SAN ONOFRE NUCLEAR GENERATING STATION
UNITS 2 AND 3

EXPERIMENTAL DETERMINATION OF THE INFLUENCE OF INDIVIDUAL TENDON STRESSING UPON CONTAINMENT POST-TENSIONING STRAIN

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TABLES

FIGURES

Section 2
SUMMARY AND CONCLUSIONS

2.1 DATA RECORDED

Strain data were recorded on all strain-gaged rebar transducers during the post-tensioning period in accordance with Bechtel Specification No. CS-C15, which is included as Appendix A. Strain and temperature data were recorded daily. In addition, strain and temperature data were recorded from all transducers one hour before and after tensioning the tendons specified in Section 6.2 of CS-C15. These data were used to determine the incremental strain that accrued during stressing of the specified tendons and the influence coefficients given in this report. Incremental strain data at each transducer location were reduced to membrane and bending strain influence coefficient distributions and are discussed in Section 4.

2.2 CONCLUSIONS

The following conclusions are made based on data recorded in this investigation:

- Measurable change of hoop membrane post-tensioning strain by stressing a single hoop tendon in a typical wall section is limited to seven nominal 4-ft wall thicknesses vertically above and below the tendon location.
- Stressing a single hoop tendon contributes 6 percent of design wall hoop membrane post-tensioning strain at the location of the tendon in a typical wall section.
- Measurable change in vertical membrane post-tensioning strain by stressing a single U-tendon in a typical wall section is limited to twelve nominal 4-ft wall thicknesses horizontally on each side of the tendon location.
- Stressing a single U-tendon contributes 7 percent of the design wall vertical membrane post-tensioning strain at the location of the tendon in a typical wall section.
- The largest measured incremental post-tensioning strain induced by the tendons from which data were recorded occurred at the transducers in the dome 28 degrees above the springline. The maximum measured incremental compression membrane strain was 25 percent of the design membrane strain for the stressing of a single U-tendon. These greater strains which occur at some locations of the dome due to tensioning of a single U-tendon are a result of the geometry of these tendons.

Section 3
STRAIN MEASUREMENT

3.1 STRAIN-MEASURING INSTRUMENTATION

Transducers used to measure concrete strain were made by attaching strain gages to short lengths of No. 4 (1/2-in. nominal diameter) steel reinforcing bars which were then embedded in the concrete during containment construction. Output of this type of transducer is linearly related to local concrete strain. Reinforcing bars are approximately 42 in. long, as shown in Figure 3-1, and have two parallel flat areas 3 in. long and 5/16-in. wide milled on opposing sides at the center of each bar for attaching strain gages. The strain gage installation consists of two dual-element encapsulated gages bonded to the milled flats at the bar center and wired into a full-bridge configuration as shown in Figure 3-2. Stable strain gage backing and high-temperature cure adhesive were used to minimize long-term drift. The full-bridge circuit provides strain gage temperature compensation. Strain readout was accomplished with an Acurex Auto Data Nine System giving a strain measurement resolution of 1 microinch/inch.

Gages on reinforcing bars are covered with heat-shrinkable boots lined with mastic material to protect against damage and moisture. The covering also acts as a bond-breaking sleeve over an 18-in. section of the bar. The effective gage length of the transducer is estimated to be 18 to 24 in. Accuracy of the entire strain measuring system (including No. 4 reinforcing bar, strain gages, cabling, and readout unit) is estimated to be within +5 percent of the actual strain, due to reinforcing bar area reduction at gage locations, and ±1 microinch/inch due to instrumentation uncertainty.

The locations and axis directions of the strain transducers are shown in Figure 3-3. Sixty transducers were installed at ten locations. Transducers were aligned in the hoop (circumferential) and vertical (meridianal) directions in the containment walls and in the meridianal and hoop directions in the dome.

Strain-gaged rebar transducers were embedded in the containment to measure structural response at the following generic locations:

- Basemat-to-wall junction
- Typical wall section
- Typical wall section at buttress
- Wall to dome transition (springline)
- Typical dome section with hoop and U-tendons
- Dome transition from hoop to U-tendons

Section 4
EVALUATION OF MEASURED DATA

Response of the containment during post-tensioning activities was measured by daily recording the strains. Strain transducers were located in a section of the vertical wall away from the discontinuities of the buttresses, springline, and base-mat-to-wall juncture at 204 degrees and elevation 91 ft 0 in.

Data from this location can be compared directly to design calculations for a nominal 4-ft thick typical wall section. The accumulated vertical and hoop membrane strain history for this typical wall section during the entire stressing period is shown in Figures 4-1 and 4-2, respectively. The calculated post-tensioning force level just after tendon system stressing at this location, not including elastic losses, based on the actual forces from Section 3, was 608 k/ft in the vertical direction and 1035 k/ft in the hoop direction. Calculated strains at the transducer location in the typical wall were -187 and -374 microinch/inch in the vertical and hoop directions. A comparison of the calculated and measured strains indicate that the measured post-tensioning levels were higher in the vertical direction and lower in the hoop direction than the calculated design level as shown in Figures 4-1 and 4-2.

4.1 INFLUENCE OF TENDON STRESSING ON WALL STRAIN

The resulting incremental membrane and bending strains (influence coefficients) at wall transducer locations caused by stressing individual tendons are discussed in detail below.

4.1.1 Base-Mat-to-Wall Juncture (Figures 4-3 and 4-4)

Measured hoop (circumferential) strains were negligible upon stressing a hoop or U-tendon. The primary influence of stressing hoop tendons on the juncture vertical strain occurs through a region that extends from the lowest tendon to approximately 10 wall thicknesses above the juncture and is negligible at 12 wall thicknesses above the juncture as shown in Figure 4-3. The influence of U-tendons is maximum at the transducer location. Tendons within a 35-degree zone influence measured membrane and bending vertical strains as shown in Figure 4-4. The maximum influence coefficients from hoop or U-tendons are approximately equal at 10 microinch/inch.

4.1.2 Typical Wall Section (Figures 4-5, 4-6 and 4-7)

The influence of stressing hoop tendons on the typical wall section is shown in Figures 4-5 and 4-6. The influence on the vertical membrane (Figure 4-5) and hoop bending strain (Figure 4-6) is negligible. The influence on vertical bending (Figure 4-5) and hoop membrane strain (Figure 4-6) is maximum for stressing hoop tendons at the same elevation as the transducer and is -22 and -24 microinch/inch, respectively. The maximum hoop membrane strain is approximately 6 percent of the total measured strain. The effects on the vertical bending strain are negligible for hoop tendons beyond ±4 wall thicknesses from the transducer. The effects on the hoop membrane strain are negligible for tendons beyond ±7 wall thicknesses from the transducer.

The influence of stressing vertical tendons on the typical wall section is shown in Figure 4-7. The influence on the hoop membrane and bending strains and the vertical bending strain is negligible. Stressing tendons within a ±35-degree zone (12 nominal 4-ft wall thicknesses) of the transducers resulted in measurable vertical membrane strains. The maximum measured strain corresponded to stressing the tendon at the transducer location. This maximum vertical membrane strain (-12 microinch/inch) was half of the maximum hoop membrane strain (-25 microinch/inch). The maximum membrane strain influence coefficient is -12 microinch/inch and is approximately 7 percent of the measured total strain.

4.1.3 Typical Wall Section at Buttress (Figures 4-8 and 4-9)

The influence on the buttress strains from stressing the hoop tendons is shown in Figures 4-8 and 4-9 for vertical and hoop strains, respectively. Stressing hoop tendons gives negligible vertical membrane strain. Maximum vertical bending strain was reduced by approximately 10 percent from the strain recorded in the typical wall section, and the extent of the influence was reduced to 2-1/2 typical wall thicknesses. Some hoop bending strains were induced by tendons terminating at anchorages in this buttress. The maximum hoop membrane strain that was recorded is approximately equal to the corresponding strain measured in the typical wall section. Distribution of these influence coefficients shows that strains recorded for the stressing of individual tendons are more localized than in the typical wall.

4.1.4 Wall to Dome Transition (Springline) (Figures 4-10 and 4-11)

Influence on wall strains from the stressing of hoop tendons is shown in Figure 4-10. The distribution of influence coefficients for hoop membrane strain below the location of the transducer is very similar to the distribution in the typical wall section. The effect of the dome geometry extends this distribution above the transducer's location. Measurable hoop bending strains were recorded for the stressing of hoop tendons in the dome.

The distribution strain influence coefficients for stressing U-tendons is shown in Figure 4-11. The effect of stressing U-tendons is negligible on the hoop membrane strain. The distribution of vertical membrane strain has the same general shape as the typical wall section but the maximum recorded strain is 170 percent higher than the typical wall strain. The extent of tendons affecting this strain is nearly the same as a typical wall section. Both hoop and vertical bending strains are induced. Distribution of the strain influence coefficients is similar but the maximum induced hoop strain is double the maximum vertical strain.

4.2 INFLUENCE OF TENDON STRESSING ON DOME STRAIN

Significant comments about the influence coefficients at the locations of dome transducers are given below.

4.2.1 Typical Dome Section with Hoop and U-Tendons (Figure 4-12)

Influence coefficients for induced strain from stressing hoop tendons were not analyzed because dome response is influenced to a far greater degree by U-tendons than by hoop tendons. The effects of stressing U-tendons are shown in Figure 4-12. Large compressive meridianal membrane and bending strains were induced. The maximum recorded influence coefficients were

from tendon V-145 at 205 degrees-30 ft. The influence on hoop bending strain was maximum for tendons near the edges of each group of dome tendons. The effects on hoop membrane strain were negligible.

4.2.2 Dome Transition From Hoop to U-Tendons (Figure 4-13)

The distribution of the influence coefficients for stressing U-tendons is shown in Figure 4-13. Discernable increases in all the strain influence coefficients occurred for stressing tendons near 187 degrees. The dome tendon geometry would place these tendons passing near the location of the strain transducers. The distribution of the meridianal and hoop membrane strain influence coefficients is similar. The maximum meridianal and hoop membrane coefficients occurred at 187 degrees with the magnitude of the meridianal coefficient approximately double that of the hoop coefficient. Distribution of bending influence coefficients is also very similar. A large meridianal bending influence coefficient was recorded for the stressing of tendon V-157 at 229 degrees-30 ft.

In summary, the total post-tensioning strain in a typical wall section agreed well with design requirements.

The effect of the variation in post-tensioning level on the influence coefficients for strains due to individual tendon stressing was approximately equal to the instrumentation error and can be disregarded. Influence coefficients for strain in the typical wall are consistent with the expected results. Stressing individual hoop tendons contributes 6 percent of the total accumulated hoop strain at the tendon location. Effects of stressing individual hoop tendons on hoop strain extend seven vertical wall thicknesses. Stressing individual U-tendons contributes 7 percent of the total accumulated vertical strain in a typical midheight wall section at the azimuth of the tendon. The distribution of the induced strain was within twelve wall thicknesses.

Table 3-1

AZIMUTHS AND ELEVATIONS OF SELECTED TENDONS ADJACENT TO STRAIN TRANSDUCERS

Hoop Tendons (Wall)		
	Elevation (Feet)	
Tendon No.	@144°	@204°
H-2	25.0	25.9
H-4	26.0	28.0
H-8	33.8	32.2
H-22	46.8	46.8
H-23	47.8	47.8
H-40	65.5	65.5
H-41	66.6	66.6
H-61	90.0	87.4
H-62	91.0	88.4
H-65	92.8	91.6
H-70	96.8	96.8
H-71	97.8	97.8
H-77	104.1	104.1
H-82	109.3	109.3
H-83	110.3	110.3

Inverted U Tendons	
	Azimuth
Tendon No.	Angle*
V-121	157° – 30′
V-124	163° – 30′
V-127	169° – 30′
V-130	175° – 30′
V-136	187° – 30′
V-139	193° – 30′
V-142	199° – 30′
V-145	205° – 30′
V-148	211° – 30′
V-157	229° – 30′
V-163	241° – 30′

*At springline and base slab

Hoop Tendons (Dome)		
	Vertical	Angle
Tendon No.	@144°	@204°
H-90	8° 15′	8° 15′
H-104	29° 15′	29° 15′
H-113	42° 45′	42° 45′

Table 3-2

CONSTRUCTION LOCK-OFF FORCES FOR SELECTED HOOP TENDONS

Tendon	Lock-Off Force (KIPS) at Buttress		
	1 (24°)	2 (144°)	3 (264°)
H-2	1583		1612
H-4	1598	1581	
H-8	1636		1598
H-22	1587	1570	
H-23	1625		1569
H-40	1587	1548	
H-41	1625		1601
H-61	1598	1592	
H-62	1609		1601
H-65	1625		1601
H-70	1576	1581	
H-71	1615	1623	
H-77	1625		1601
H-82	1598	1570	
H-83	1646		1623
H-90		1641	1581
H-104	1615		1569
H-113	1636		1612

At buttress 1 F_{avg} = 1611 kip F_{design} = 1590 kip

Table 3-3

CONSTRUCTION LOCK-OFF FORCES FOR SELECTED U-TENDONS

Tendon	Lock-Off Force (KIPS)			
	End A		End B	
	Number	Force	Number	Force
V-121	31	1580	121	1592
V-124	28	1606	124	1586
V-127	25	1558	127	1592
V-130	22	1612	130	1590
V-136	16	1612	136	1590
V-139	13	1601	139	1592
V-142	10	1590	142	1590
V-145	97	1618	145	1624
V-148	94	1570	148	1580
V-157	85	1640	157	1612
V-163	79	1580	163	1580

In vertical wall $F_{avg} = 1593$ kip $F_{design} = 1590$ kip

Table 3-4
COMPARISON OF MEASURED AND CALCULATED STRAINS

	HOOP	VERTICAL
CALCULATED STRESS	(F_i) AVE,H = 180 KSI $f_{ch} = \frac{-180 \times 8.415 \times 10^3}{144 \times 4 \times 1.56} = -1686^{PSI}$	F_i, ELV = 91'.V = 194 KSI $f_{cv} = \frac{-194 \times 8.415 \times 10^3}{144 \times 4 \times 2.72} = -1042^{PSI}$
CALCULATED STRAIN	$\epsilon_h = \frac{1}{E_c}\left[-1686 - .17\,(-1042)\right]$ $= -374\ \mu$ IN/IN	$\epsilon_v = \frac{1}{E_v}\left[-1042 - .17\,(-1686)\right]$ $= -187\ \mu$ IN/IN
MEASURED STRAIN	$-345\ \mu$ IN/IN	$-225\ \mu$ IN/IN

WHERE $E_c = 4.03 \times 10^6$ PSI

$\mu = .17$

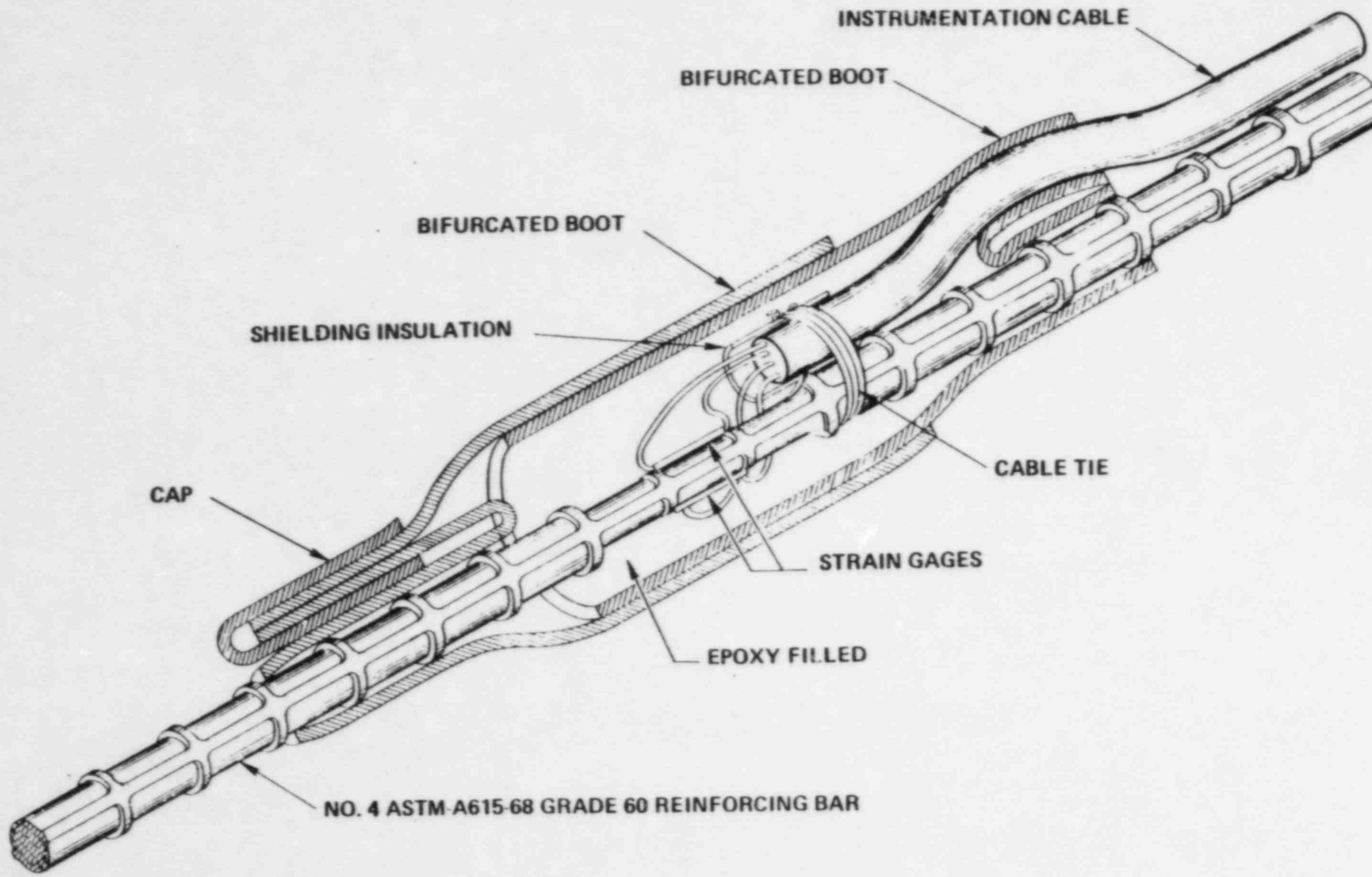
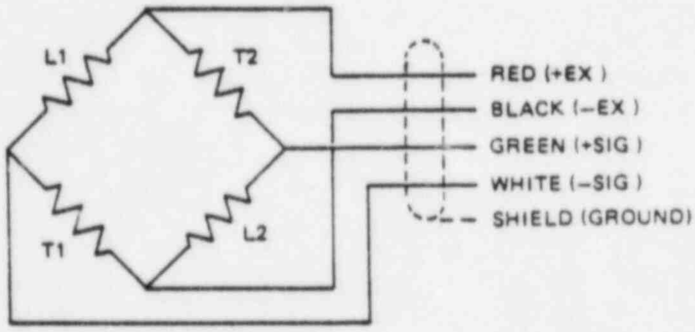
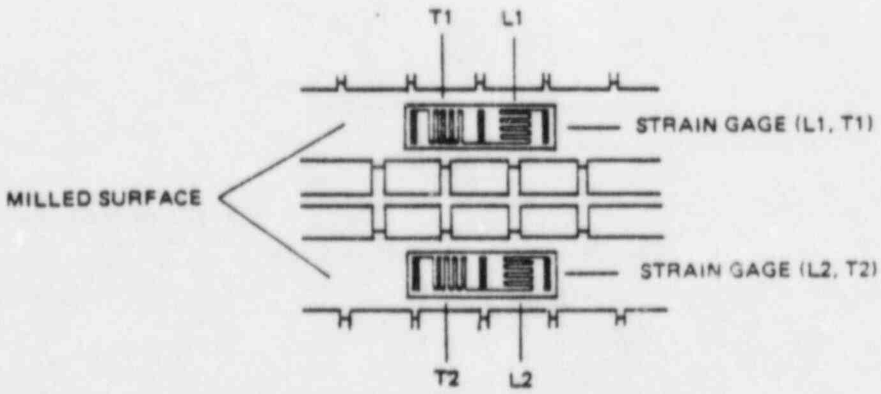


Figure 3-1 — STRAIN TRANSDUCER



BRIDGE WIRING SCHEMATIC

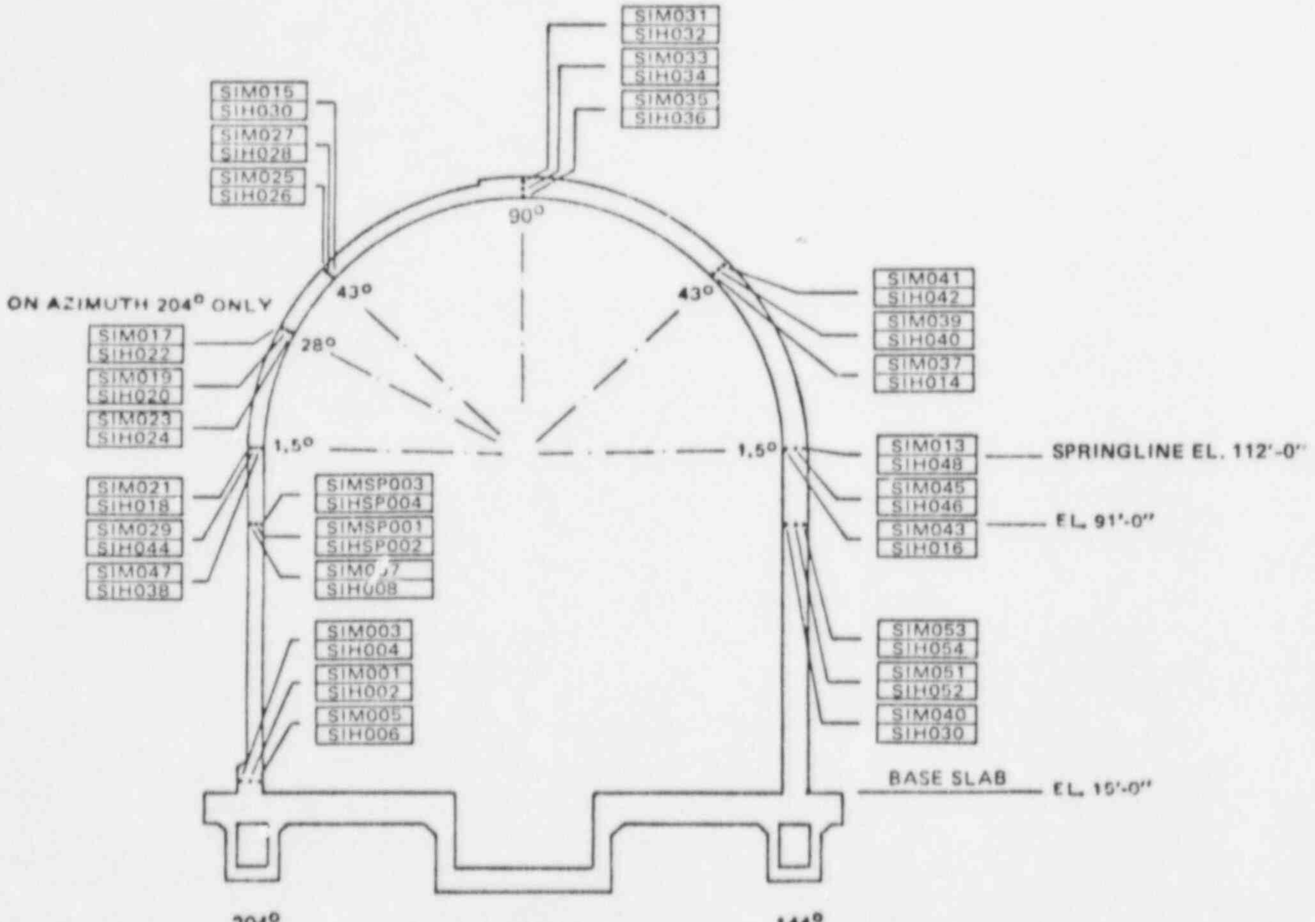
LEGEND:
+EX = POSITIVE EXCITATION VOLTAGE
-EX = NEGATIVE EXCITATION VOLTAGE
+SIG = POSITIVE SIGNAL VOLTAGE
-SIG = NEGITIVE SIGNAL VOLTAGE



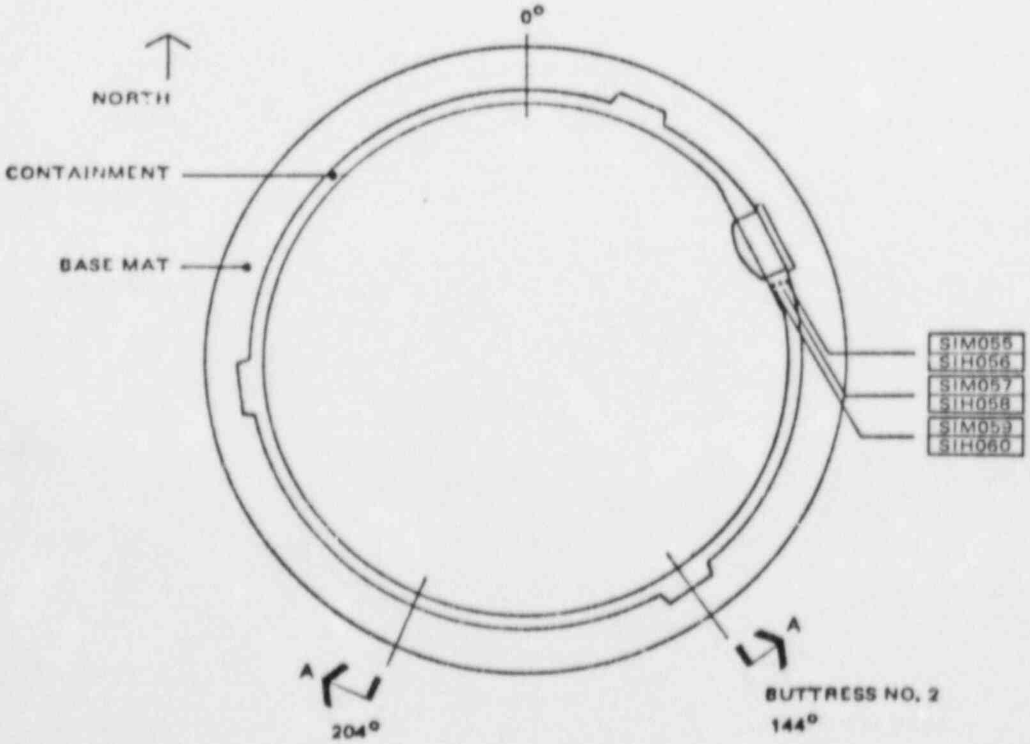
DEVELOPED REBAR SURFACE AT STRAIN GAGE LOCATION

LEGEND:
L1 = LONGITUDINAL STRAIN GAGE ON FACE NO. 1
L2 = LONGITUDINAL STRAIN GAGE ON FACE NO. 2
T1 = TRANSVERSE STRAIN GAGE ON FACE NO. 1
T2 = TRANSVERSE STRAIN GAGE ON FACE NO. 2

Figure 3-2 – STRAIN GAGE BRIDGE



SECTION AA



PLAN DOME INSTRUMENTATION

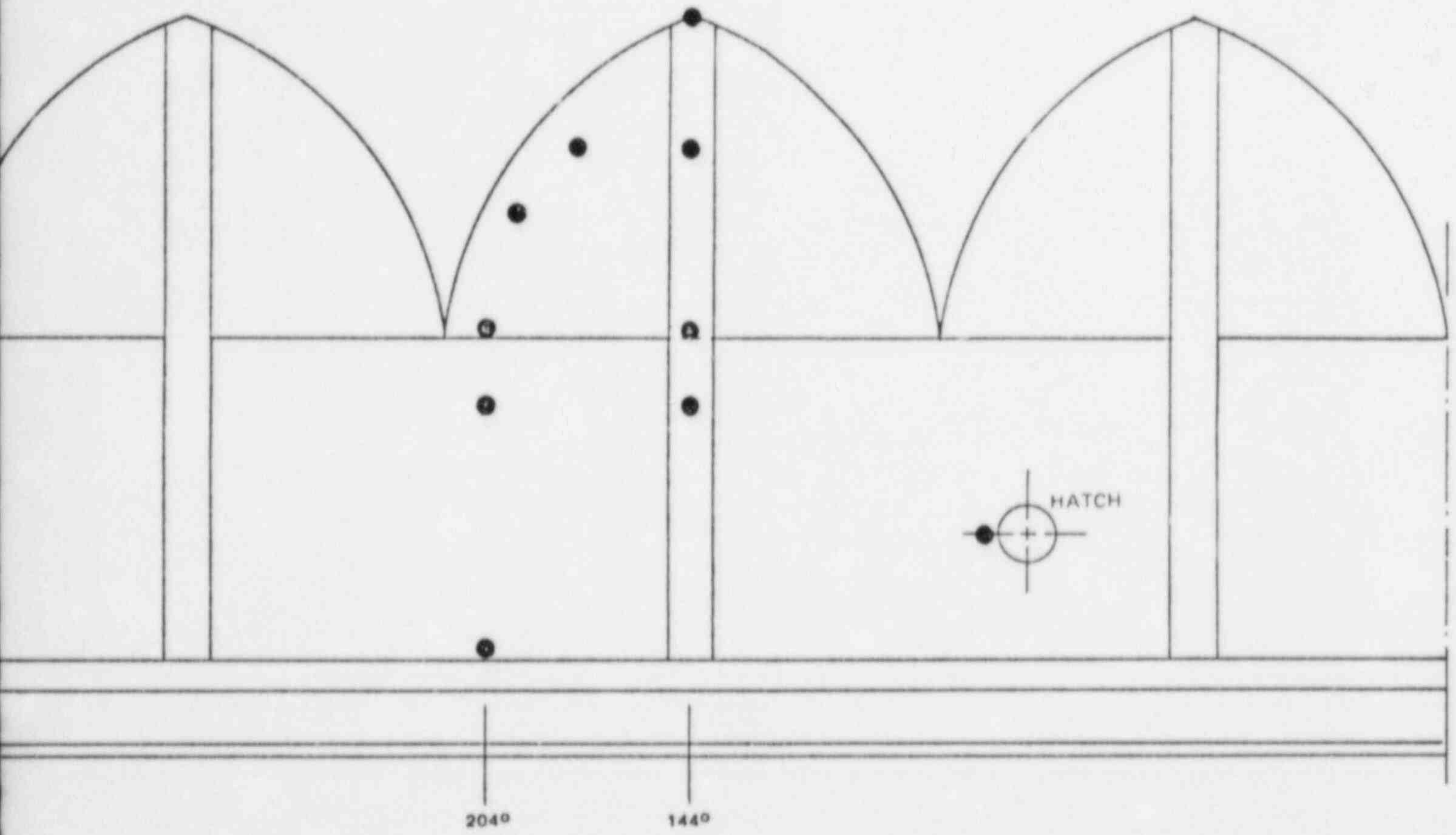


Figure 3-3
LOCATIONS OF EMBEDDED STRAIN
TRANSDUCERS IN THE CONTAINMENT

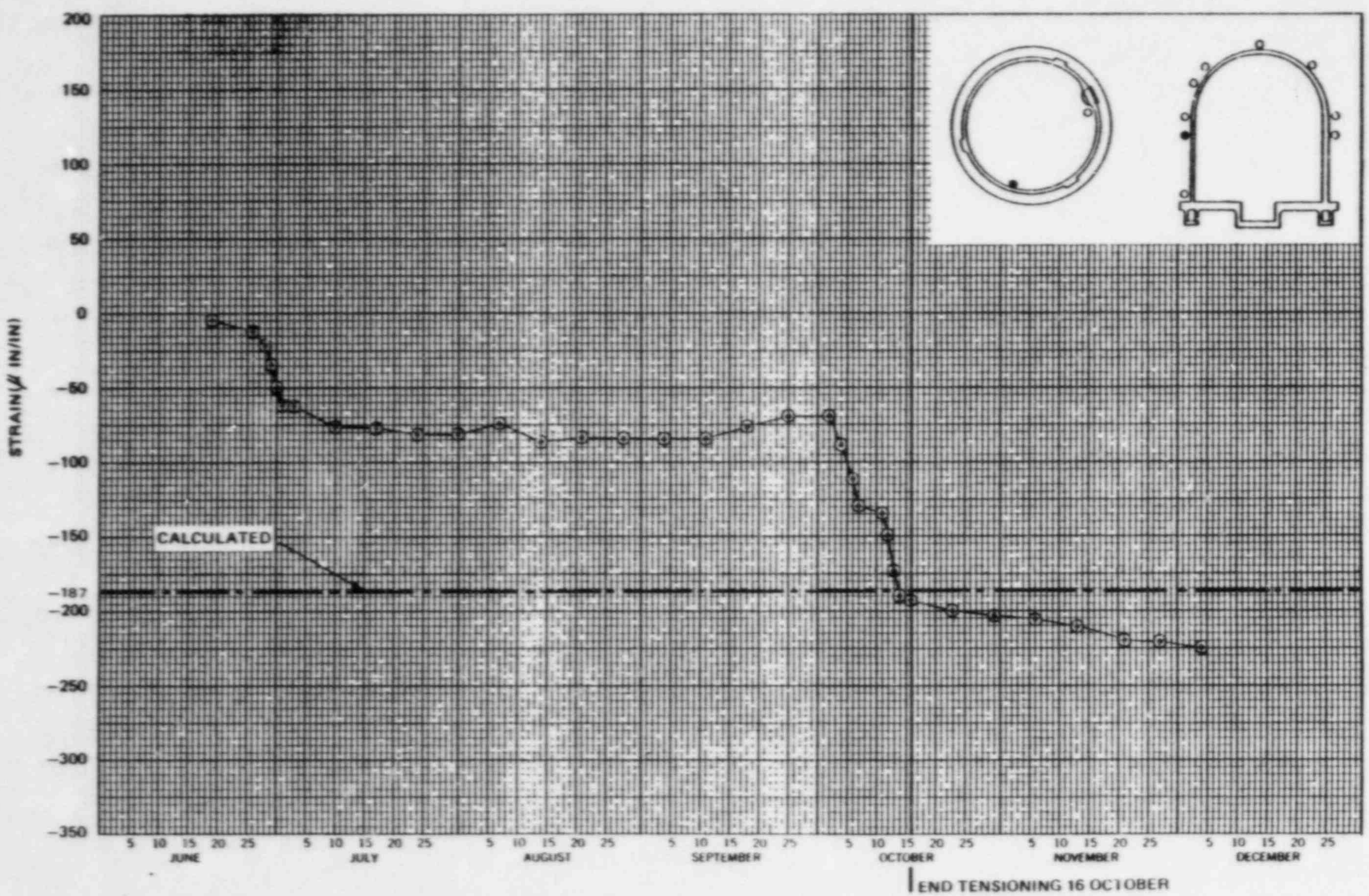
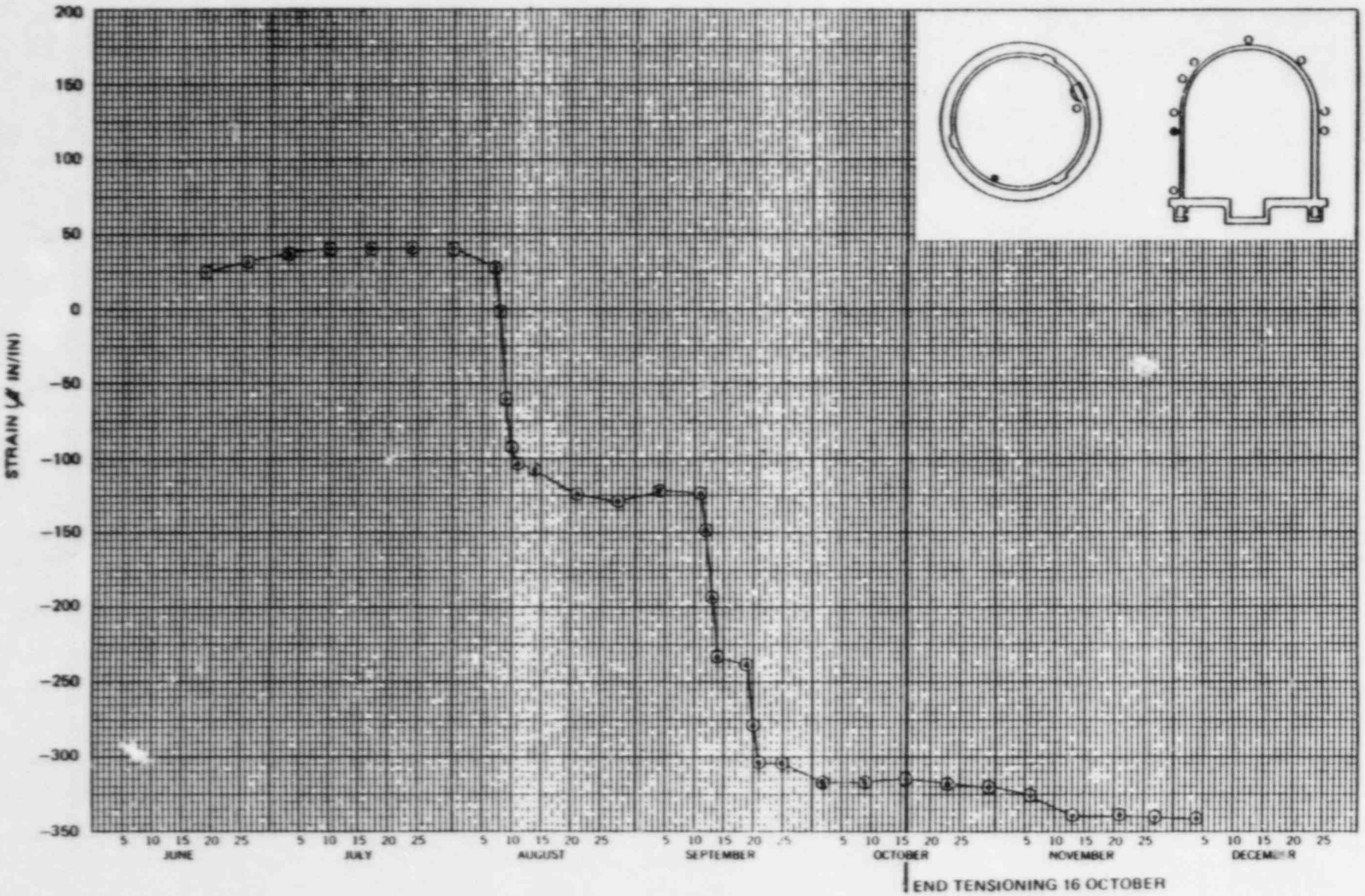


Figure 4-1 VERTICAL MEMBRANE STRAIN IN A TYPICAL WALL SECTION



CALCULATED VALUE – 374 μ IN/IN

Figure 4-2 HOOP MEMBRANE STRAIN IN A TYPICAL WALL SECTION

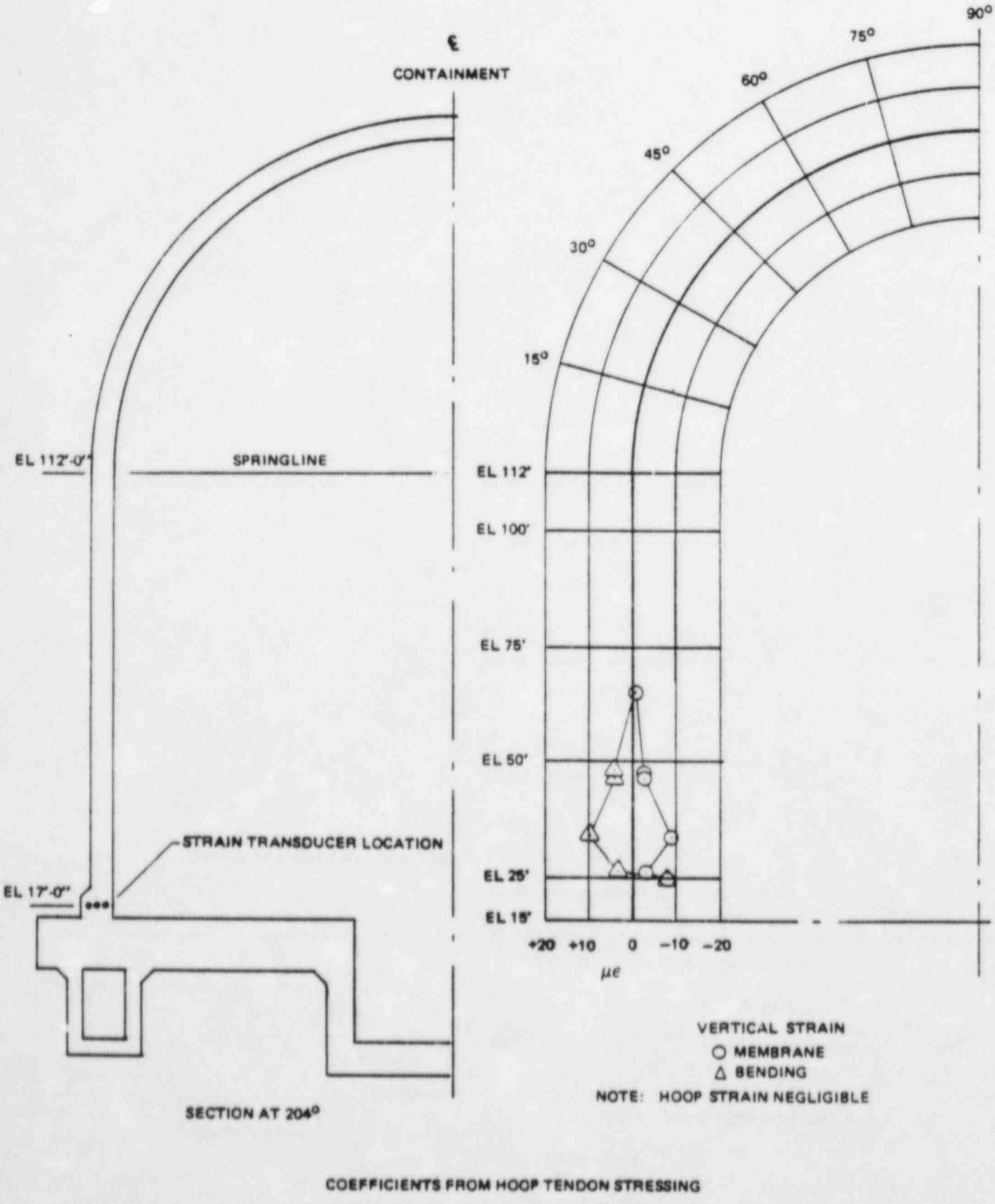


Figure 4-3 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION 17'-0"

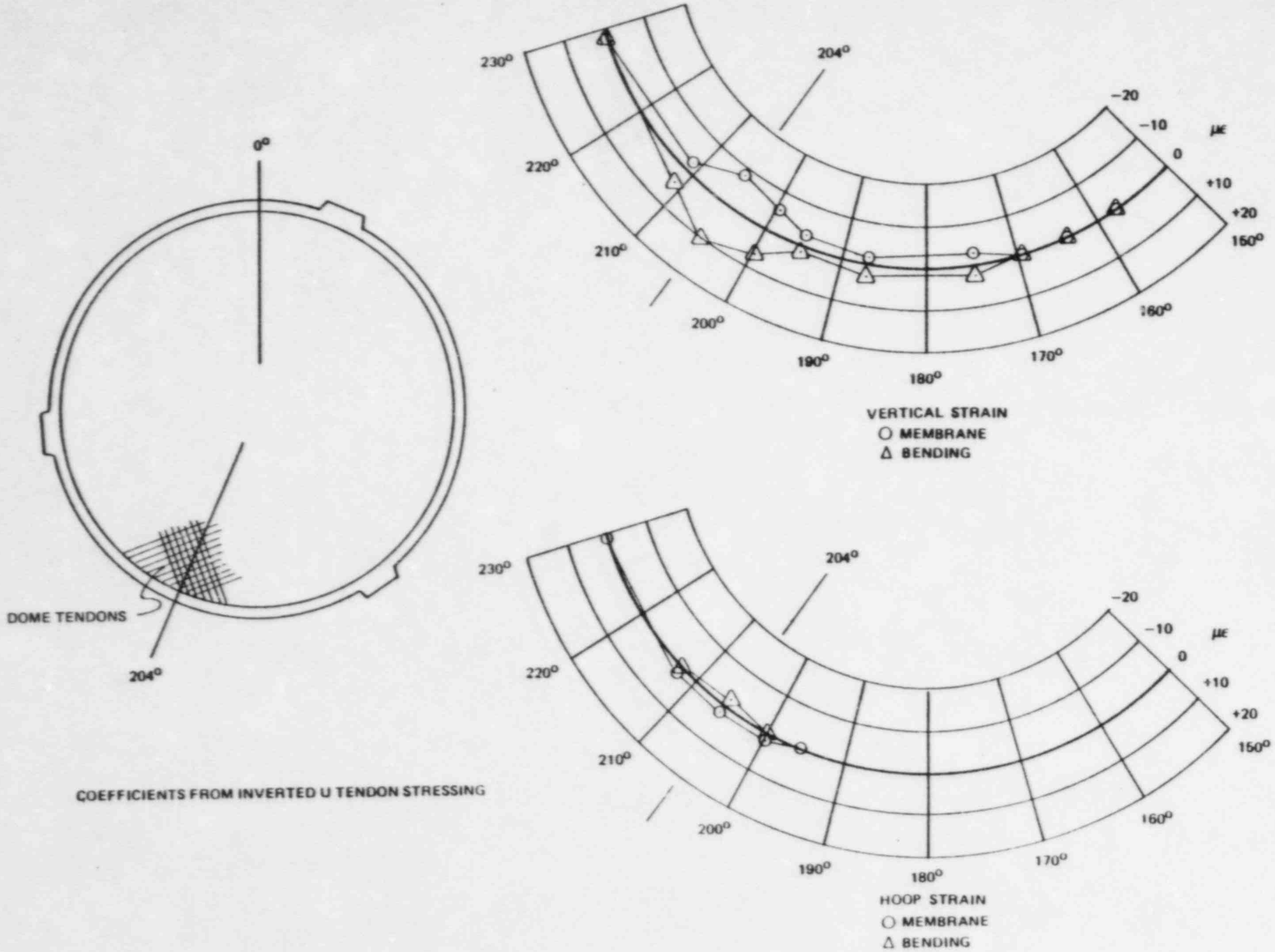


Figure 4-4 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION 17′-0″

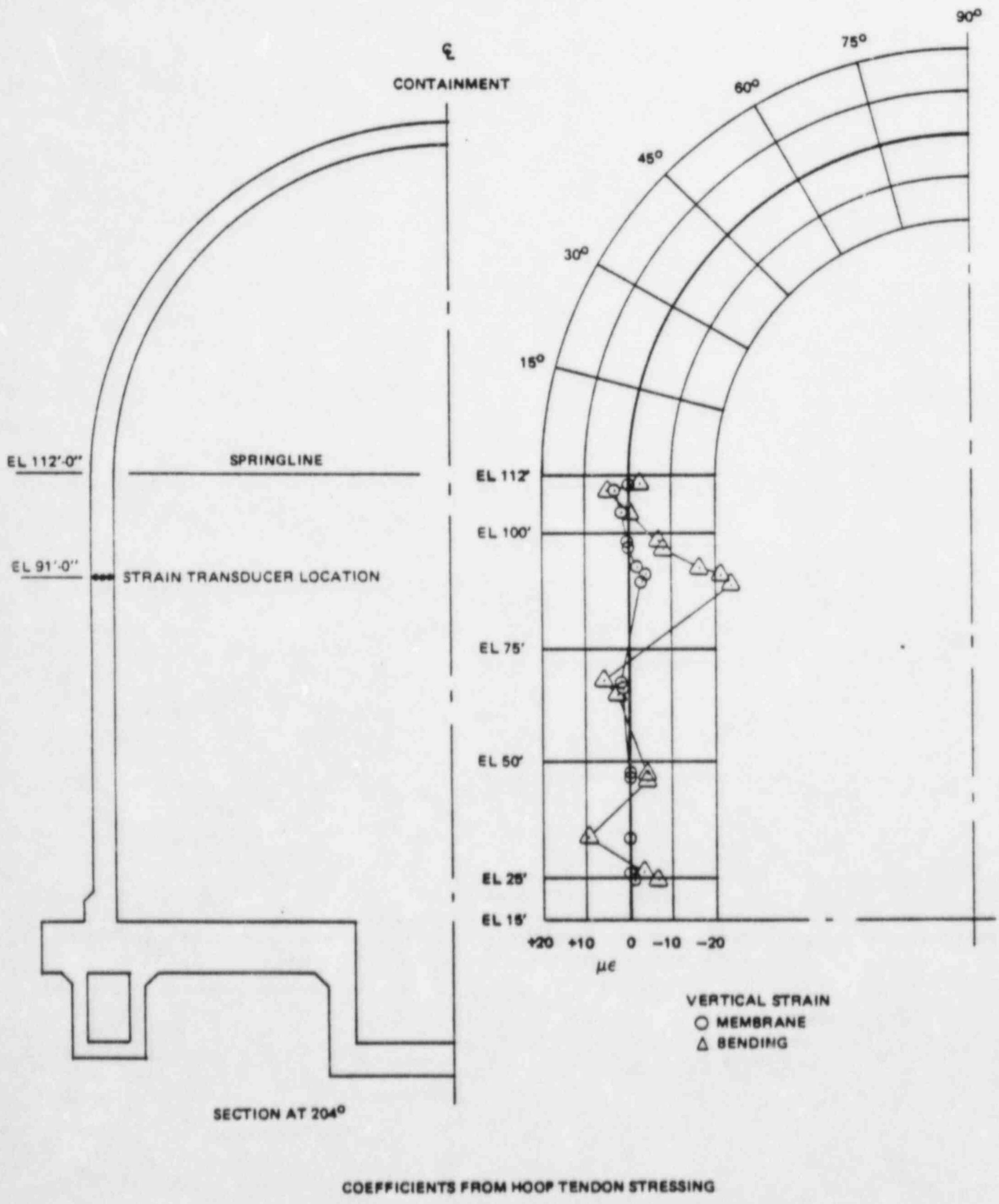


Figure 4-5 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION 91'-0"

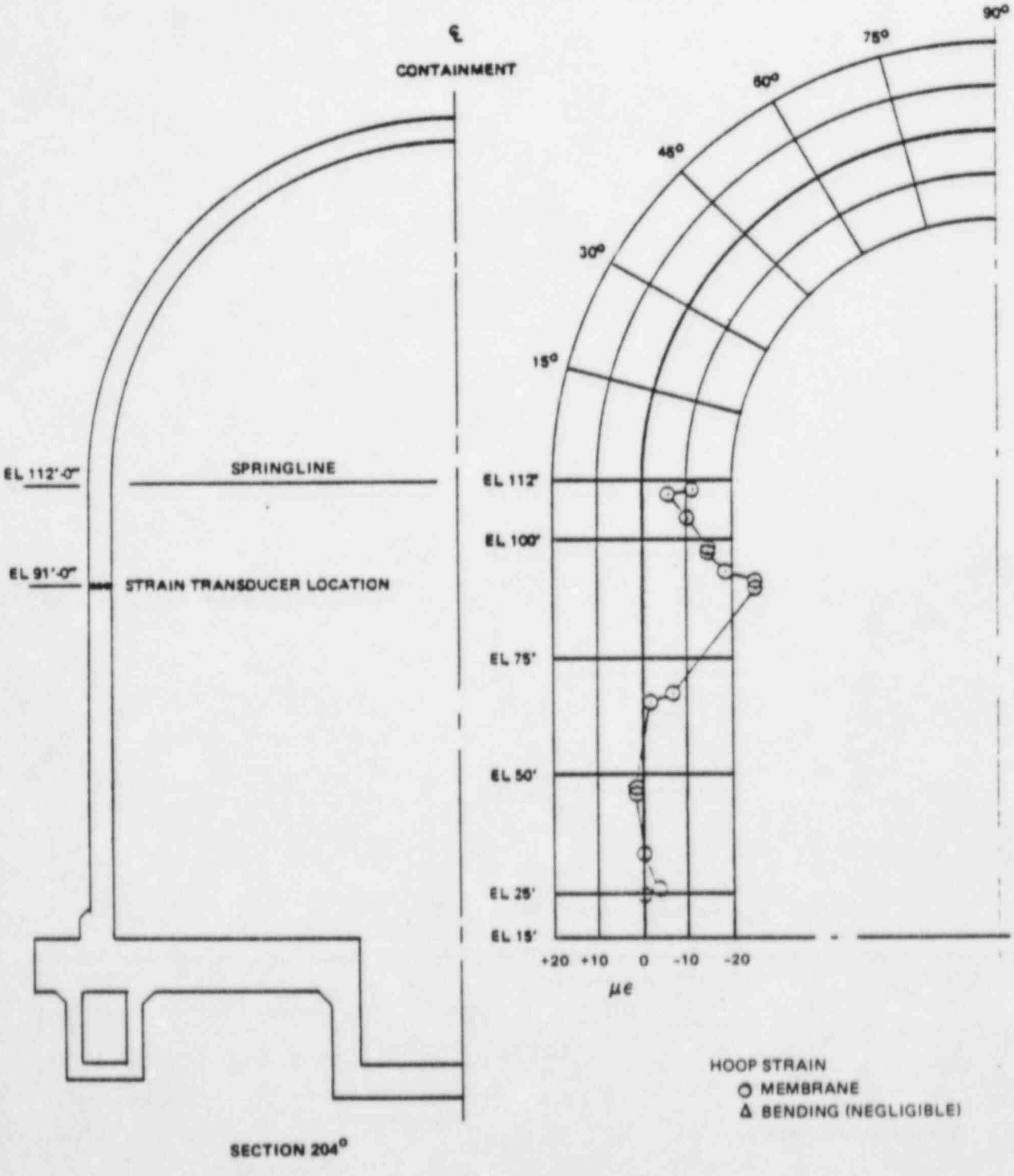


Figure 4-6 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION 91'-0"

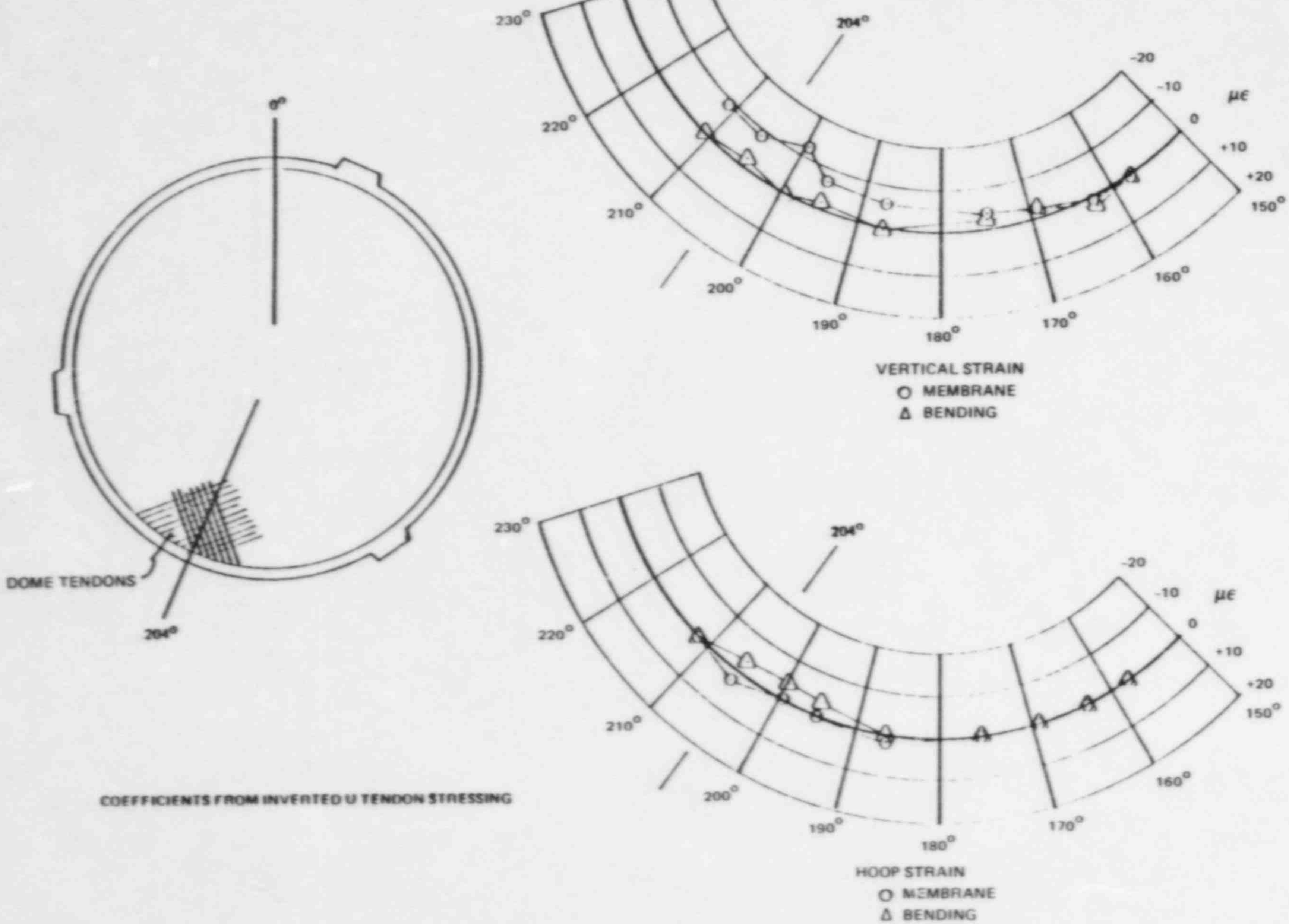
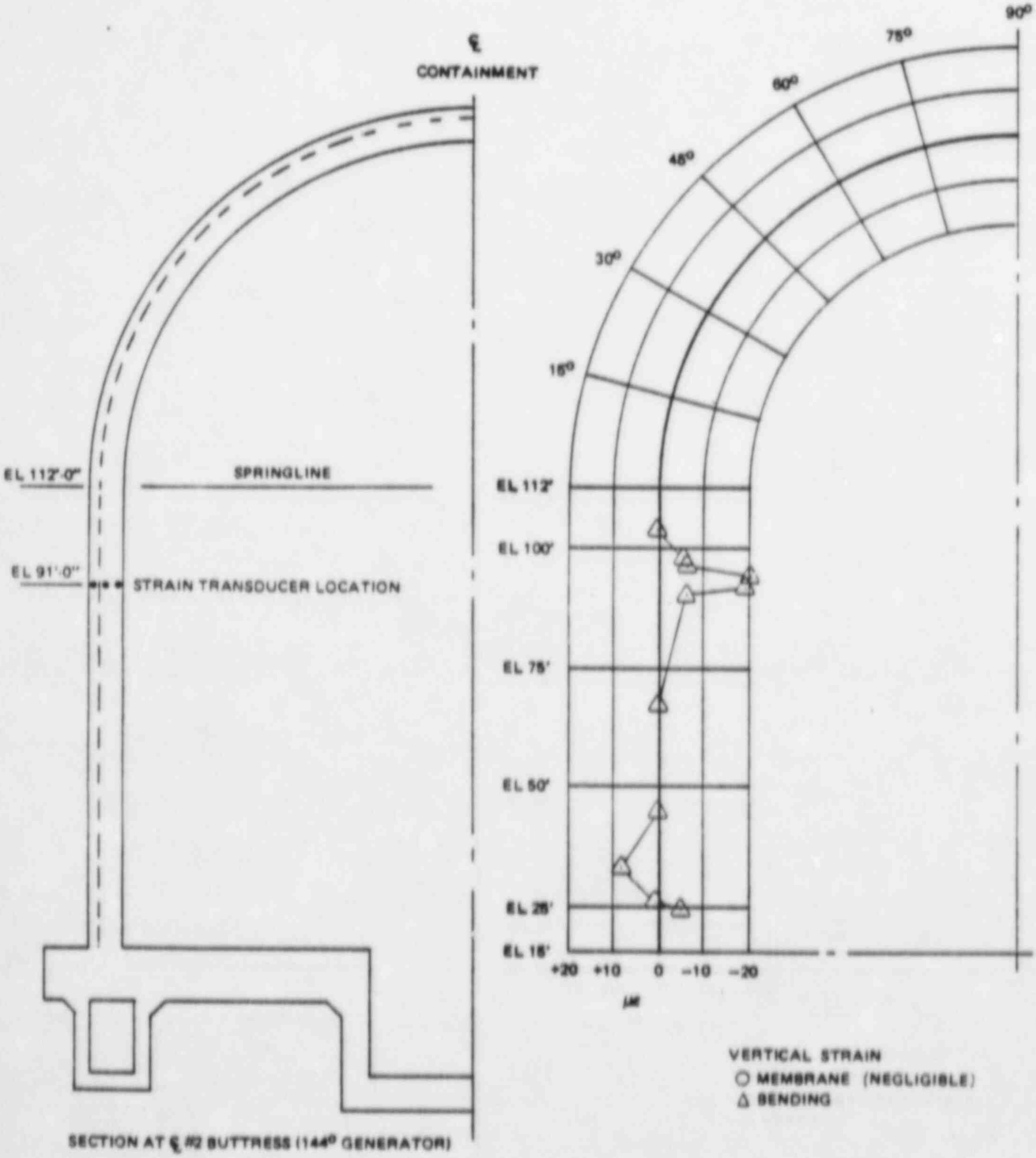
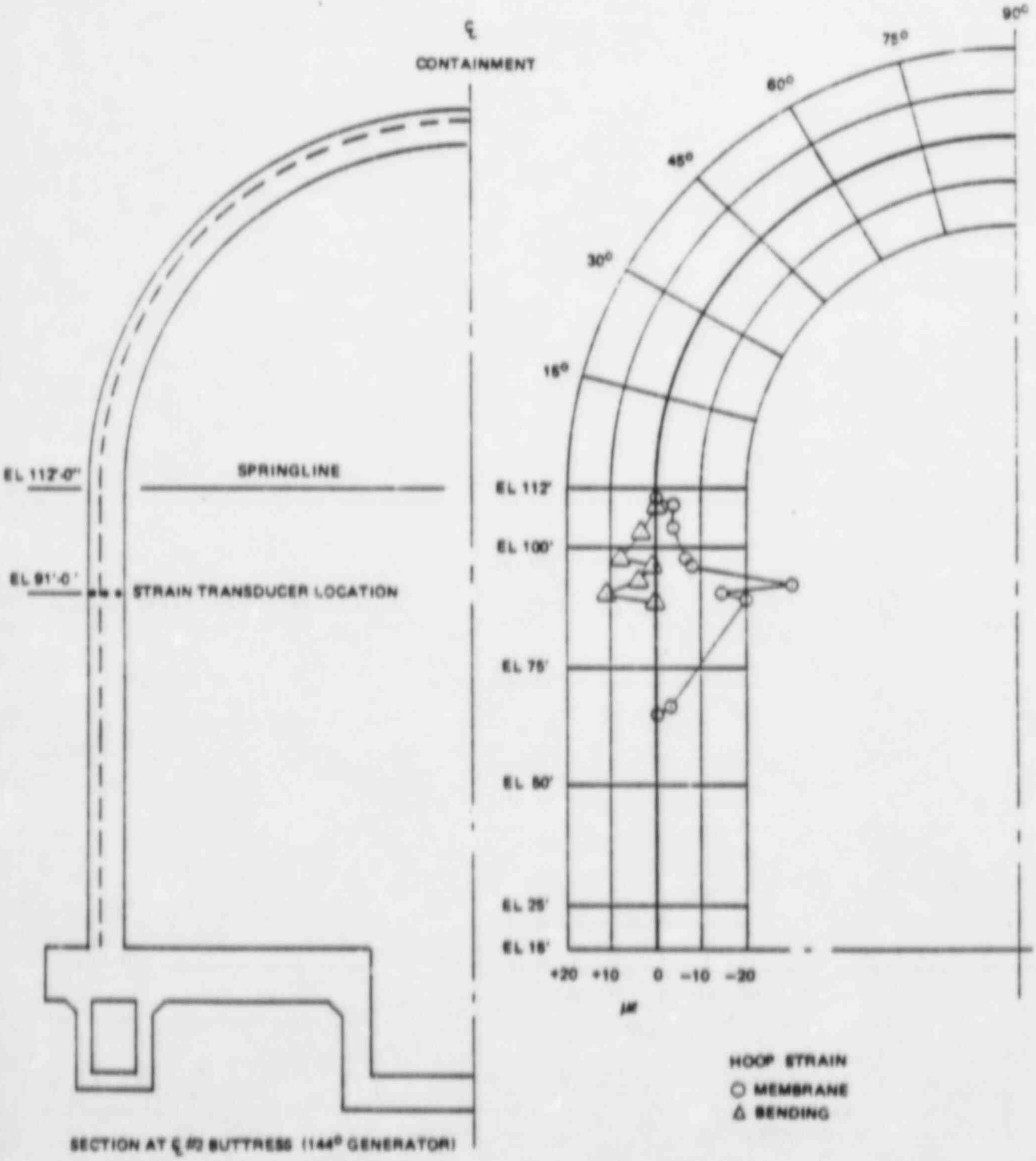


Figure 4-7 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION 91'-0"



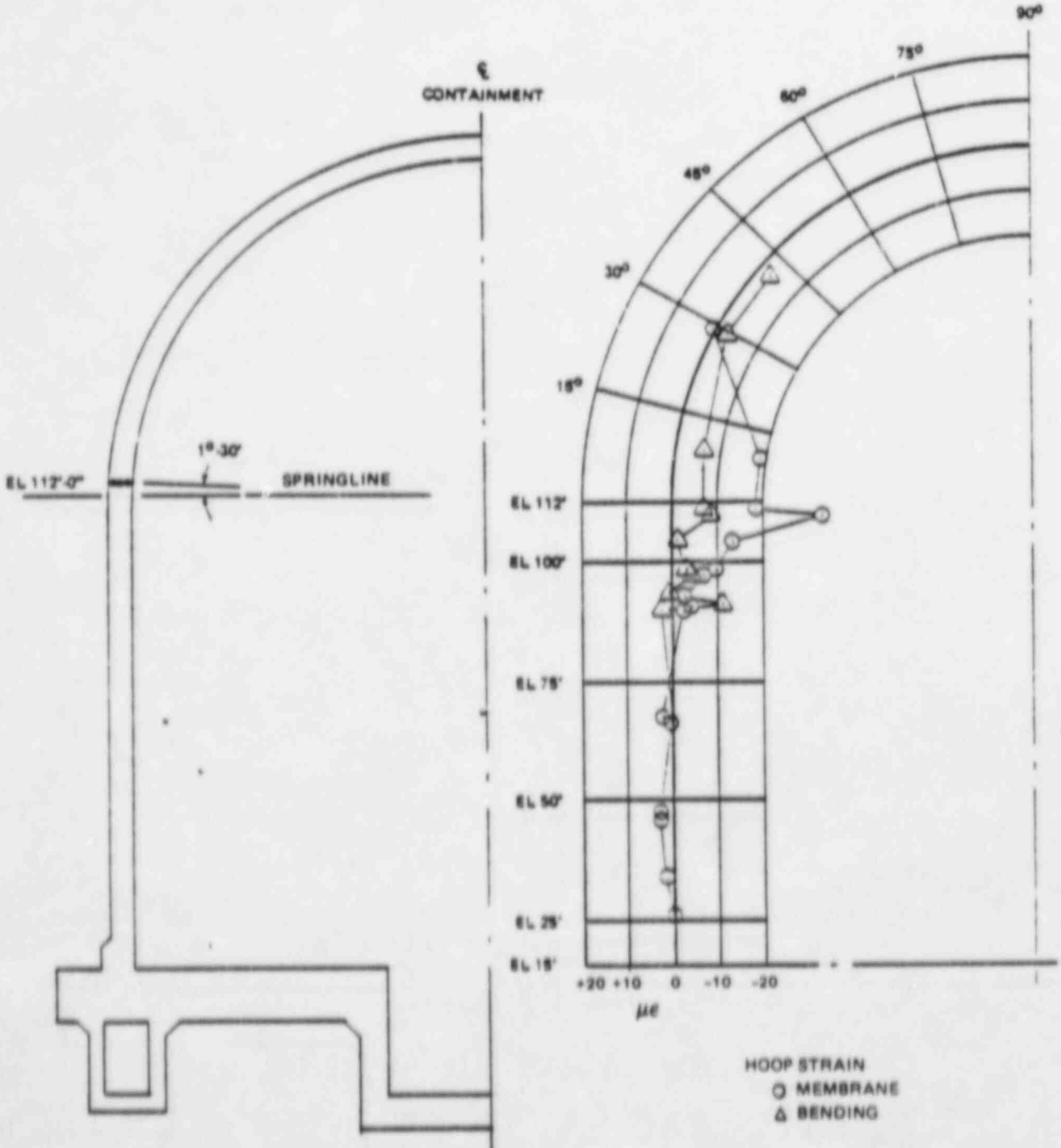
COEFFICIENTS FROM HOOP TENDON STRESSING

Figure 4-8 INFLUENCE COEFFICIENTS FOR STRAIN AT #2 BUTTRESS (144° GENERATOR) ELEVATION 91'-0"



COEFFICIENTS FROM HOOP TENDON STRESSING

Figure 4-9 INFLUENCE COEFFICIENTS FOR STRAIN AT #2 BUTTRESS (144° GENERATOR) ELEVATION 91'-0"



COEFFICIENTS FROM HOOP TENDON STRESSING

Figure 4-10 INFLUENCE COEFFICIENTS FOR STRAIN AT 204° GENERATOR ELEVATION ANGLE 1°-30' ABOVE SPRINGLINE

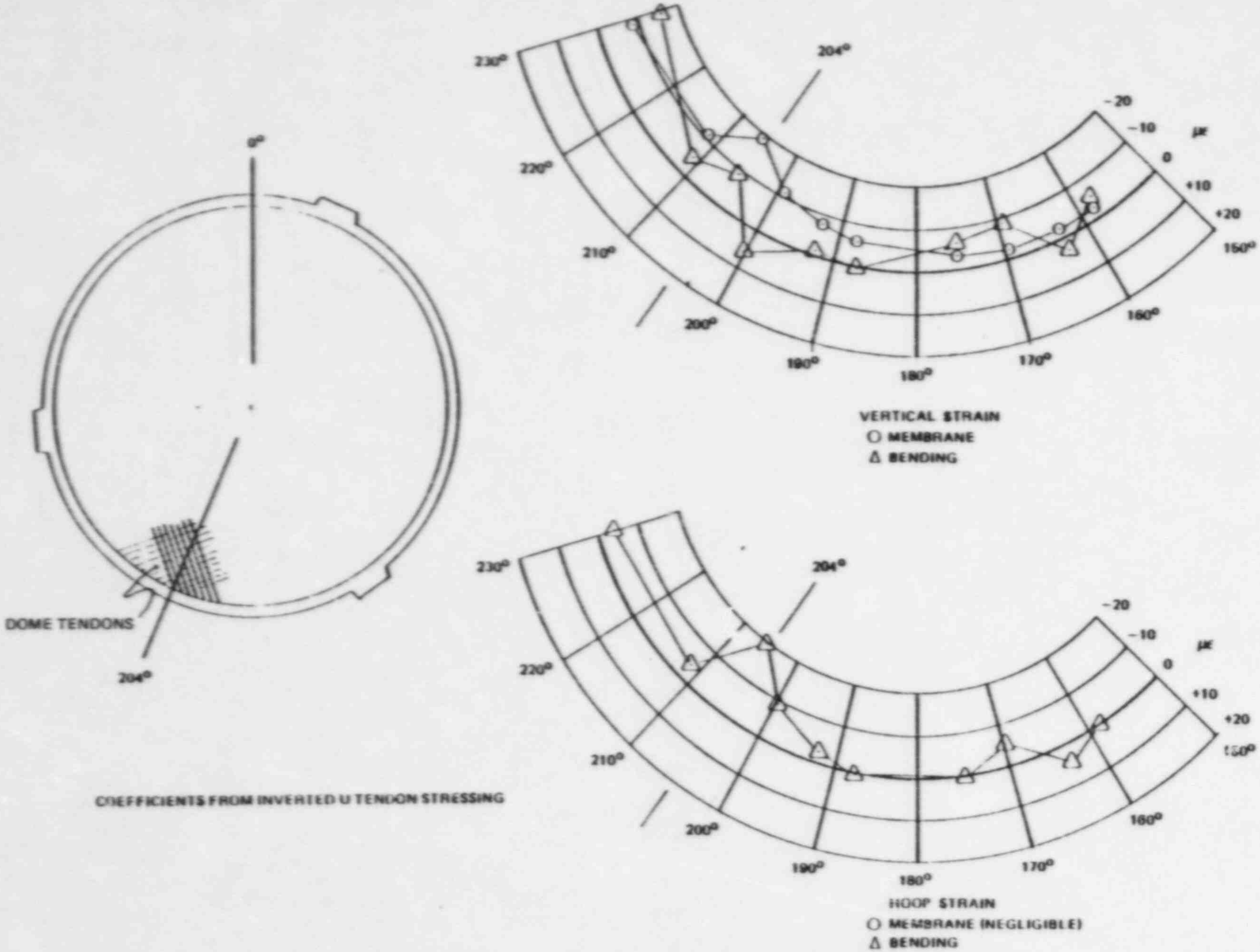


Figure 4-11 INFLUENCE COEFFICIENTS FOR
STRAIN AT 204° GENERATOR ELEVATION ANGLE 1°-30′ ABOVE SPRINGLINE

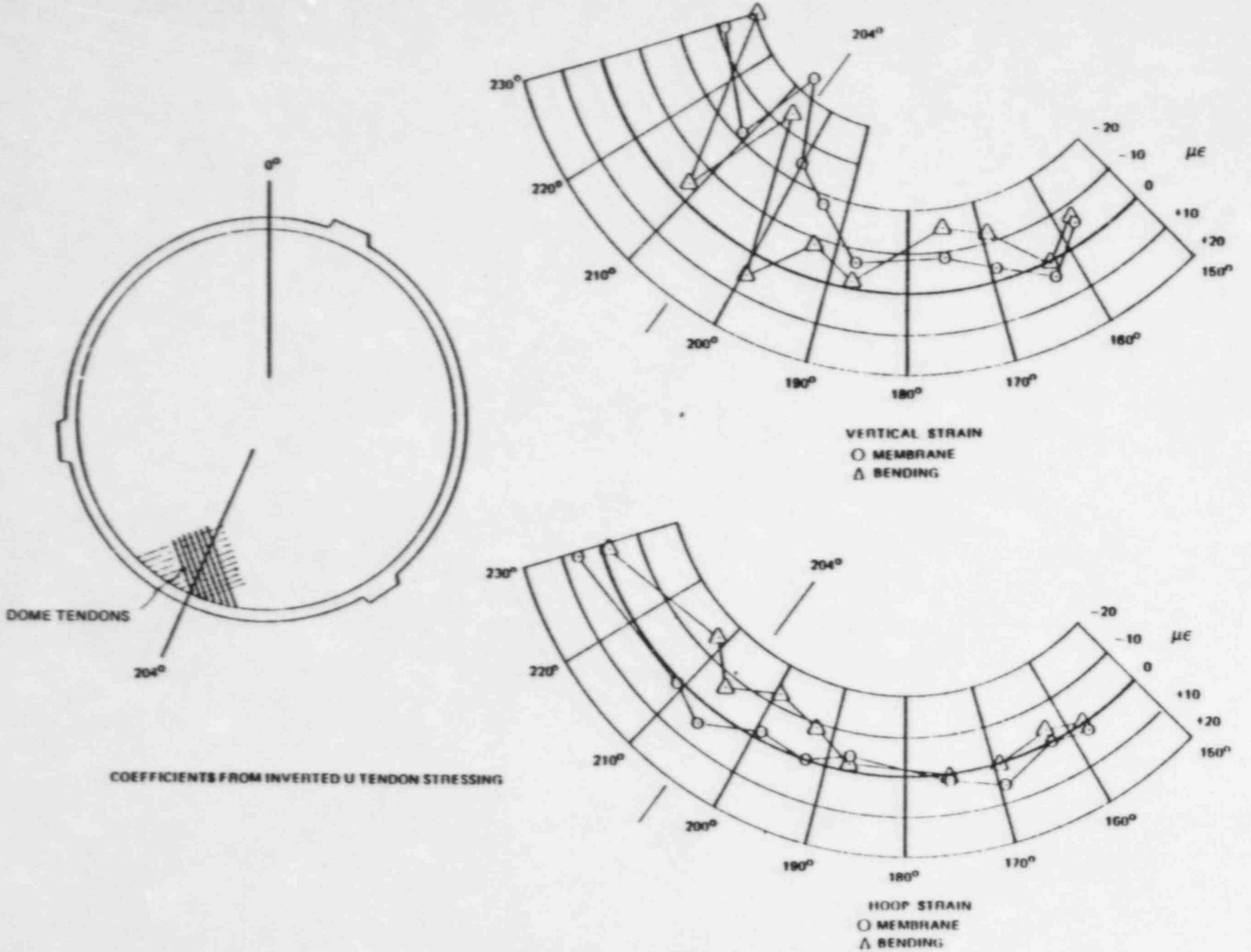


Figure 4-12 INFLUENCE COEFFICIENTS FOR
STRAIN AT 204° GENERATOR ELEVATION ANGLE 28° ABOVE SPRINGLINE

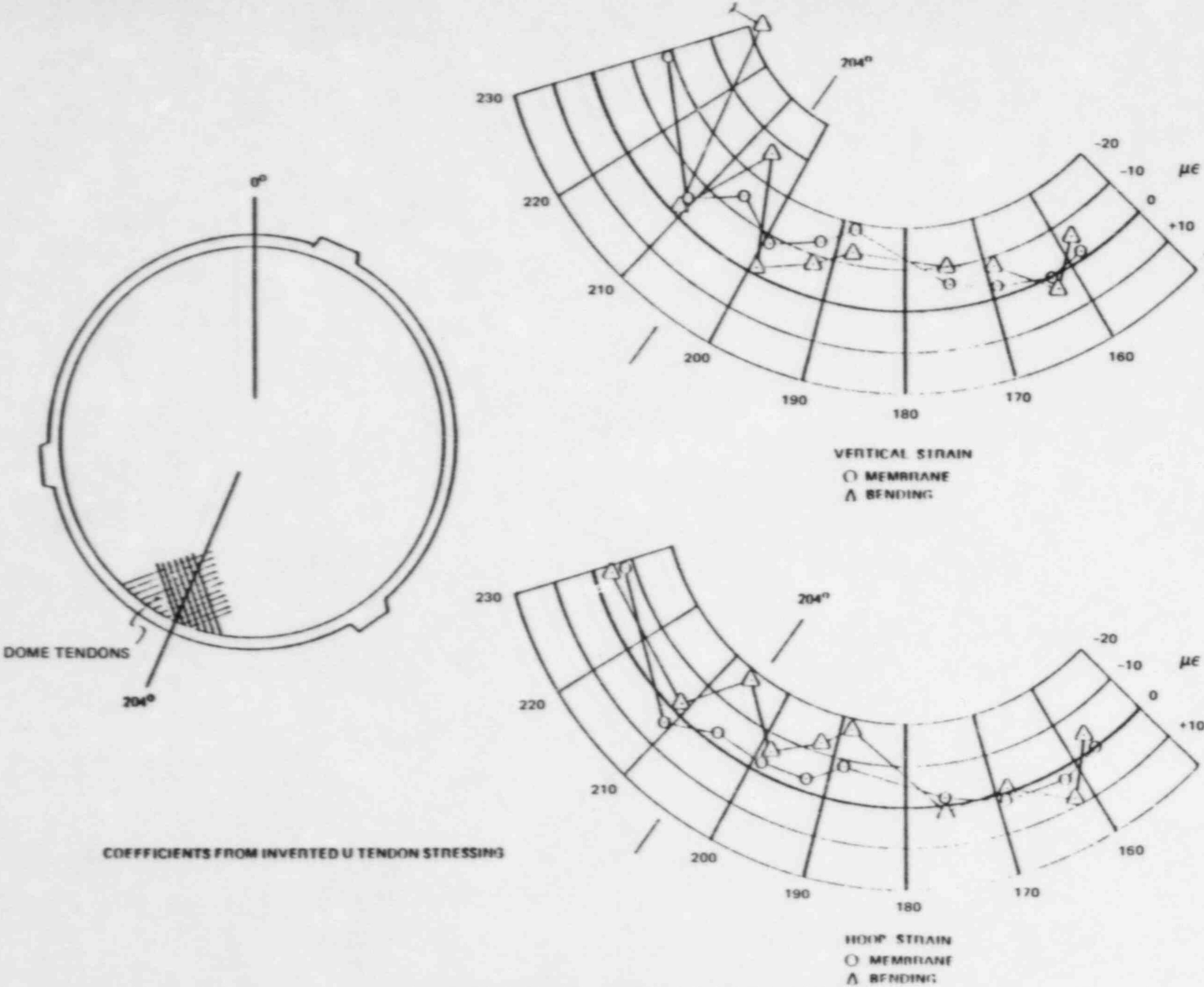


Figure 4-13 INFLUENCE COEFFICIENTS FOR
STRAIN AT 204° GENERATOR ELEVATION ANGLE 43° ABOVE SPRINGLINE

APPENDIX A

SPECIFICATION NO. CS-C15
PROCEDURE FOR CONCRETE STRAIN AND TEMPERATURE

DATA ACQUISITION

QUALITY CLASS IV
CIVIL/STRUCTURAL
CONSTRUCTION SPECIFICATION
FOR THE
SOUTHERN CALIFORNIA EDISON COMPANY
SAN ONOFRE NUCLEAR GENERATING STATION UNITS 2 & 3
SAN ONOFRE, CALIFORNIA

SPECIFICATION NO. CS-C15
PROCEDURE FOR CONCRETE STRAIN AND TEMPERATURE

DATA ACQUISITION

Job 10079
BECHTEL POWER CORPORATION
NORWALK, CALIFORNIA

SPECIFICATION NO. CS-C15

PROCEDURE FOR CONCRETE STRAIN AND TEMPERATURE DATA ACQUISITION

1.0 SCOPE

This procedure covers the acquisition of containment concrete strain and temperature data prior to the start of the acceptance pressure test. The acquisition of concrete strain and temperature data during the acceptance pressure test is covered by the Containment Structural Integrity Test Procedure. The installation of data acquisition equipment and of containment deformation measuring devices are not covered herein.

2.0 ABBREVIATIONS

The abbreviations listed below, where used in this specification, shall have the following meanings:

NRC	Nuclear Regulatory Commission
DAS	Data Acquisition System

3.0 GOVERNING CODES AND STANDARDS

Acquisition of containment structural data shall conform to the following governing codes and standards to the extent indicated by references herein. The date of issue (or revision) indicated shall apply:

NRC Regulatory Guide 1.18, Revision 1, Structural Acceptance Test for Concrete Primary Reactor Containments.

4.0 REFERENCE DRAWINGS

The locations of strain and temperature sensing devices as well as associated signal cables and connections are shown on Drawing (Nos.).

35033 (5)	Unit 2 Reactor Building Structural Instrumentation
PT- 7-4 (3)	VSL Vertical Tendons from base slab to springline
PT-12-3 (2)	VSL Dome Horizontal Tendons

5.0 DATA ACQUISITION PROCEDURE

5.1 Manual Recording Instrumentation:

Strain and temperature data shall be recorded on forms as shown in Attachment A & B. In addition to the raw sensor data, time of day, data takers intitials and comments pertinent to weather conditions and unusual circumstances which could affect the data shall

be noted on the form. The sensor number and data acquisition system channel number shall be noted on each form. In the case that data is being recorded for individual tendon tensioning, the appropriate note shall be indicated and the tendon number shall be recorded.

5.2 Automatic recording instrumentation:

A check shall be made of the automatically recorded data to insure that the equipment is functioning properly. The data tape shall be initialled by the checker. Any abnormal data shall be noted on the recorded tape. Data recorded for individual tendon tensioning shall be anotated with tendon number.

5.3 A post tensioning record shall be maintained in addition to the strain and temperature data. This record shall be compiled weekly and shall list the identification numbers of each tendon stressed and the date of the stressing operation.

5.4 The data acquisition equipment shall be operated in accordance with supplier's instructions.

6.0 FREQUENCY OF MEASUREMENTS

Strain and temperature data shall be recorded as follows:

6.1 Prior to the start of post-tensioning strain and temperature will be recorded once weekly. Initial strain or temperature data for a sensor will be recorded 24 to 48 hours following the completion of concreting at the sensor location.

6.2 Strain and temperature data will be recorded once daily between the start and completion of post-tensioning operations. In addition, data from all transducers shall be recorded within one hour before and one hour after tensioning of the following tendons are defined on VSL reference drawings:

Hoop

2	61	83
4	62	90
8	65	104
22	70	113
23	71	
40	77	
41	82	

Vertical

121	136	148
124	139	157
127	142	163
130	145	

6.3 Strain and temperature data will be recorded once weekly between the time of completion of post tensioning and the start of the acceptance pressure test.

7.0 DATA MAINTENANCE AND FORWARDING

Completed data forms and/or recorded data tapes shall be maintained in the construction office files. Copies of current data forms or tapes shall be forwarded to the project engineer weekly during post tensioning and bimonthly at other times. The data forwarded during post-tensioning shall include the tendon stressing records. A copy of the stressing sequence shall be included with the first data recorded during post-tensioning operations.

SAN ONOFRE NUCLEAR GENERATING STATION
UNIT 2 CONTAINMENT
STRAIN DATA

DATE
TIME
RECORDER INITIALS

( ) DAILY
( ) BEFORE TENSIONING TENDON NO.
( ) AFTER TENSIONING TENDON NO.

DAS CHANNEL NO.	TRANSDUCER NO.	μ STRAIN	COMMENTS
01	SIM001		
02	SIH002		
03	SIM003		
04	SIH004		
05	SIM005		
06	SIH006		
07	SIM007		
08	SIH008		
09	SIMSP001		
10	SIHSP002		
11	SIMSP003		
12	SIHSP004		
13	SIM013		
14	SIH014		
15	SIM015		
16	SIH016		

ATTACHMENT A1

DATA SHEET