrane components. In areas where bending was unlikely, strain gages were only applied to the inside surface of the liner. Typical interior and exterior liner and liner anchor gages are shown in Figure 3.11.

[25]SMARTEC SA, Via Pobbiette 11, 6928 Manno, Switzerland. (http://www.smartec.ch/Home.htm)

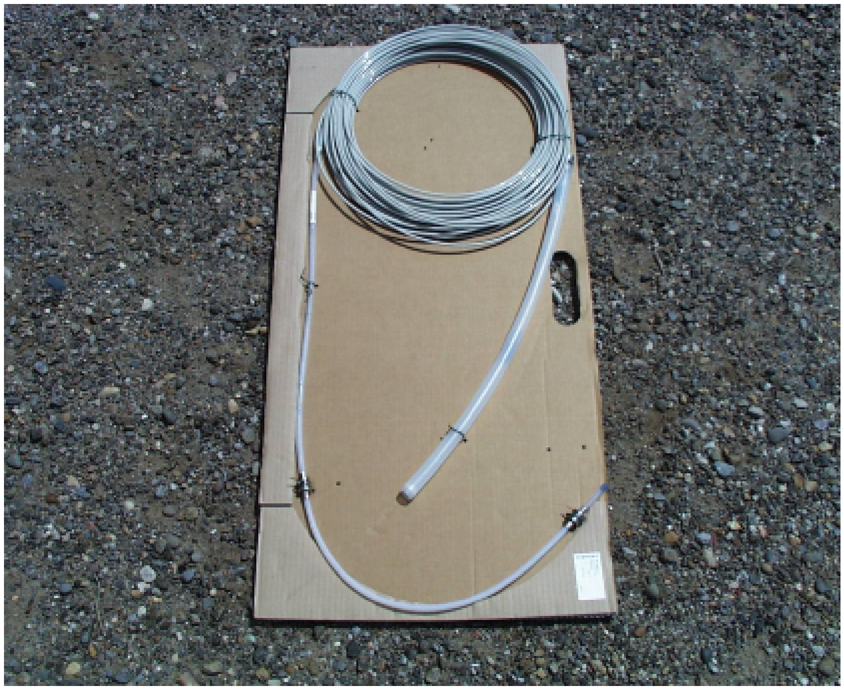


Figure 3.10 SOFO Fiber Optic Strain Gage

Table 3.11 Strain Gage Specifications (Liner & Liner Anchor)

Specification Item	Data
Type of measurement required	Point strain (approx.) in the "hoop," "meridional," and "radial" directions, both internal and external on the liner, liner anchors, and stiffeners embedded in the concrete.
Anticipated exposure conditions	**Internal:** non-purified nitrogen gas at pressures from ambient to approx. 2.1 MPa-g (300 psig), duration of elevated pressures not more than 20 days (500 hours), temperatures from -5 to 50/C. **External:** concrete placement, curing, and long term exposure
Operational range	Strip gages (2-10 elements): 20% 0-45-90 rosettes (3 elements): 20% single gages: 10 - 20%
Desired strain sensitivity (gage factor, k)	$1 < k < 2$ (all gages)
Transverse sensitivity, k_t	$k_t < 2\%$ (all gages)
Mounting configuration	Carrier matrix material bonded to surface of liner (both internal and external), model liner material is carbon steel, painted internally
Logistics (installation, electrical connection, cabling requirements, etc.)	Three wire twisted, insulated cable, junctions to pin-type pressure feedthroughs

Figure 3.11 Liner and Liner Anchor Strain Gages

3.2.5.4 Residual Liner Strain

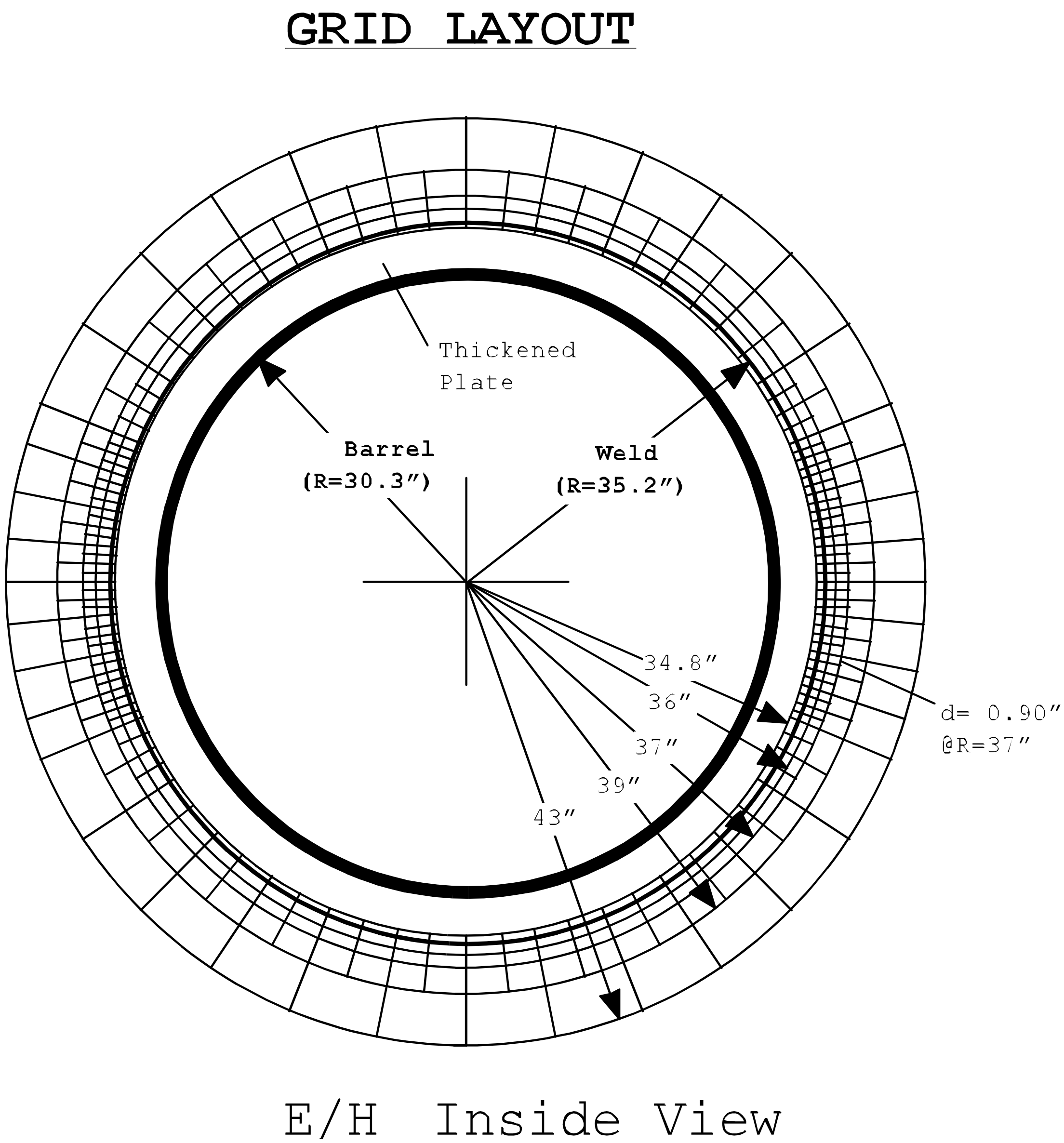
Considering pretest analysis results that predicted high liner strain concentrations around the E/H insert plate and ranked them most likely to tear the liner, an attempt was made to measure the residual strain fields in the liner at this location after high pressure testing. This was performed by placing a grid on the interior liner surface and, using a digital position mapping tool, recording the position of the grid points before and after testing. Based on the change in position, coupled with strain data from liner strain gages located within the grid, it was hoped that a more accurate map of the strain field could be obtained. The grid placed around the E/H is shown in Figure 3.12

3.2.6 Tendon Measurements

Tendon strain and force measurements were discussed Section 2.2.3 in the context of prestressing operations. The basic instrumentation plan called only for tendon anchor forces to be measured during the tests. It was, however, desirable to measure the force at points along the tendon length to confirm the design force distribution described in Section 2.1.3, both initially, after prestressing, and during pressure testing as the PCCV model deformed.

3.2.6.1 Tendon Anchor Force (At Ends)

Load cells were installed at both ends of selected hoop tendons and meridional hairpin tendons to measure the anchor forces during and after prestressing and during pressure testing. Due to the relatively high cost of the load cells, only approximately one-sixth of the model tendons were monitored with load cells. The load cells were inserted between the tendon anchor and the bearing plate embedded in the concrete to measure the compressive force.



5 radial Circles
120 radial Lines
480 points
Smallest grid ~ 1" x 1"

Figure 3.12 Grid Layout around Inside of E/H

From this data, tensile stresses at each end of the tendons were computed. All loads cells were installed just prior to the prestressing operations and measurements were taken throughout the prestressing operations. The requirements for the load cells are provided in Table 3.12.

Table 3.12 Load Cell Specifications

Specification Item	Data
Type of measurement required	Tendon load at both ends
Anticipated exposure conditions	Ambient outdoor temperatures and humidity
Operational range	0 to 890 kN (200 kips)
Desired accuracy	1% of total input range
Temporal response times	Unspecified, not critical
Logistics (electrical connection, cabling requirements, etc.)	Six wire, twisted insulated pairs

Due to limited availability and to reduce cost, two different load cells were used in the model. Higher accuracy (and higher cost) HBM Model C6-100t load cells[26] were used for the instrumented tendons, while somewhat lower accuracy (and less expensive) Geokon Model GK-3000-200-2.0[27] load cells were used for the remaining tendons. The HBM load cell with spherical washers (provided to balance the force applied to the load cell) and bearing plates are shown in Figure 3.13. Both the installation jig used for positioning the load cells for the hoop tendons and the arrangement for the vertical tendons is shown. The Geokon load cell with the bearing plates is shown in Figure 3.14. Although the Geokon load cells came equipped with spherical washers provided by the manufacturer, laboratory calibration tests showed the output was more accurate if very thick bearing plates were used in place of the spherical washers. (Also, the spherical washers exhibited an unfortunate tendency to shatter at loads below the load cell capacity, ejecting fragments in a highly energetic manner.) Both the installation jig used for positioning the load cells for the hoop tendons and the arrangement for the vertical tendons is shown.

3.2.6.2 Tendon Force Distribution (Along Length)

The tendon force distribution was determined by measuring the strain at discrete points of individual wires and strands comprising the tendon. Extensive research was conducted to investigate the efficacy of commercially-available transducers to provide the desired data. Laboratory and mock-up testing of tendon strands were conducted to investigate the performance of the gages and led to a scheme utilizing two types of gages. These tests were also used to develop calibration relationships between wire or strand strain and tendon force, and demonstrate methods to protect the gages from damage during construction and tensioning.

In addition to standard strain gages placed directly on the wires (specified in Table 3.8), strain gages specially designed to measure the axial strain in seven-wire strands, Tensmeg®[28] gages, were used. Tensmeg gages are a single wire gage attached with rubber end-blocks around a tendon strand to measure uniaxial strain in the tendon. The specifications for the Tensmeg gages are summarized in Table 3.13.

Based on the laboratory and mock-up tests that demonstrated the variability of strain from wire to wire within a given strand and from strand to strand, along with the likelihood of a high mortality rate for the strain gages, each measurement location used combinations of wire and strand strain gages, along with special hardware, to protect the gages and lead wires. Special handling and tensioning procedures were also employed to minimize damage to the tendon strain gages.

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[26] HBM, Inc., 19 Bartlett Street, Marlborough, MA 01752. (http://www.hbm.com)

[27] Geokon, Inc., 48 Spencer Street, Lebanon, NH 03766. (http://www.geokon.com/)

[28] Roctest Ltd., 665 Pine Avenue, Saint-Lambert, Quebec, Canada J4P 2P4. (http://www.roctest.com/roctelemac/product/product/tensmeg.htm)

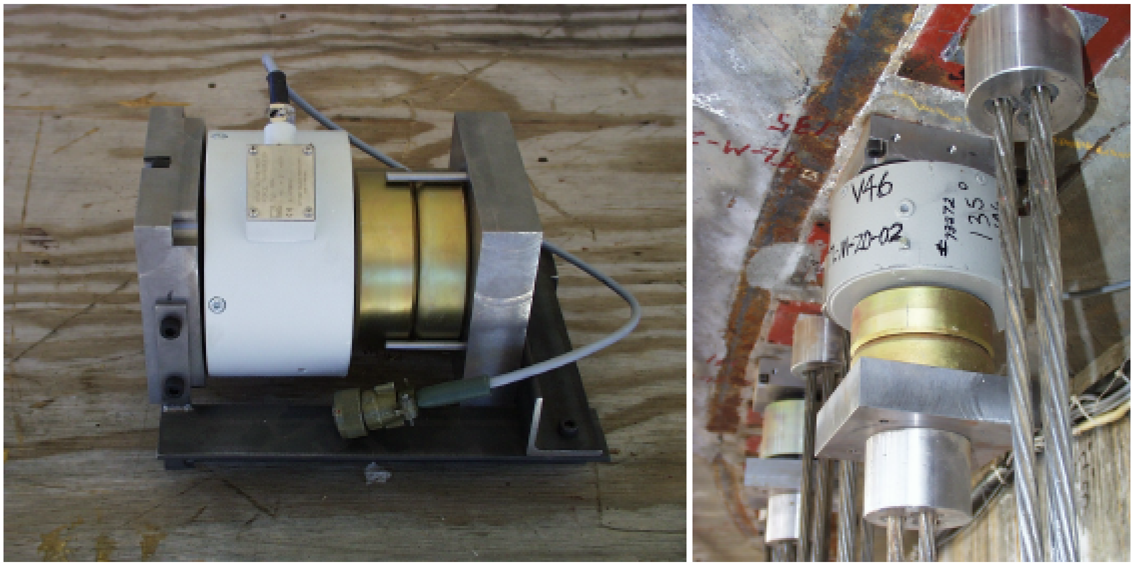


Figure 3.13 HBM Load Cell (a) Installation Jig, (b) In-Place

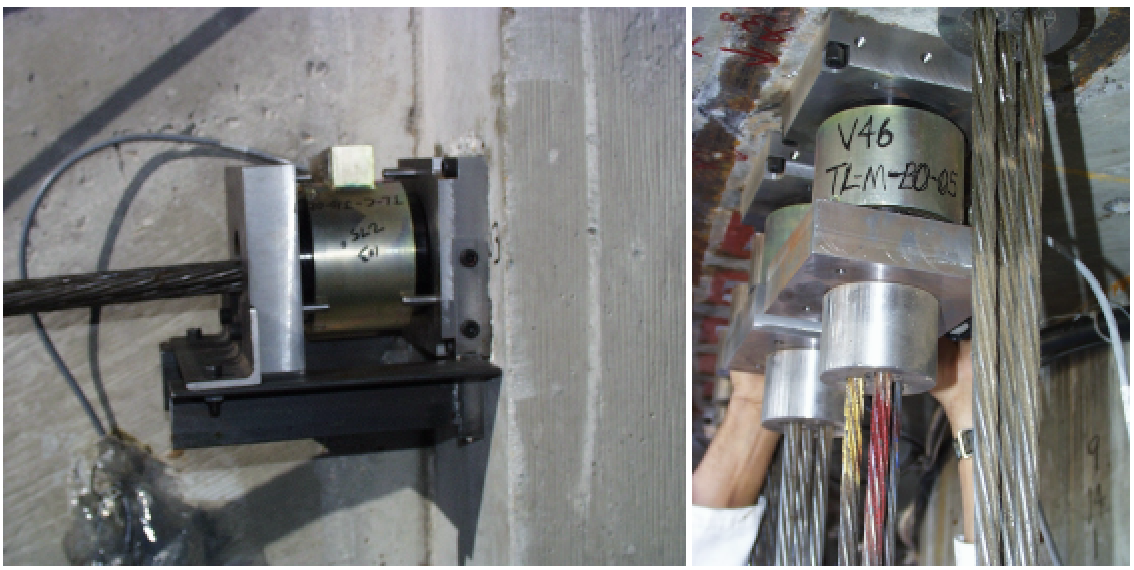


Figure 3.14 Geokon Load Cell (a) Installation Jig, (b) In-Place

Table 3.13 Tensmeg Gage Specifications

Specification Item	Data
Type of measurement required	Point strain (approx.) in the “hoop” and “meridional” directions, inside the tendon ducts, embedded in the concrete
Anticipated exposure conditions	Concrete placement, curing, and long term exposure
Operational range	4 – 6%
Desired strain sensitivity (gage factor, k)	$1 < k < 2$ (all gages)
Transverse sensitivity, k_t	$k_t < 2\%$ (all gages)
Mounting configuration	Gages will be adhesively bonded directly on each strand
Logistics (installation, electrical connection, cabling requirements, etc.)	Three wire twisted, insulated cable

A set of representative hoop and vertical hairpin tendons were instrumented with gages along the length of the tendon. Five hoop tendons were instrumented: H11 near the base of the cylinder wall, H53 near the mid-height, H35 (which is deflected around the E/H and A/L penetrations), and a pair of tendons H67 and H68 halfway between the cylinder mid-height and springline, which were not equipped with the protective hardware. Three vertical tendons were also instrumented: V46, which had the shortest radius in the dome, V37, which had the largest radius in the dome, and V85, which was also deflected around the E/H penetration.

The typical arrangement of the strain gages at a measurement location is shown in Figure 3.15. This figure also illustrates the positioning of the load blocks on the tendons to protect the gages from damage. The specific arrangement of gages at a given measurement location is described in Section 3.3.

3.2.7 Visual Observations

Both video and still photography was employed inside and outside of the PCCV model at locations where large deformation or other signs of damage, such as liner tearing, concrete cracking, or crushing might be expected to occur. These observations were intended to supplement the discrete measurements obtained by the other transducers. Visually monitoring the model with live video during the test was also a safety requirement. It was important to observe various sections of the model visually to properly conduct the high-pressure test.

The video cameras were placed outside the model to monitor the overall behavior, while some were placed close to the model to monitor specific areas, such as the E/H, A/L, and wall-basemat junction. Interior video cameras monitored the liner behavior. A sketch of the video and camera layout is shown in Figure 3.16 In addition, several still cameras were placed near the outside of the model to record snap-shots at each pressure step during the test. Based on the pseudostatic nature of the pressure tests and the unlikelihood of a catastrophic rupture, the video cameras were of normal speed (30 frames/sec) and there were no requirements to use high-speed video cameras during testing.

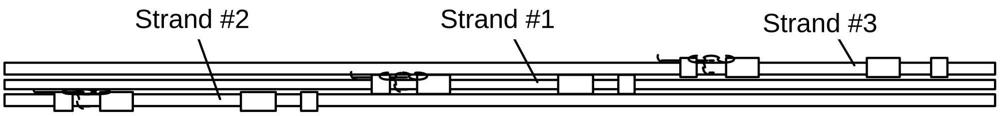
3.2.8 Acoustic Monitoring

Acoustic monitoring was not specified in the basic instrumentation plan, but incorporated into the final instrumentation plan to allow monitoring of the entire structure and identify damage that could occur at locations not monitored via other methods. The specific goals of the acoustic monitoring system were to:

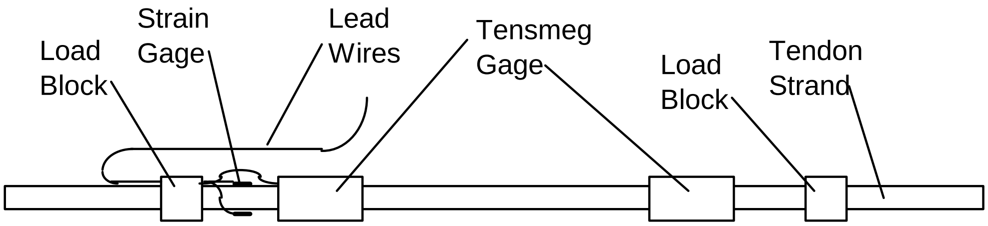
1. detect tendon wire breaks,
2. detect rebar breaks,
3. detect concrete cracking and crushing, and
4. detect liner tearing and leakage.

Acoustic monitoring of the PCCV model during both the prestressing and low and high pressure tests was performed by Pure Technologies Inc. of Calgary, Canada under a turn-key contract. Pure Technologies developed the SoundPrint® acoustic monitoring system[29] and has extensive experience in acoustically monitoring structures, especially prestressed concrete structures, such as parking garages and bridges. This system was run independently of the main data acquisition system (DAS). The system consisted of acoustic sensors, essentially piezo-electric accelerometers, bonded to the structure and connected to a separate DAS. One unique feature of this system is the capability to perform real-time data processing and analysis to identify event types and locations. Thirty-two sensors were glued to the external surface of the model and 16 sensors were placed inside the model. The sensors are shown in Figure 3.17.

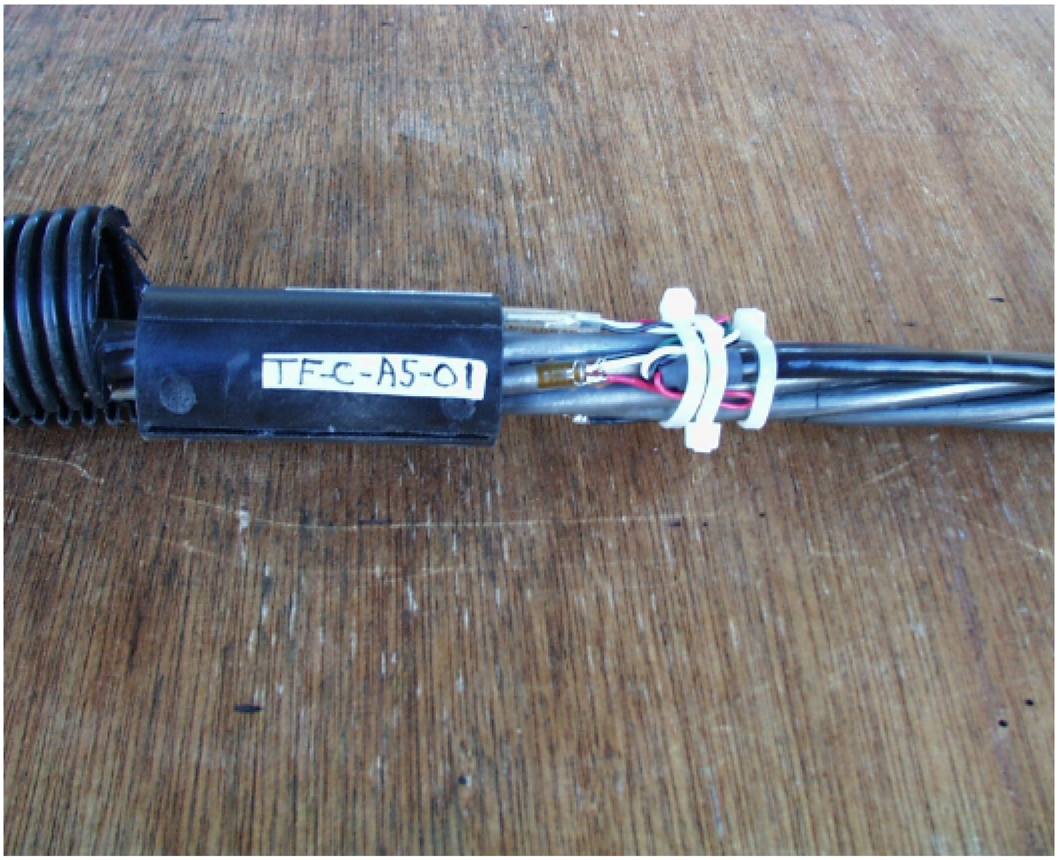
[29]Pure Technologies Ltd., 705 11th Avenue SW, Calgary, AB, Canada T2R 0E3 (http://www.soundprint.com/)



(a) Tendon Instrumentation Layout (Typical)



(b) Strand Instrumentation Layout (Typical)



(c) Tensmeg End Block and Wire Strain Gage

Figure 3.15 Tendon Strain Instrumentation Arrangement

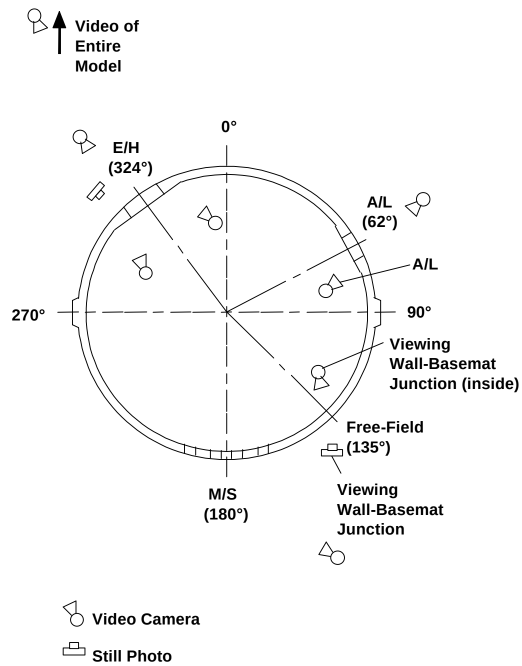


Figure 3.16 Video and Camera Layout

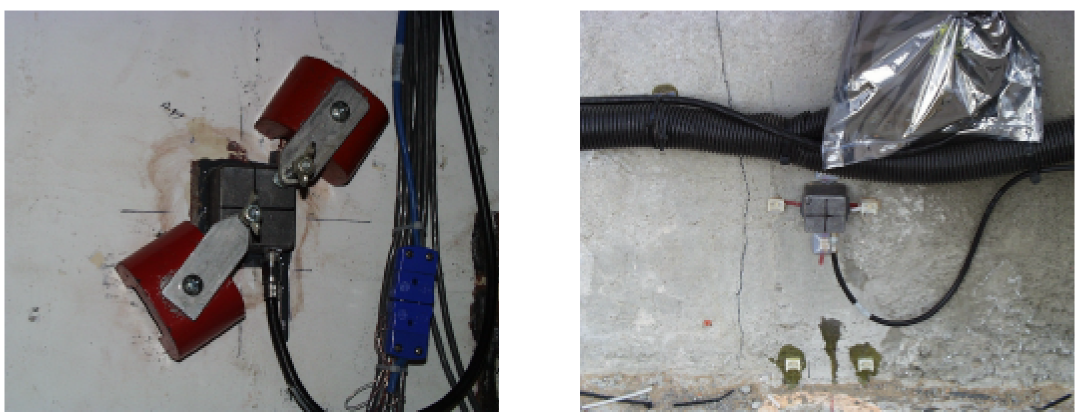


Figure 3.17 Interior and Exterior Acoustic Sensor (clamps during installation only)

3.3 Instrument Installation

3.3.1 Instrument Locations

The final list of gages installed on the PCCV model is provided in Appendix D. This list identifies every gage installed on the model and any gages that were damaged during construction or testing. The format of the tables in Appendix D is given in Table 3.14.

Because of the large number of transducers and the DAS requirement to have a unique address or label, a Gage ID scheme was developed to provide basic information about the type of gage and its orientation and location while providing each gage with a unique identity for subsequent reference and data management. A set of gage type abbreviations were developed to form the first part of the name. These abbreviations are listed in Table 3.15.

Table 3.14 Instrumentation List Format

Column	Description
1	Gage ID (name) AAA-B-CC-DD AAA Type abbreviation (Table 3.15) B Orientation (R-radial, M-meridional, C-circumferential CC General location designator (azimuth *letter*/ elevation *number* from Figure 3.1) DD Sequential numbering (for each similar type and location)
2	Azimuth
3	Vertical Elevation
4	Radial Distance (from centerline of containment)
5	Transducer Designation (for procurement)
6	Location Drawing No. (Appendix E)
7	Details Drawing No.
8	Basic Mark Number (construction designation)
9	Modified Mark Number (instrumented designation)
10	Comments
11	Calibration (pre- and post-calibration status)

Table 3.15 Gage Type Nomenclature

Type Abbreviation	Description
RS	rebar strain, single element gage
GB	gage bar, multiple elements
CE	concrete strain, embedded fiber optic gage
LSI	liner strain, single element gage, inside surface
LRI	liner strain, rosette gage, inside surface
LSO	liner strain, single element gage, outside surface
LRO	liner strain, rosette gage, outside surface
LSA	liner strain, single gage, on anchor
LRA	liner strain, rosette gage, on anchor
LSS	liner strain, single gage, on stiffener
LRS	liner strain, rosette gage, on stiffener
DL	linear variable differential transformer displacement transducer
DT	Temposonics linear displacement transducer
CP	cable potentiometer displacement transducer
IT	inclinometer displacement transducer
TC	thermocouple, embedded in concrete basemat, type K
TW	thermocouple, embedded in cylinder wall, type T
TI	thermocouple, inside liner surface, type T
RT	resistance temperature detector
PG	pressure gauge
TL	tendon load cells
TT	tendon strain, Tensmeg
TF	tendon strain, foil

The location designation is based on the cardinal azimuth and elevation lines shown in Figure 3.1. For example, gage DT-R-Z6-01 is easily recognized as a Temposonics displacement transducer (DT) measuring the radial displacement ®) at Azimuth 135 degrees (Z), Elevation 6200 (6). Since there is only one transducer at this location, it is by default number one (01). These gage IDs are used in reporting and discussing the test data in Chapter 5.

The nominal location of the gages are shown in Figures 3.18 to 3.23. A set of detailed instrumentation drawings is provided in Appendix E. The total number of each type of instrument installed on the PCCV Model is shown in Table 3.16.

Table 3.16 PCCV Instrument Summary

Instrument Type		Number of Gages
Strain	Liner	559
	Rebar	391
	Tendons (Tensmeg)	37
	Tendons (wire)	156
	Concrete	94
Displacements		101
Load Cells (1/3 of Tendons)		68
Temperature and Pressure		100
Acoustic		54
Total		**1560**

3.3.2 Quality Assurance and Control

The PCCV Instrumentation QA Task Plan [33] describes and documents the SNL process for installing instrumentation on the PCCV model. The Task Plan addresses transducer calibration, installation, and wiring to the terminal boards, instrument check-out procedures, and compliance records. In addition, personnel roles, responsibilities, and training appropriate to accomplish the PCCV instrumentation installation task are described. As-installed measurements were made and the exact location of each instrument was recorded as a permanent quality record for the experiment. The tasks, objectives, and responsible project team member described in the Task Plan are summarized in Table 3.17.

Table 3.17 PCCV Instrumentation Procedures Summary

Tasks	Objectives	Responsible Member
1. Provide Instrumentation Drawings for: Transducer Location Deliver As-Built Drawings	Assure proper sensor location to match predicted deformation analysis Assure correct channel assignment to terminal board Assure integrity of instrumentation installation	Instrumentation Engineer
2. Instrument the PCCV Model	Monitor PCCV deformation behavior	Instrumentation Leader
3. Develop/Issue Environmental Safety and Health (ES&H) Operating Procedure	Control hazardous material/processes	Test Leader
4. Install Terminal Boards/Sensor Wiring	Maintain channel assignments	Instrumentation Leader
5. Check Instrument Functionality	Assure sensor integrity	Instrumentation Leader
6. Obtain Required Transducer Calibrations	Assure data accuracy/acceptance	Instrumentation Engineer
7. Complete All Documentation	Assure integrity/traceability of acquired data	Instrumentation Engineer

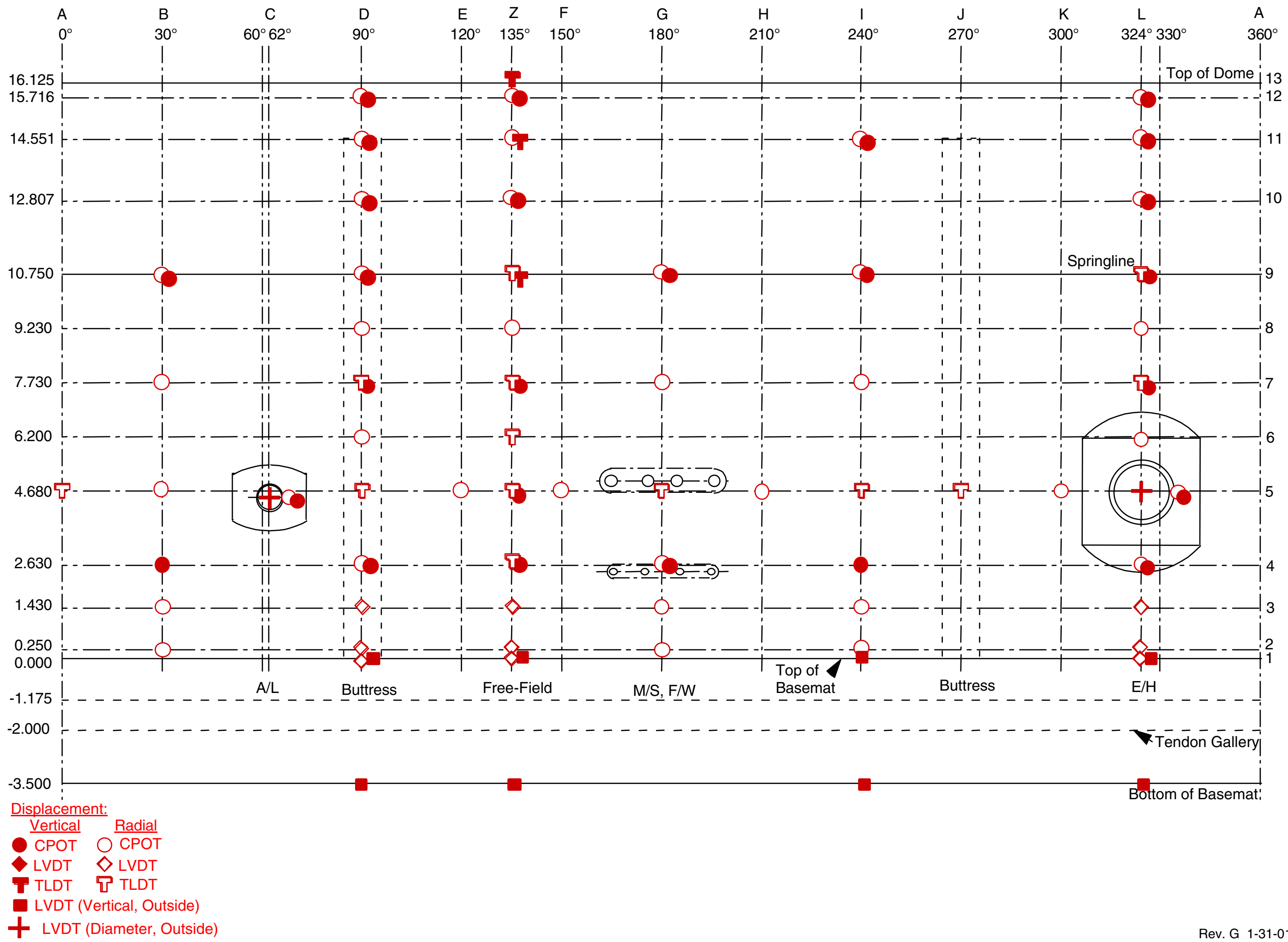


Figure 3.18. Displacement Instrumentation Locations

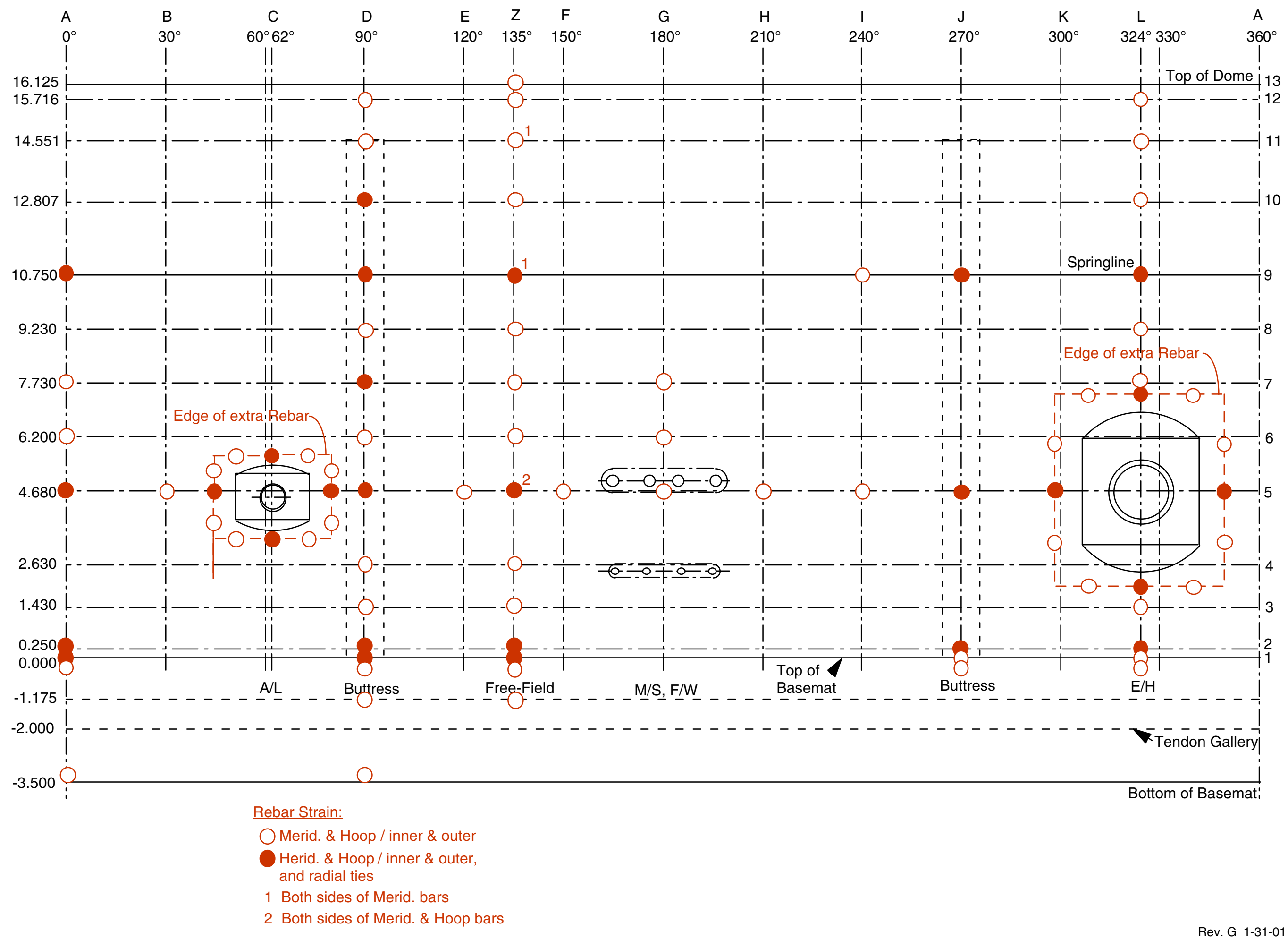


Figure 3.19. Rebar Instrumentation Locations

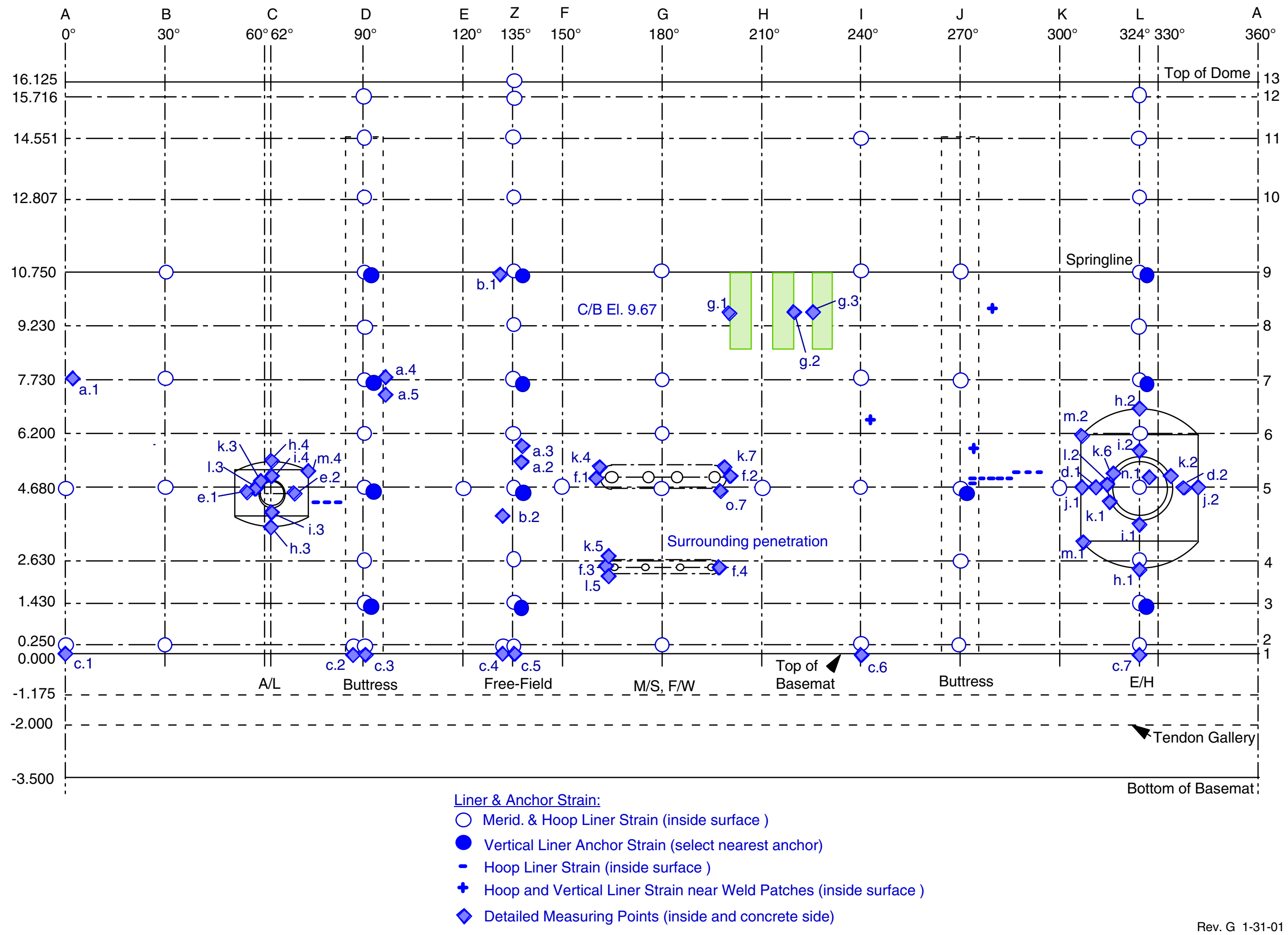


Figure 3.20. Liner and Liner Anchor Instrumentation Locations

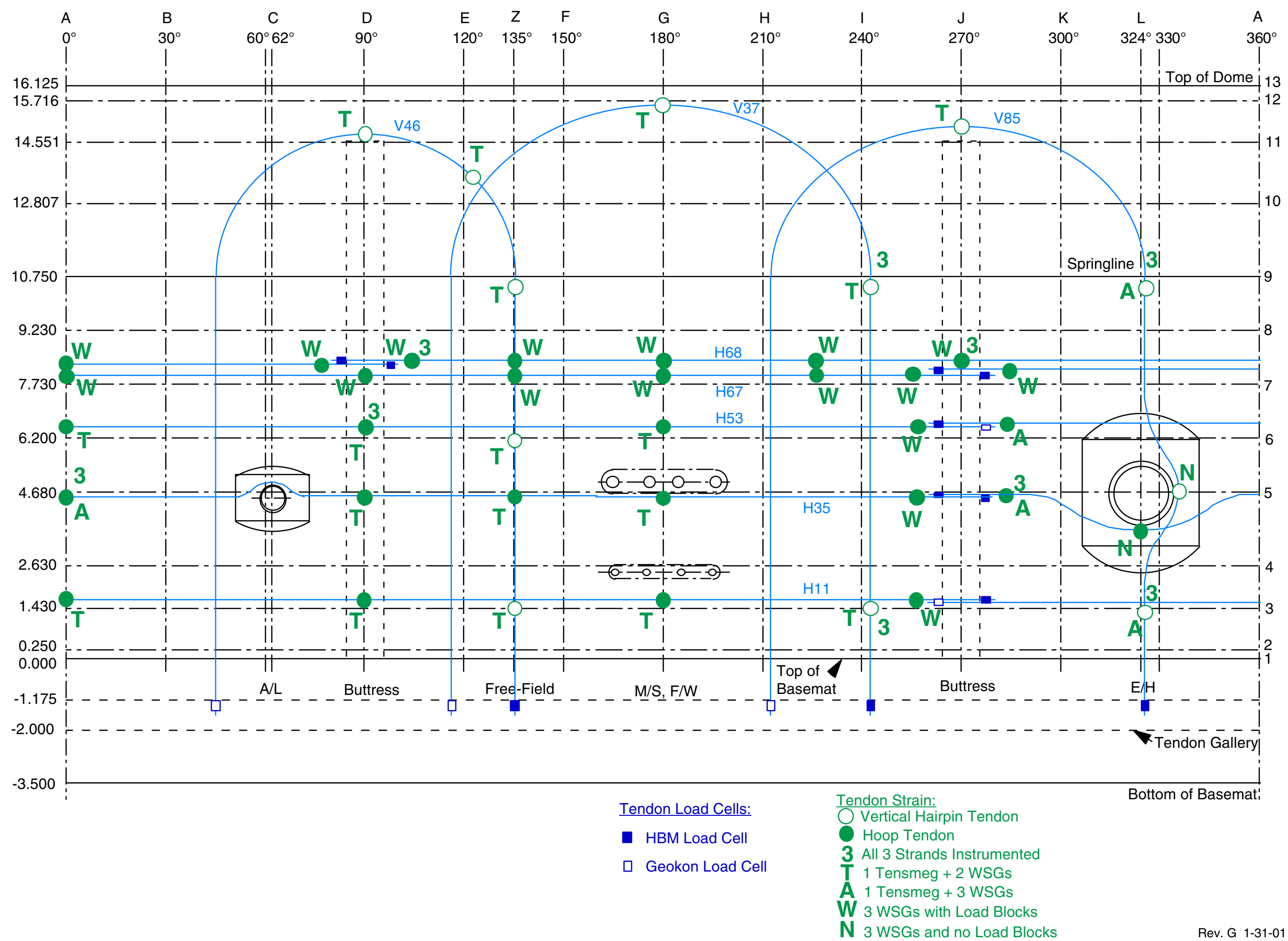


Figure 3.21. Tendon Instrumentation Locations

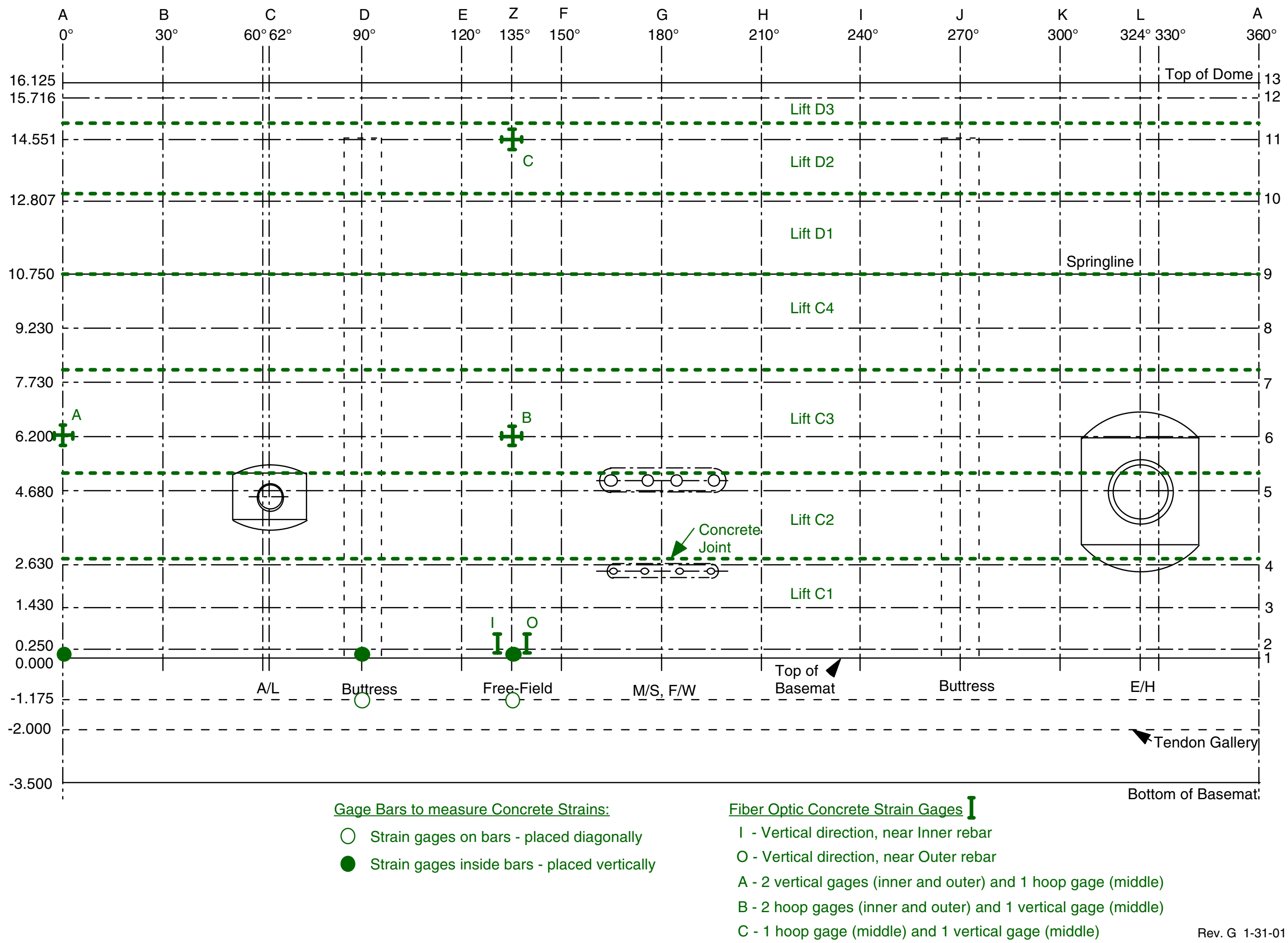


Figure 3.22. Concrete Instrumentation Locations

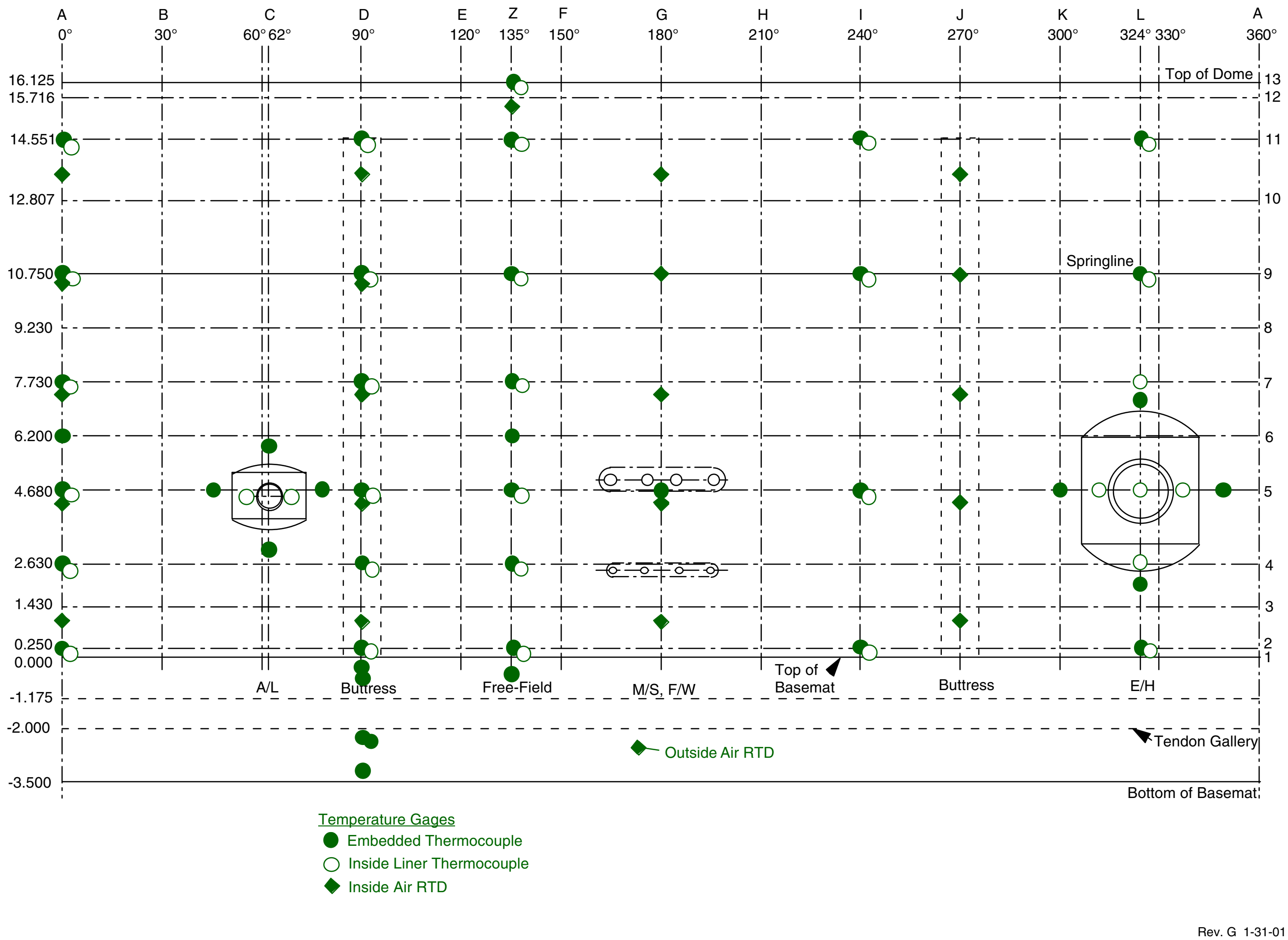


Figure 3.23. Temperature Instrumentation Locations