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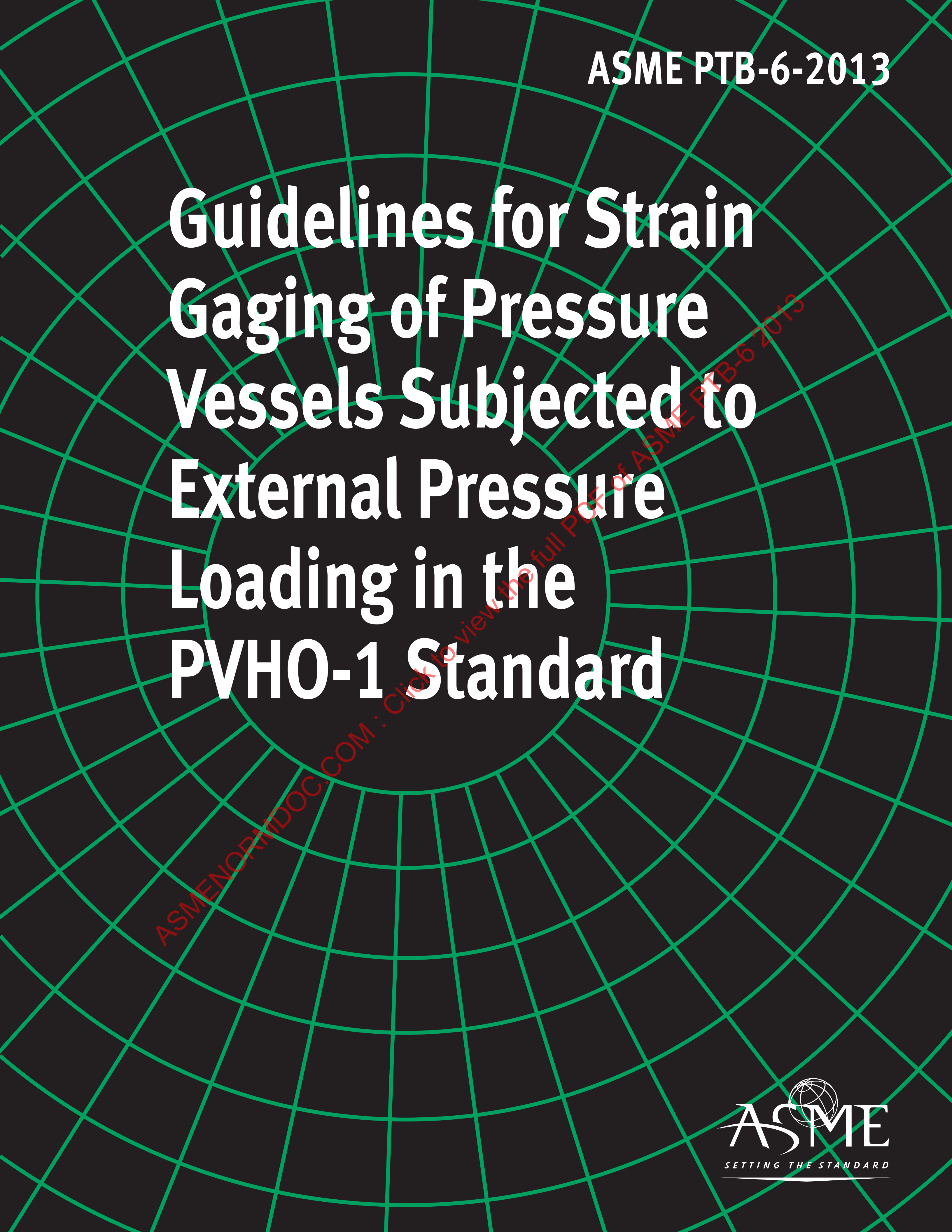

Guidelines for Strain Gaging of Pressure Vessels Subjected to External Pressure Loading in the PVHO-1 Standard

ASME

SETTING THE STANDARD

PTB-6-2013

GUIDELINES FOR STRAIN GAGING OF PRESSURE VESSELS SUBJECTED TO EXTERNAL PRESSURE LOADING IN THE PVHO-1 STANDARD

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SETTING THE STANDARD

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FOREWORD

Strain gaging of pressure vessels (also known as pressure hulls) subjected to the external hydrostatic test pressure loading serves to monitor the structural behavior and response of the pressure vessel under external pressure load conditions. Monitoring the gages during the hydrostatic test can allow the hydrostatic test to be halted prior to causing significant damage and/or collapse of the hull. Therefore the use of strain gaging is recommended to help observe any deviation from the predicted strains (stresses) vs. external pressure in order to avoid unexpected deformation of the hull and possible collapse during the hydrostatic test.

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ABSTRACT

This document provides information and guidance regarding the use of strain gaging of pressure hulls subjected to external hydrostatic test pressure loading. The document presents two examples of strain gaging a pressure vessel subjected to external pressure loading. The first example shows a basic strain gaging plan useful for validating strain and stress analyses, which requires a minimal number of strain gages located at general positions on the hull, and the second example shows a strain gage layout plan which is useful for not only validating strain and stress analyses, but also for monitoring the behavior of the hull during the hydrostatic test, which requires the most number of strain gages since gages are placed at both general locations and regions of concern due to hull as-built geometries that might initiate collapse. These two strain gaging examples are provided as illustrative examples only. These examples in no way establish actual strain gaging requirements per any code, design rules, or jurisdictional body. They do not establish required placement gage locations, gage types to be used, or number of gages. For each hull, the actual strain gaging plan implemented is a function of many factors, such as the chamber's configuration, number and size of openings, attachments, actual as-built geometry, weld details, and whether just validating an analysis and/or monitoring hull behavior to preclude collapse.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the review performed by the following members of the PVHO Standards Committee: Michael Allen, William Crowley, William Davison, Michael Frey, Thomas Galloway, Gary Jacob, Barton Kemper III, James Lawrence, Peter Lewis, Jack Maison, Guy Richards, Thomas Schmidt, John Selby, James Sheffield, Robert Smith, Kenneth Smith, Deepak Talati, Roy Thomas, Matthew Walters, George Wolfe, Eric Fink, Harald Pauli, Todd Marohl, Stephen Reimers and John Witney.

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1 PURPOSES OF STRAIN GAGING PRESSURE HULL

1.1 General

The strain gaging of pressure vessels (also known as pressure hulls) subjected to the external hydrostatic test pressure loading serves two purposes. First and foremost, the gaging is to monitor the structural behavior and response of the pressure vessel under external pressure load conditions. The resulting strains and stresses can then be compared to those obtained from the design analyses performed.

Secondly, proper strain gaging can indicate the onset of collapse of the pressure hull under the external hydrostatic pressure test. Theoretically, using the design rules of the latest ASME PVHO-1 "Safety Standard for Pressure Vessels for Human Occupancy," standard, the pressure hull will not collapse during the external hydrostatic pressure test and serves as the proof test. However, given an unknown circumstance such as an undetected out-of-tolerance fabrication issue, onset of the collapse of the pressure hull can be detected by monitoring the strain gages.

Deviation from the predicted strains (stresses) vs. external pressure is an indicator that the hull is behaving unexpectedly, deforming more than expected, and possibly be near collapse. Monitoring the gages during the hydrostatic test can allow the test to be halted prior to causing significant damage and/or collapse of the hull.

Two examples of strain gaging a pressure vessel subjected to external pressure loading are presented herein. The first example, presented in Section 5.0, shows a basic strain gaging plan useful for validating strain and stress analyses. This level of gaging requires a minimal number of strain gages located at general positions on the hull. The second example, presented in Section 6.0, shows a strain gage layout plan which is useful for not only validating strain and stress analyses, but also for monitoring the behavior of the hull during the hydrostatic test. This level of strain gaging requires the most number of strain gages since gages are placed at both general locations and regions of concern due to hull as-built geometries that might initiate collapse.

These two strain gaging examples are provided as illustrative examples only. These examples in no way establish actual strain gaging requirements per any code, design rules, or jurisdictional body. They do not establish required placement gage locations, gage types to be used, or number of gages. For each hull, the actual strain gaging plan implemented is a function of many factors, such as the chamber's configuration, number and size of openings, attachments, actual as-built geometry, weld details, and whether just validating an analysis and/or monitoring hull behavior to preclude collapse. Other factors not mentioned here might also dictate the placement of strain gages.

1.2 Monitoring For Behavior

The primary purpose of strain gaging a pressure hull subjected to external pressure loading is to monitor its structural behavior under load. Monitoring the behavior consists of measuring the resulting strains, and then typically calculating the corresponding stresses. Traditionally, the desired type of strains and stresses are the maximum and minimum principal strains and stresses. Given these principal stresses, the von Mises stress (also known as the equivalent stress) and stress intensity can then calculated if desired. Given these strains and stresses, they then can be compared to the predicted strains and stresses calculated by classical formulations and/or finite element analysis, thereby validating the analyses performed. The key to obtaining the correct principal strains at a particular location is knowing the principal strain directions on the structure at the location in question. Whether or not these principal strain directions are known is a deciding factor in choosing the proper type of strain gage or strain gage rosette to use. (A strain gage rosette consists of two or three uniaxial gages combined together in a predefined orientation relative to one another as a single unit.) The three types of strain gages and rosettes are:

(a) The uniaxial strain gage,
(b) The biaxial strain gage rosette, and
(c) The triaxial strain gage rosette.

A discussion of these types of gages and their use for monitoring hull response during test conditions is discussed in Section 2.0 of this document.

It is noted that a strain gage rosette provides strain data only in the plane on which the rosette is attached. In many cases, the structure is 3 dimensional in nature with loads resulting in 3 orthogonally oriented principal strains and stresses. See Section 2.1 for a discussion of the use of planar (2D) strain gage rosettes and three dimensional (3D) structures.

1.3 Monitoring For Stability

The secondary purpose of strain gaging a pressure hull subjected to the external hydrostatic pressure test loading is to indicate the possible onset of hull collapse. Theoretically, using the design rules of the latest ASME PVHO-1 "Safety Standard for Pressure Vessels for Human Occupancy," standard, the external hydrostatic pressure test serves as a proof test, and the pressure hull should not collapse during the test.

However, given an unknown circumstance such as an undetected out-of-tolerance fabrication issue or test equipment malfunction, onset of the collapse of the pressure hull can be detected by real-time monitoring of the strain gages. Unexplained deviation from predicted strains (stresses) vs. external pressure is a possible indicator that the hull is deforming more than expected and possibly near collapse. This can allow the test to be halted prior to complete hull collapse. The hull can then possibly be repaired, strengthened, or rerated to a shallower depth if acceptable, and retested.

Just as for monitoring the hull for structural behavior, uniaxial strain gages and biaxial/triaxial strain gage rosettes are utilized for this purpose.

Although not a requirement of the PVHO-1 rules, for the hydrostatic tests of some pressure hulls, the internal volume of the hull is filled with water and vented through an orifice and piped to the atmosphere. As the external pressure on the hull is increased, the water in the hull's internal volume is expelled. The internal volume change as a function of increasing external pressure, determined by measuring the amount of water expelled from the internal volume, is another set of data that can be monitored. Deviation from the expected amount of internal volume change might also indicate the onset of collapse. (Another reason for an increase of the amount of water expelled from the hull's internal volume would be a leak at a fitting or other interface.) It is noted that for some pressure hulls, the use of internal volume water is impractical and might be undesirable.

As a side note, the use of internal water in the pressure vessel being tested serves as a safety means for the test tank being used to perform the hydrostatic test. The use of internal water in the pressure vessel being tested and a small orifice from the pressure vessel vented to the atmosphere prevents sudden implosion of the pressure hull. This eliminates or reduces the shock wave created by a sudden collapse event, thereby protecting the test chamber from damage.

2 STRAIN GAGE ROSETTE TYPES AND RECOMMENDED USES

2.1 General

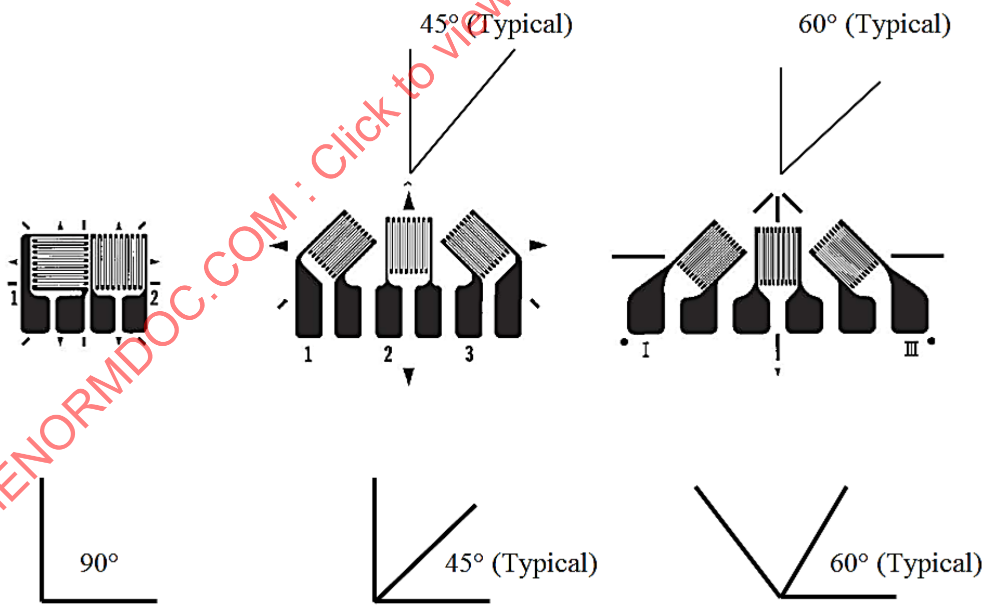
Three general types of strain gages and rosettes are used for the gaging of pressure hulls. They are listed below, and an example of each type of gage and rosette is shown in Figure 2.1.

(a) The uniaxial strain gage consists of a single strain gage (Fig. 2.1(a.)),

(b) The biaxial, or tee, strain gage rosette consists of two (2) strain gages oriented at 90 degrees relative to each other (Fig. 2.1(b)), and

(c) The triaxial strain gage rosette consists of three (3) strain gages. Two general types of triaxial gage rosettes exist, they being the "rectangular" (Fig. 2.1(c.)) and the "delta" (Fig. 2.1(d)) type rosettes. The rectangular rosette has two of the three gages oriented 45 and 90 degrees from the first gage. The delta rosette has two of the three gages oriented 60 and 120 degrees from the first gage.

(a.) Uniaxial Strain Gage



(b.) Biaxial, or "Tee" Strain Gage Rosette

(c.) Triaxial "Rectangular" Strain Gage Rosette

(d.) Triaxial "Delta" Strain Gage Rosette

Figure 2.1 – Examples of Uniaxial and Typical Strain Gage Rosettes

The examples shown of the rectangular (Fig. 2.1(c.)) and delta (Fig. 2.1(d)) strain gage rosettes are typical. Other geometrically different but functionally equivalent configurations exist.

Manufacturers' literature present other types of rectangular and delta strain gage rosettes not shown in Figure 2.1. Also given in the literature, both the manufacturers' and classical texts are the appropriate equations for calculating the maximum and minimum principal strains and stresses from the measured strains.

As shown in Figure 2.1, the strain gages are planar and therefore are applied on a surface of the structure. This results in the fact that only the principal strains and stresses in the plane of the applied strain gage rosette can be determined. For a 3-dimensional structure, a third principal strain and stress exists, which is perpendicular to the plane on which the strain gage rosette is applied. The third principal stress is determined by other means.

For example, given a cylinder under external pressure, the longitudinal and circumferential strains and stresses (2 of the 3 principal strains and stresses) can be measured using a strain gage rosette since these lie in a plane. The third principal stress is known from the fact that on the outer surface of the cylinder, the radial stress (the third principal stress) is equal in magnitude (in compression) to the external pressure. Likewise, if located on the inside surface of the cylinder, the radial stress (the third principal stress) is equal to zero (0), assuming no internal gage pressure exists. Once the 3 principal stresses are known, other 3D stress quantities such as von Mises (or equivalent) stress can be calculated.

It is important to note that when comparing only the planar principal strains and stresses obtained experimentally (from the strain gages) with those obtained analytically, care must be taken that only the corresponding analytical planar values be used in the comparison study.

In almost all cases, the purpose of using strain gages during a test is to determine the planar principal strains and stresses. Knowledge about the principal strain/stress directions is required to choose the correct type of strain gage rosette or uniaxial strain gage. For pressure vessels subjected to external pressure loadings, it is expected that most (if not all) strain gages will be biaxial or triaxial strain gage rosettes.

2.2 Use of Uniaxial Strain Gages

If the state of strain and stress is uniaxial, then the principal strain/stress direction is known. The use of a uniaxial strain gage at this location would be sufficient to determine the principal strain and stress. A simplistic example of uniaxial strain is a straight bar in tension. An example of such a location in a pressure hull is on the inside surface of the flange of a tee stiffener (circumferential direction, mid-width of flange) for a tee-stiffened cylindrical hull.

2.3 Use of Biaxial (Tee) Strain Gage Rosettes

When the directions of the planar principal strains/stresses are known, then the use of a biaxial (tee) strain gage rosette is satisfactory. In order to measure the principal strains, the rosette is oriented such that the gages are in line with the principal directions. The principal stresses are then calculated by closed form equations. It is noted that there will be some strain measurement error if the gages of the rosette are misaligned with these principal directions. For more information on this type of measurement error, the reader is referred to literature regarding this subject available from strain gage manufacturers.

An example of a structure where the principal strain directions are known is a cylinder under internal or external pressure. The principal strain directions are the longitudinal and circumferential directions. It is noted that this is true only if no other localized structural features or loads are in close proximity that can affect the principal directions.

2.4 Use of Triaxial Strain Gage Rosettes

When the directions of the principal strains are not known, then triaxial strain gage rosettes must be used. The triaxial strain gage rosette can be applied to the structure at any orientation. The principal strains and stresses are calculated by closed-form equations. If desired, the actual principal strain and stress directions can be calculated by closed-form solution with respect to the "reference" gage within the rosette.

For complicated structures with complicated loadings, although the direction of the principal strains can be determined through analysis such as finite element analysis, the triaxial gage is preferred since it can be applied without concern for orientation. As mentioned previously, the principal strains and stresses can be calculated with the triaxial rosette oriented in any direction.

A couple of examples of locations where the triaxial strain gage rosette is useful for determining the principal strains and stresses in a complicated strain/stress field are described as follows. In a ring stiffened cylindrical hull, where a large opening exists and intersects with the stiffening rings, complicated peak strain/stress fields can exist in the hull at these locations. Also, if a location on a welded spherical shell results in a non-uniform "flat" spot and is at the limits for acceptable sphericity, then it might be prudent to place a series of triaxial rosettes within this region and monitor their behavior during the hydrostatic test.

3 NOMENCLATURE FOR PRESSURE HULLS

Before proceeding with the discussion of guidelines for recommended general locations for strain gages and strain gage rosettes, it is helpful to present some nomenclature and associated description (in the form of figures and narrative as appropriate). The commonly used nomenclature associated with pressure vessels subjected to external pressure loading is:

(a) Ring Stiffened Compartments (Figure 3.1)
(b) End Bay Regions (Figures 3.1 and 3.2)
(The end bay region normally consists of the 1st and 2nd stiffeners from the end closure and cylinder intersection region, and the mid bay shell regions are between the 1st, 2nd, and 3rd stiffeners.)
(c) Inter-Stiffener Shell, or Midbay Region (Figure 3.1)
(d) Typical (Small) and Deep (Large) Stiffeners (Figure 3.1)
(e) Cylinder Hull Out-Of-Circularity (OOC) (Figure 3.3)
(Out-of-circularity is defined as the radial deviation from the true mean circle and the actual hull shape, measured at a hull cross section.)
(f) Cylinder Hull Out-Of-Fairness (OOF) (Figure 3.4)
(Out-of-fairness is defined as the maximum distance between a straight longitudinal line between stiffeners and the actual hull form, measured in the radial direction of the hull.)
(g) Spherical Shell Out-Of Sphericity (OOS) (Figure 3.5)
(Out-of-sphericity is defined as the radial deviation from the true mean sphere and the actual spherical hull shape, measured at a cross section. This is applicable for spherical hulls, hemispherical end closures, and spherical segment heads, such as the crown region of an elliptical head.)

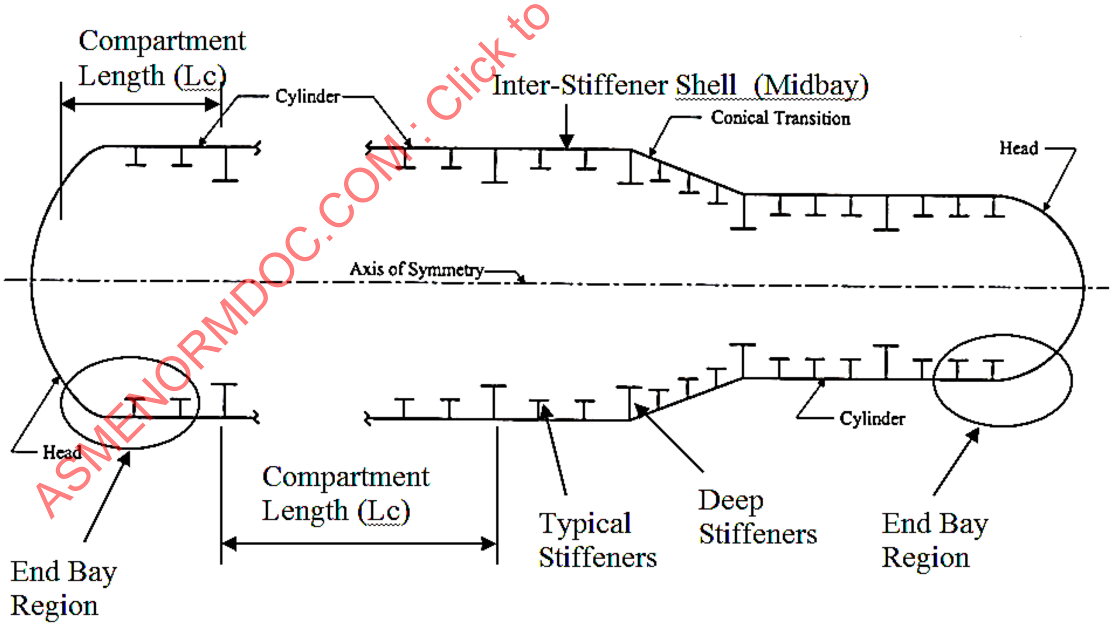


Figure 3.1 – Illustrative Hull Components

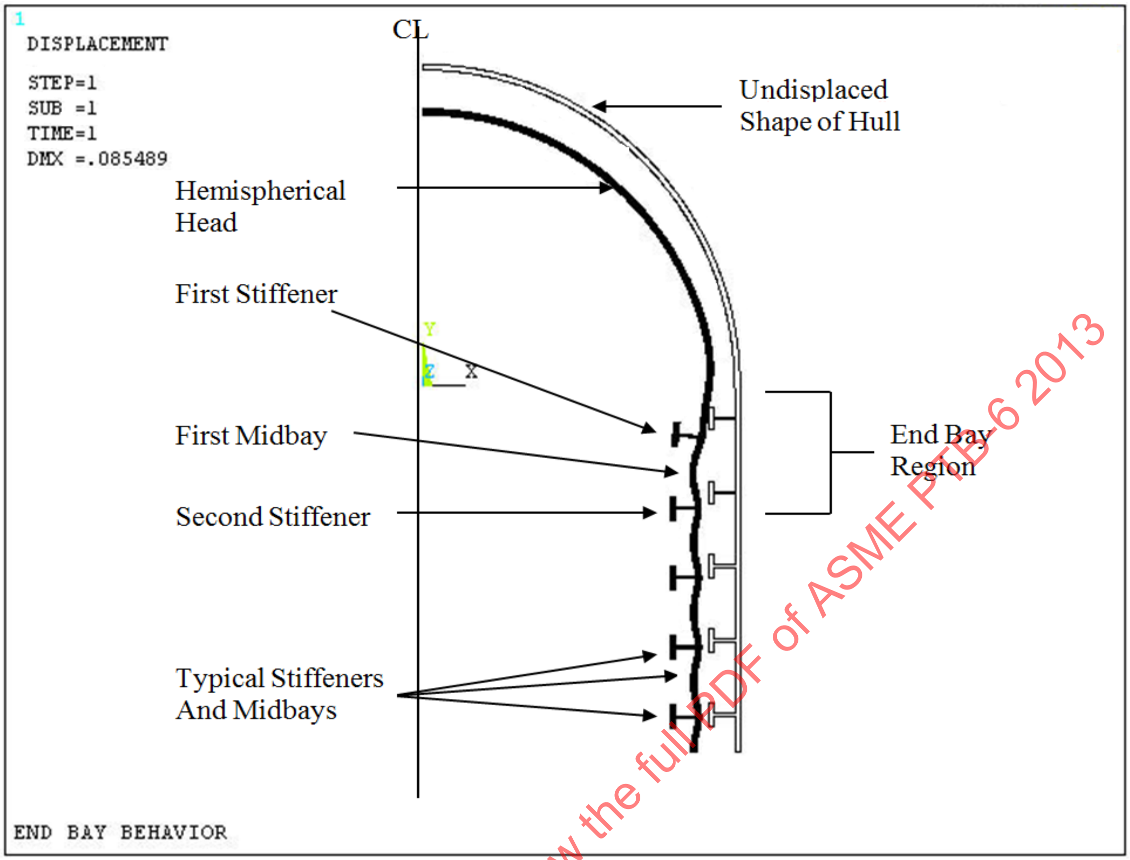


Figure 3.2 – End Bay Region in Typical Ring Stiffened Hull (and Exaggerated Displaced Shape under External Pressure Load)

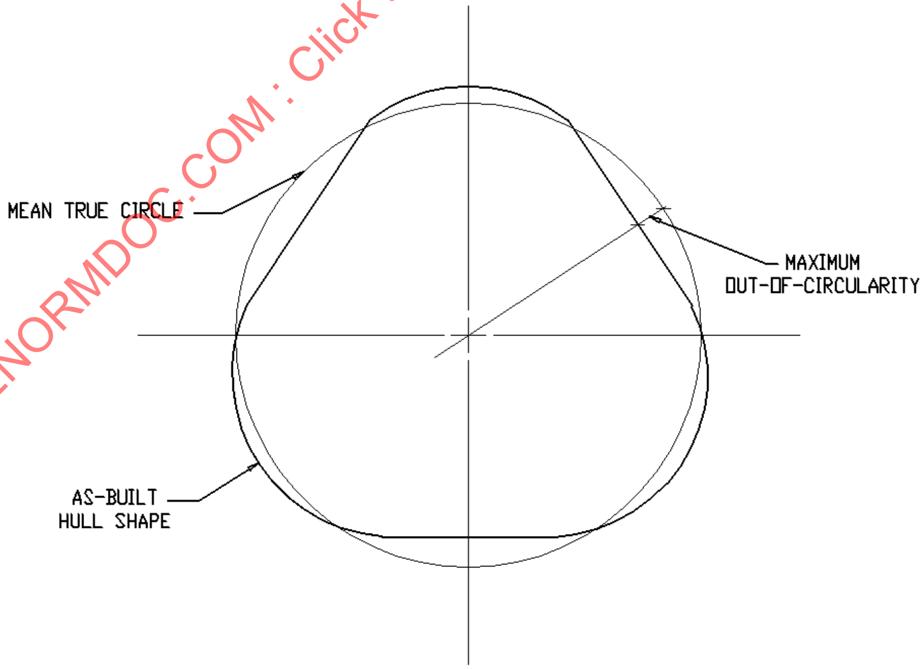


Figure 3.3 – Out-of-Circularity (OOC) of Cylindrical Pressure Hull

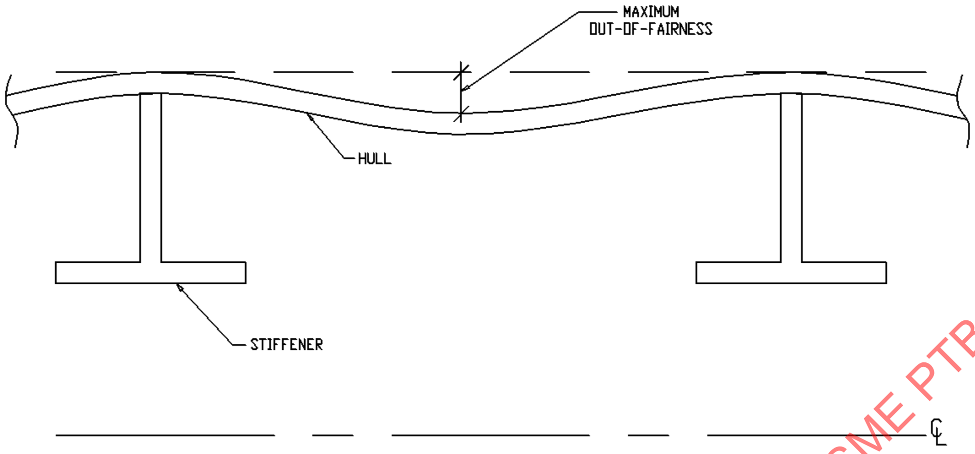


Figure 3.4 – Out-of-Fairness (OOF) of Cylindrical Pressure Hull

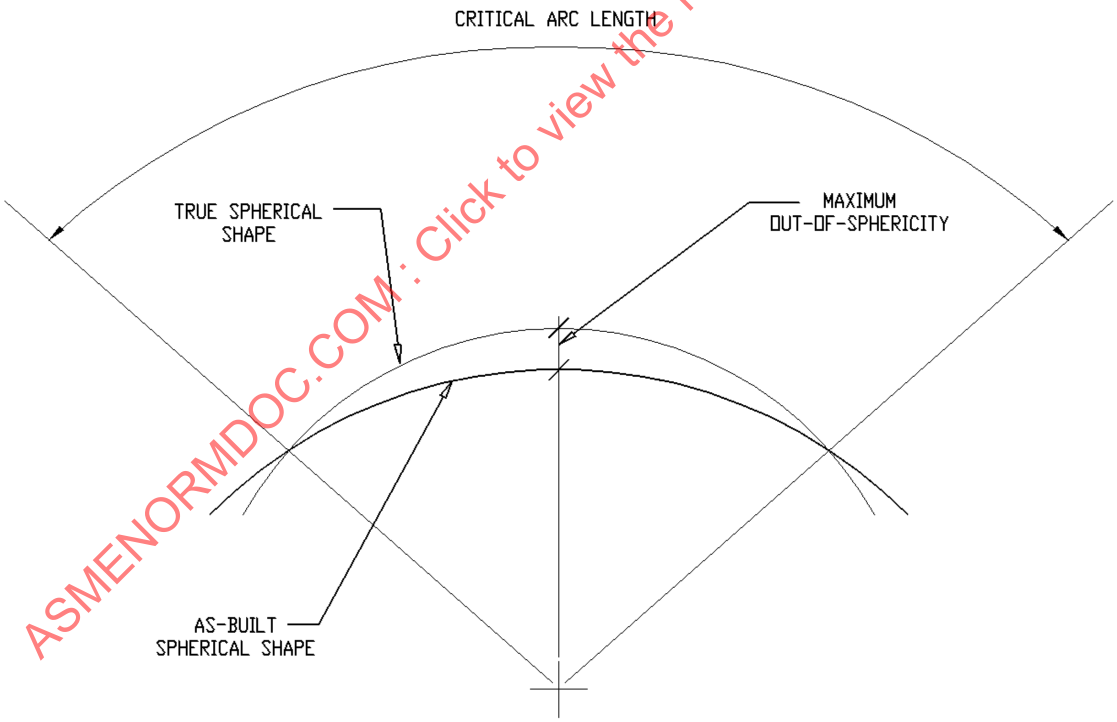


Figure 3.5 – Out-of-Sphericity (OOS) of Spherical/Hemispherical Pressure Hull

4 GENERAL GUIDELINES FOR LOCATIONS OF STRAIN GAGES AND ROSETTES

The following suggested general locations for strain gage and strain gage rosette placement are not all inclusive. They represent guidelines for identifying locations used for monitoring the structural behavior and stability of a pressure hull subjected to the external hydrostatic pressure test loading. Each pressure vessel should be evaluated for strain gage locations due to its uniqueness in design, loading conditions other than external pressure, fabrication issues, as-built configuration, etc.

For monitoring the general behavior and stability of the pressure hull under the external pressure loading, the following general locations for strain gages and strain gage rosettes are recommended:

(a) *General shell membrane* - These locations verify membrane behavior of the shell(s) and should be in open areas away from the influence of any localized opening or structure. If the shell is a ring-stiffened cylindrical shell, the region selected for strain gaging would be the midbay region.

(b) *Local shell membrane at regions of significant out-of-sphericity (OOS) for spherical shells and heads, and out-of-circularity (OOC) and out-of-fairness (OOF) for cylindrical shells* - These locations determine local membrane behavior of the shell regions that significantly depart from true spherical form for spherical shells, or circular and fairness form for cylindrical shells.

(c) *Shell regions at large openings* - These locations determine shell response and stress concentration effects caused by these openings in the hull.

(d) *Shell regions at and between multiple openings* - These locations determine shell response and stress concentration effects caused by multiple openings and their proximity to each other.

(e) *Locations at structural discontinuities, hard spots, etc.* - These locations determine peak stresses and gradients at structural discontinuities, hard spots, etc. Determining gradients involves the use of several gages normally spaced at equal intervals apart from one another. This technique is useful if a strain gage rosette cannot be placed at an exact location of peak stress. By measuring the strain gradient, the peak strain can then be determined by extrapolation.

(f) *Flanges and webs of tee-stiffened (or rings of ring-stiffened) cylindrical hulls* - These locations verify the compressive circumferential stress in the stiffener. Strain gages may also be placed on both sides of stiffener webs or rings to monitor possible bending behavior.

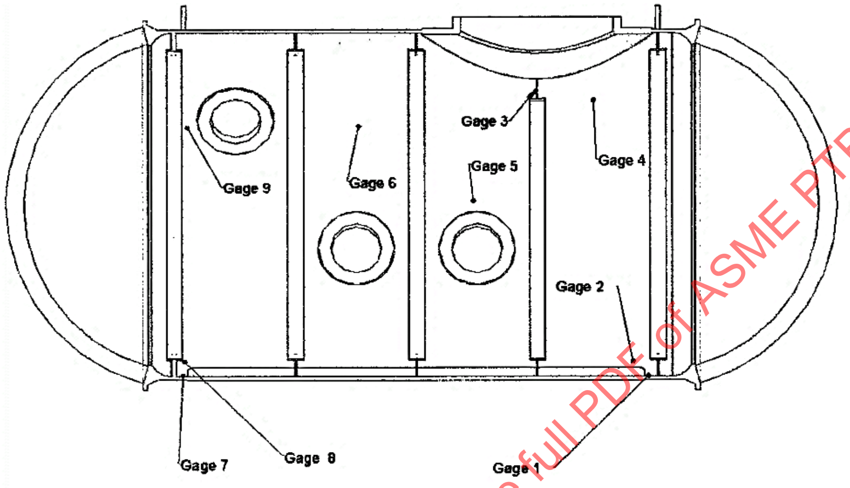
(g) *Any locations not covered above but are shown to have unusual behavior, and high stresses and/or gradients, etc.* - These locations determine unusual behavior, and peak stresses and gradients.

Ideally, when shell behavior is of interest, both the inside and outside surfaces at each location on the pressure vessel hull should be strain gaged. By comparing the measured strains at each inside and outside location, not only can the associated desired strains and stresses be determined, but any shell bending behavior can be determined.

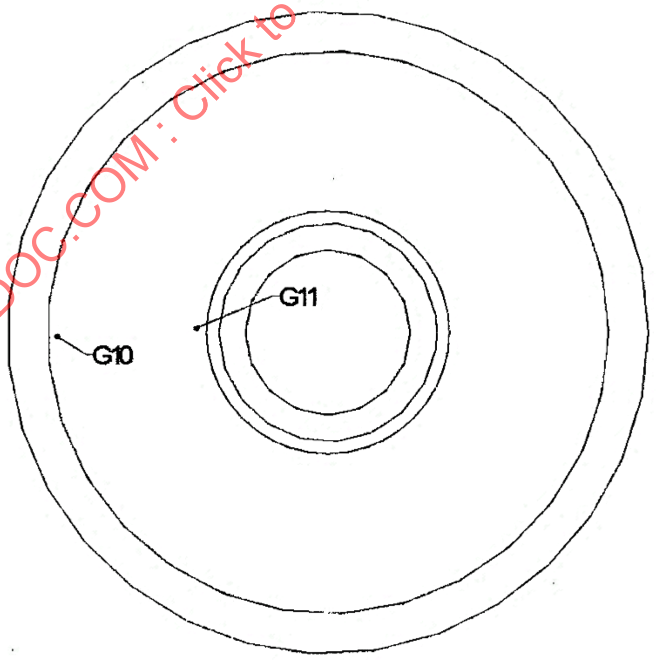
5 EXAMPLE OF BASIC STRAIN GAGE LOCATIONS

The following is an example of basic locations for strain gages and rosettes for a submersible hull.

The example hull configuration is a tee-stiffened cylindrical hull with acrylic hemispherical end closures. The cylindrical hull contains a large diameter access opening and hatch with viewport. A thickened shell section around the hull opening is provided as hull reinforcement. Several viewports and their reinforcements exist in the hull. The hull configuration is shown in Figure 5.1.



Strain Gage Rosette Locations on Hull



Strain Gage Rosette Locations on Hatch

Figure 5.1 – Basic Strain Gage Location on Pressure Hull

Of interest is the behavior of the shell when subjected to the external hydrostatic test pressure. Ten (10) locations on the hull's shell are chosen for strain gaging. These locations are indicated in Figure 5.1, and are as follows:

(a) Shell midbay membrane region away from influence of the large opening, penetrations, or other structures.
  - Location 6

(b) Shell region near end stiffeners (endbay regions) and bottom hull structural component.
  - Locations 1, 2, 7, and 8

(c) Shell region between end stiffener and viewport reinforcement
  - Location 9

(d) Shell regions near the intersection with the large diameter access opening reinforcement.
  - Locations 3 and 4

(e) Shell region at midbay and viewport reinforcement
  - Location 5

(f) Hatch shell at main ring and viewport reinforcements
  - Locations G10 and G11

6 EXAMPLE OF COMPLEX STRAIN GAGE LOCATIONS

6.1 General

The following is an actual example of the strain gage locations for a deep diving submersible hull. Due to the complexity of the design, actual as-built geometry, and other considerations, many locations on the hull were chosen for strain gaging.

The basic hull configuration is a tee-stiffened cylindrical hull with hemispherical end shells, and is shown in Figure 6.1. One spherical end shell contains a hatch with associated shell reinforcement. Another hatch and shell reinforcement is located on the underside of the cylindrical hull. Multiple small diameter penetrations exist in the spherical heads and in some regions of the cylindrical shell. Thickened shell sections to which lifting and frame lugs are attached exist at various locations in the cylindrical shell and create hard spots in the shell.

Locations chosen for strain gaging were based on obtaining general shell behavior away from the influence of localized structures, shell behavior at the hatches, hull stiffener behavior, peak stresses, and stress gradients at various regions.

In addition to these locations, based on the as-built geometry of the fabricated hull, additional regions were chosen for strain gaging. These locations included:

(a) Areas in the spherical heads were the maximum out-of-sphericity (OOS) occurred,
(b) Areas in the cylindrical hull were maximum out-of-circularity (OOC) and out-of-fairness (OOF) occurred,
(c) Localized regions in the shell adjacent to some of the thickened shell plate inserts,
(d) Several regions between multiple small diameter openings in one of the spherical heads

Figures 6.1 through 6.13 present the strain gage and strain gage rosette locations for the subject hull. The locations are identified by the circled numbers. Also shown in these figures are the use of single, biaxial (tee) rosettes, and triaxial (rectangular) strain gage rosettes.

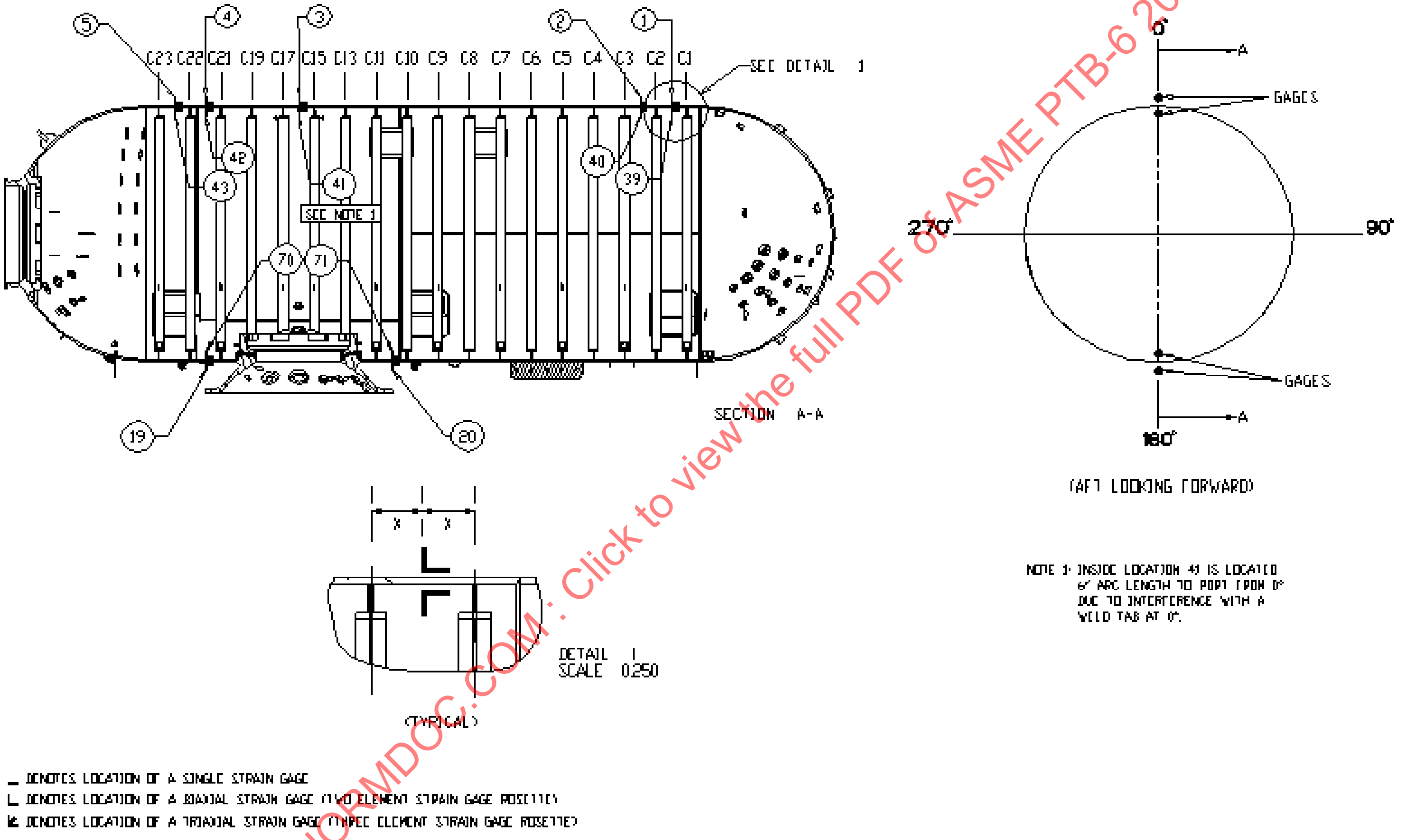
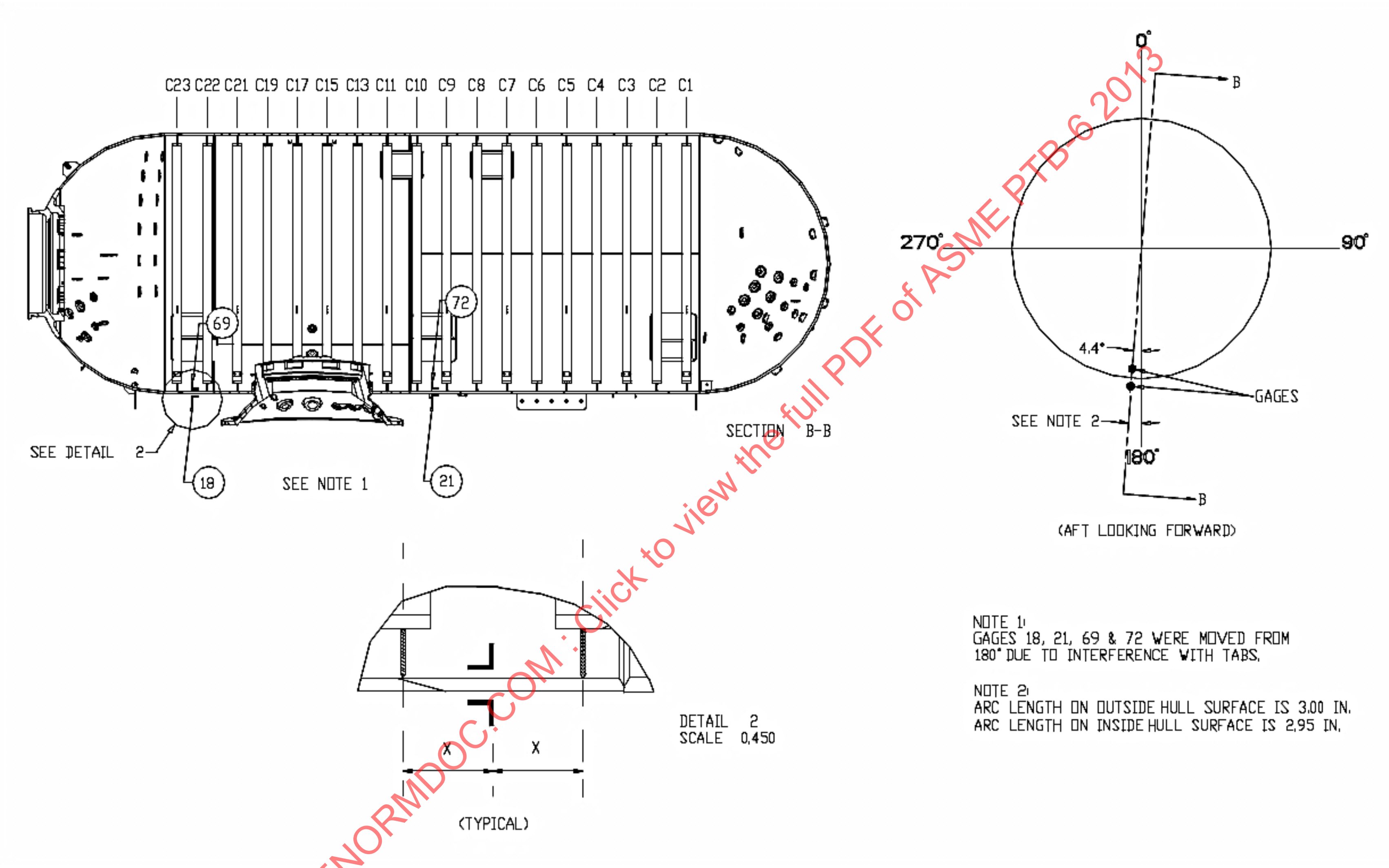


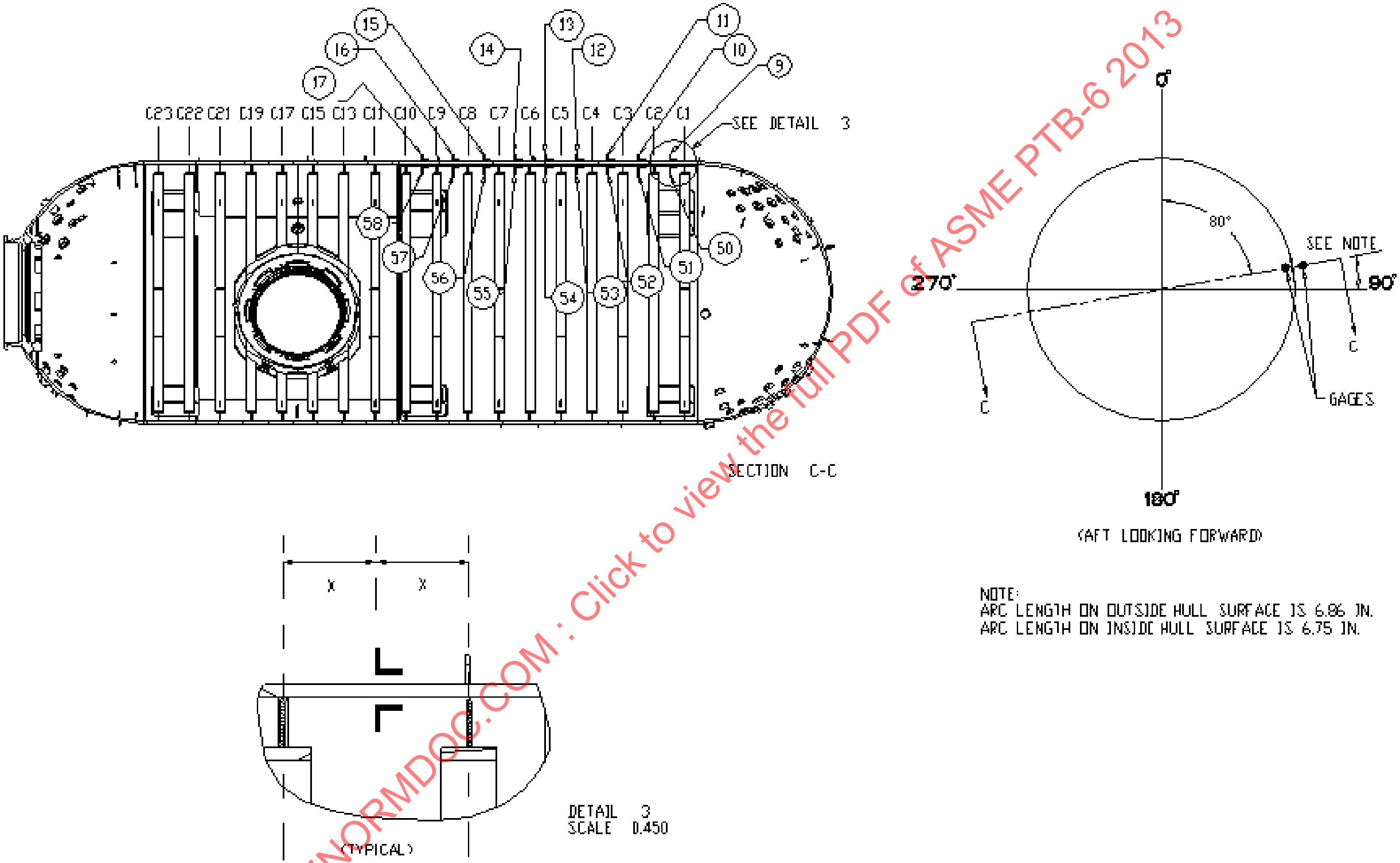
Figure 6.1 – Complex Strain Gage Locations on Pressure Hull



NOTE 1:
GAGES 18, 21, 69 & 72 WERE MOVED FROM
180° DUE TO INTERFERENCE WITH TABS.

NOTE 2:
ARC LENGTH ON OUTSIDE HULL SURFACE IS 3.00 IN.
ARC LENGTH ON INSIDE HULL SURFACE IS 2.95 IN.

Figure 6.2 – Complex Strain Gage Locations on Pressure Hull



NOTE:
ARC LENGTH ON OUTSIDE HULL SURFACE IS 6.86 IN.
ARC LENGTH ON INSIDE HULL SURFACE IS 6.75 IN.

Figure 6.3 – Complex Strain Gage Locations on Pressure Hull

The following is a general description of the strain gage and strain gage rosette locations chosen for this specific hull. Sections 6.2 and 6.3 present the exact locations both narratively and pictorially.

(a) Shell midbay region(s) away from effects of end bay regions, large and small openings, other structures, etc. for establishing typical shell midbay behavior. Biaxial gages, inside and outside surfaces.
(b) Center compartment frame(s), inside flange face, circumferential direction, 4 locations: 0, 90, 180, 270 degrees.
(c) End bay regions: Shell Midbay and stiffeners, 4 locations: 0, 90, 180, 270 degrees. Biaxial gages, inside and outside surfaces.
(d) Shell midbay and stiffener gages located on hull parallel to longitudinal axis, running the length of the hull as far as a "wave" exists.
These strain gages are located on hull at regions of maximum out-of-circularity (OOC), both high and low OOC's (lobe and trough, respectively). Biaxial gages at midbays, circumferential gages on inner flange faces. As-built OOC measurements determine positions of "wave." Number of adjacent shell midbays and stiffeners are as required to include complete "wave" of OOC on the inside and outside surfaces.
(e) Flanges and webs of stiffeners associated with "wave."
(f) Shell midbay region of maximum OOC, if not included in "wave" (item d above).
(g) Shell midbay region of maximum out-of-fairness (OOF), if not included in "wave," item d above.
(h) Shell midbay region of combination of maximum OOC and OOF, if not included in "wave," item d above.
(i) Shell midbay regions adjacent to large openings.
(j) Shell regions near small openings.
(k) Structural discontinuities.
(l) Other regions as deemed necessary by analysis or other means.

6.2 Locations on Ring-Stiffened Cylindrical Hull

(a) Shell midbay region(s) away from effects of end bay regions, large and small openings, other structures, etc. for establishing typical shell midbay behavior.
  - Locations 3 and 41.

(b) Center compartment frame(s), inside flange face, circumferential direction.
  - None, due to other frames being gaged.

(c) End bay regions: Shell midbay and stiffeners. Biaxial gages, inside and outside surfaces.
  - Locations 1, 2, 39, and 40; 4, 5, 42, and 43.

(d) Shell midbay and stiffener gages located on hull parallel to longitudinal axis for length of "wave".
  - Locations 9 through17, and 50 through 58.
  - Locations 22 through 24, and 81 through 83.

(e) Flanges and webs of stiffeners associated with "wave".
  - Locations 93 through 100, and 61 through 64.

(f) Shell midbay region of maximum OOC, if not included in "wave". (Item d above)
  - Included as others.

(g) Shell midbay region of combination of maximum OOC and OOF, if not included in "wave". (Item d above)
  - Included as others.

(h) Shell midbay regions adjacent to large openings.
  - Locations 19 and 70, 20 and 71, 18 and 69, 21 and 72, 25 and 80.

(i) Shell regions near small openings.
  - Included as others.

(j) Structural discontinuities.
  - Locations 6 and 44, and 91 and 92.

6.3 Locations on Hemispherical Heads

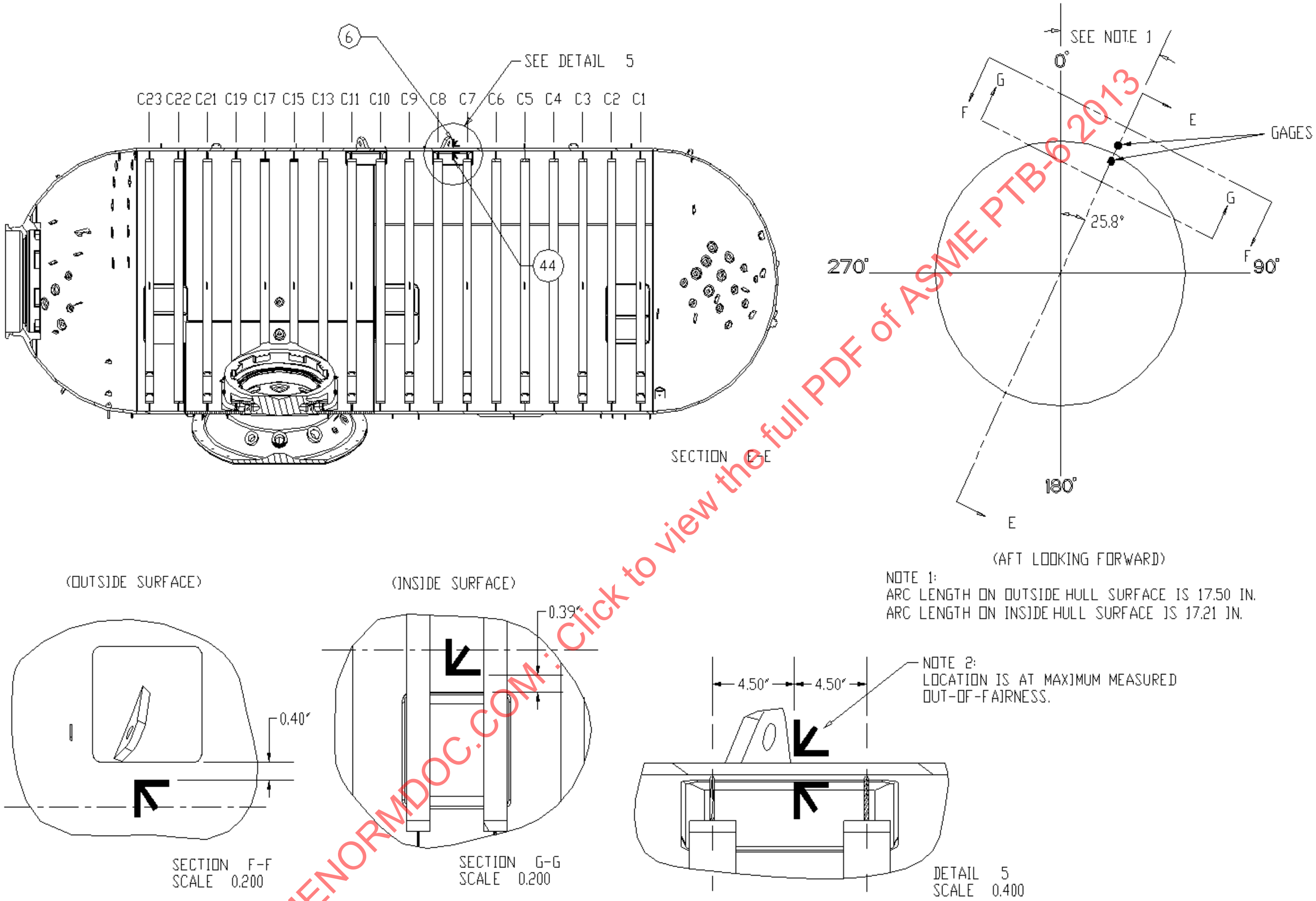
(a) Membrane region(s) away from influence of openings, penetrations, intersections with other shells.
  - Location 7.

(b) Region(s) of maximum out-of-sphericity (OOS).
  - Locations 26 and 104, and 27 through 35.

(c) Regions at intersection with large openings.
  - Locations 8 and 90.

(d) Regions at other openings and hard spots.
  - Locations 36 and 103.

(e) Other regions as deemed necessary by analysis or other means.
  - Locations 37, 38, 101, and 102.



NOTE 1:
ARC LENGTH ON OUTSIDE HULL SURFACE IS 17.50 IN.
ARC LENGTH ON INSIDE HULL SURFACE IS 17.21 IN.

NOTE 2:
LOCATION IS AT MAXIMUM MEASURED OUT-OF-FAIRNESS.

Figure 6.4 – Complex Strain Gage Locations on Pressure Hull

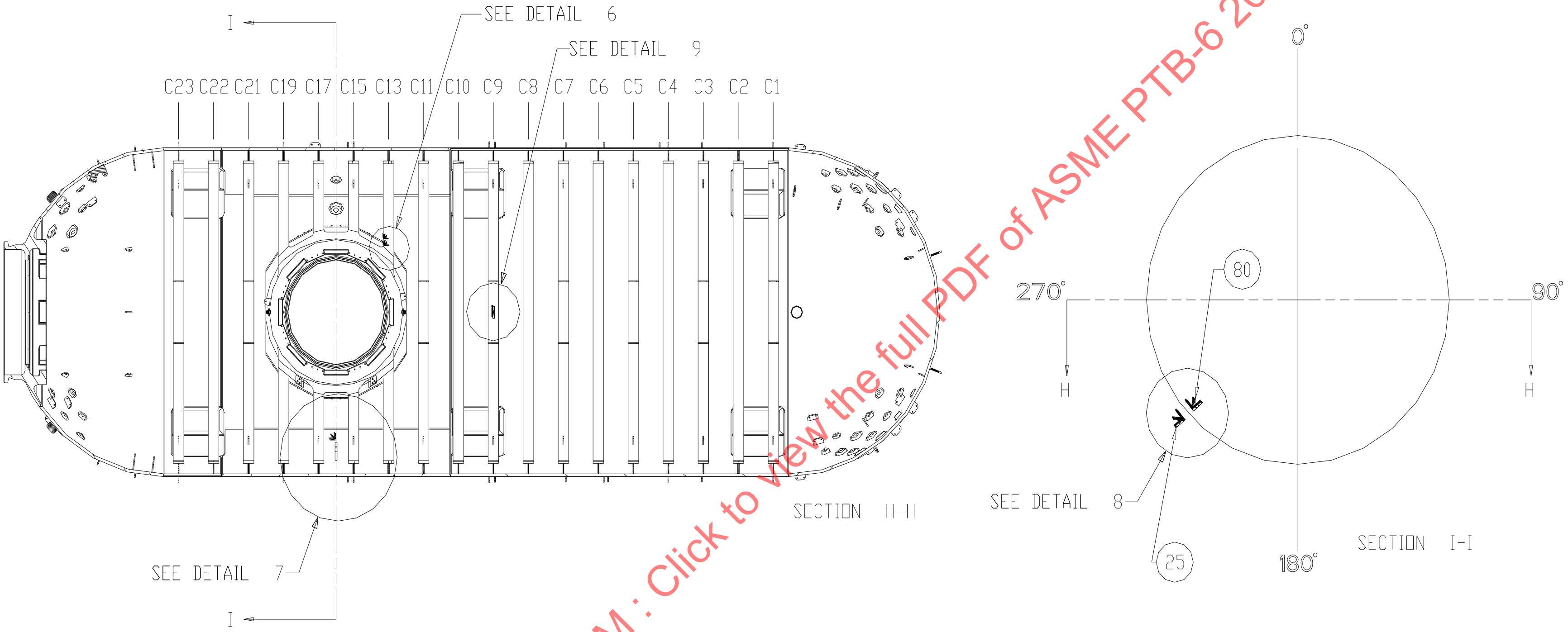


Figure 6.5 – Complex Strain Gage Locations on Pressure Hull

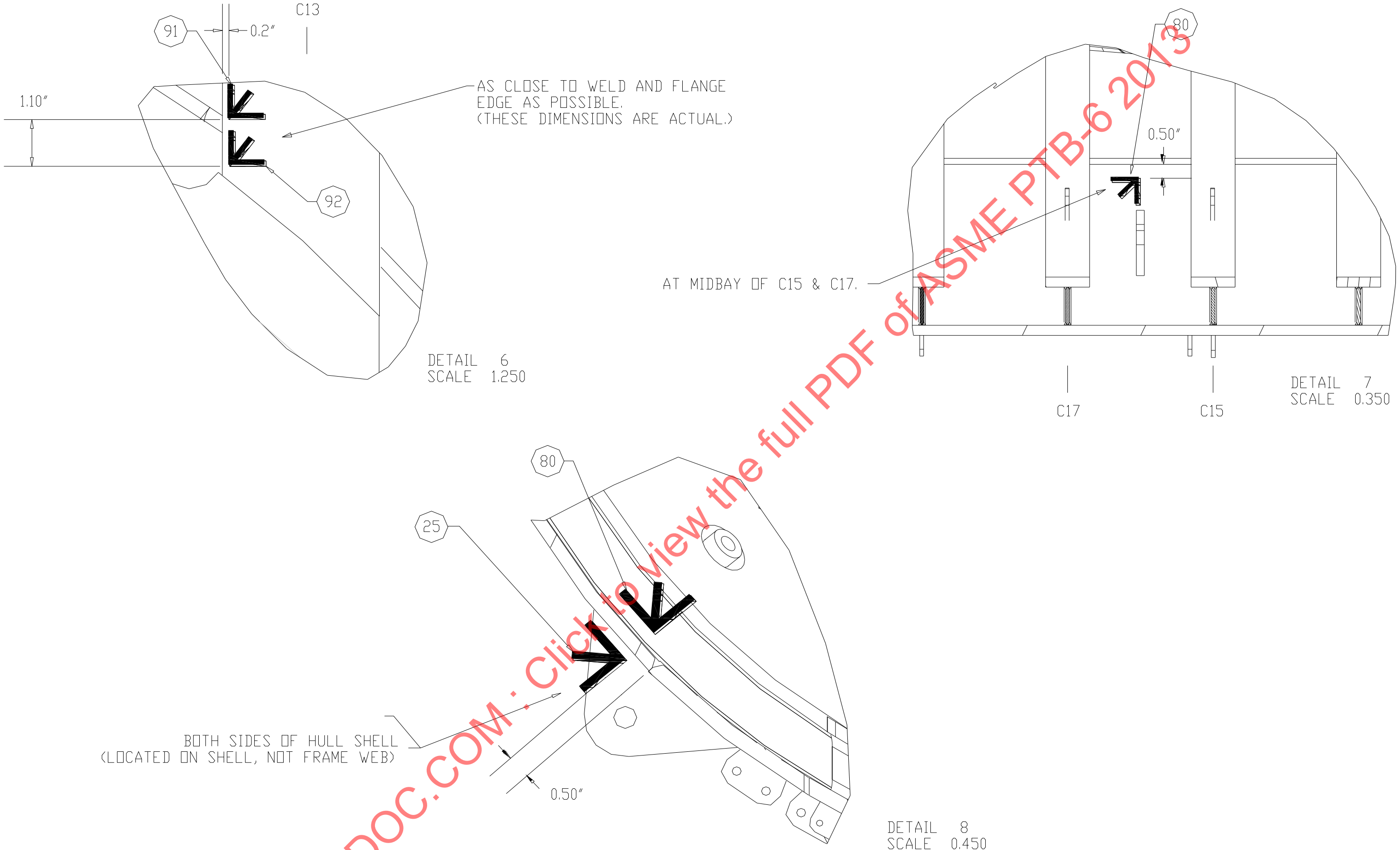


Figure 6.6 – Complex Strain Gage Locations on Pressure Hull