P-86491 Attachment 1

Amendment No. 9
Attachment D
Page D-i

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

DEC 2 7 1957

IN REPLY REFER TO:
Docket No. 50-267

Public Service Company of Colorado
Public Service Company Building
550 Fifteenth Street
Denver, Colorado 80202

Attention: Mr. L. R. Patterson
Senior Vice President
Electric Department

Gentlemen:

As a result of the ACRS Subcommittee meeting on December 6, 1967, the ACRS has requested the additional information indicated in the enclosure in order to enable completing its review of your proposed Fort St. Vrain Nuclear Generating Station.

Please submit your reply in an original and two copies signed under oath or affirmation together with seventy (70) additional copies.

Sincerely yours,

Donald J. Skovholt, Acting
Peter A. Morris, Director
Division of Reactor Licensing

CC: A. L. Habush
Gulf General Atomics

Additional Information Required Relative to the Fort St. Vrain Nuclear Generating Station

December 15, 1967

D.1. Outline any changes that would be required in the plant design if the tendon ducts were to be filled with a suitable grease in order to inhibit tendon corrosion. How would such a design change influence the surveillance program to assure adequate corrosion control?

D.2. Evaluate the potential consequences of an accident in which all forced circulation cooling of the core is lost and the PCRV liner is subsequently assumed to fail in such a manner that it offers no resistance to leakage of gas from the PCRV. Assuming no helium buoyancy effect, what off-site doses would result from PCRV internal pressures of 2 and 5 psig?

What is the equilibrium xenon plus krypton STP volume? What would be the pressure rise in the PCRV due to the Xe and Kr released during the core-heat-up accident?

D.3. Submit the results of a quantitative analysis which determines the permissible number of tendons that may fail before a definite hazard would exist. The failure of both adjacent and parallel tendons as well as adjacent but non-parallel tendons should be considered.

D.4. Submit preliminary acceptance standards or reasonably definitive criteria for the proof testing of the PCRV in sufficient detail to permit establishing the adequacy of this test program.

D.5. Expand the analysis submitted of the accident involving the loss of forced circulation gas cooling of the core so as to investigate the long term consequences of such an accident and the procedures for recovering from such an accident.

D.6. Outline the extent to which either PSC or its agents will perform an independent audit of critical stages of construction and testing.

D.7. Submit the results of an analysis which investigates the possibility of the PCRV liner failing during a loss-of-cooling accident. The analysis should include consideration of the possibility and consequences of deterioration of the liner during plant lifetime.

D.8. Assuming the opening of a crack in the PCRV sufficiently large to cause rapid depressurization, is there a possibility that the crack will not close completely so that air ingress becomes a problem?

The information below is submitted in response to Question No. D.3. enclosed in the letter from Peter A. Morris dated December 27, 1967.

D.3. Question: Submit the results of a quantitative analysis which determines the permissible number of tendons which may fail before a definite hazard would exist. The failure of both adjacent and parallel tendons as well as adjacent but nonparallel tendons should be considered.

Answer: A quantitative analysis has been performed to establish the approximate number of tendons which could fail during operation of the reactor before a hazardous condition would exist. The results of this work are presented.

Vertical Tendons. By analyzing the prestress forces on a horizontal section through the vessel, it is shown that at least six adjacent vertical tendons can be lost during vessel operation before the design condition of zero average stress across the wall is violated. This analysis was performed by removing individual adjacent tendons on one side of the cross-section until the centroid of the vertical prestressing shifted sufficiently to produce tension halfway through the wall thickness. This includes the assumption that vertical prestress losses are twice the predicted values.

Even if all vertical prestress forces were lost, the PCRV walls which are very heavily reinforced with continuous high strength bonded reinforcement still tie the two heads together. In order to assess various safety margins, the following information is submitted to show the cavity pressures which the PCRV could resist with only the rebars acting.

f_s [kip/in.^{2}]	A_s [in^2]	$A_s f_s$ [kip]	$p = \frac{A_s f_s}{31^2 \times \pi/4} \times \frac{1}{0.144}$ [psig]
$0.9\ f_{sy} = 67.5$	1640	110,500	1020
$f_{sy} = 75$	1640	123,000	1135
$f_s = 100$	1640	164,000	1515

The amount of reinforcement in the haunch areas and in the wall sections adjacent to the heads is considerably larger than the reinforcement at vessel midheight for which the analysis was performed. Concrete cracks and their effect on liner strains are still small even at 845 psi since the reinforcing steel has not yielded. 75% of the vertical reinforcement consists of #18S and #11 bars which are spliced by mechanical means to develop the minimum guaranteed tensile strength of the bars. The bars are all anchored within the heads where the concrete will be in compression and the #18S bars have anchor plates attached to their ends.

Circumferential Tendons. The loss of one "complete ring" of circumferential tendons which consists of 3 sets of six tendons each spaced over a wall height of about 5'-0" has been analyzed without taking advantage of load redistribution to adjacent complete rings. The number of tendons that can be lost at any cross-section of the ring is given below in relation to the internal pressure required to produce failure. Of the total of 18 tendons, a minimum number of 12 pass any cross-section. Reinforcing steel is taken into account.

Internal Pressure [psig]	Required No. of Tendons Passing Any 5' Cross-Section	No. of Tendons Allowed to Fail at Any 5' Cross-Section	Safety Factor
1690	9	3	2.0
1475	8	4	1.75
1265	6	6	1.50
1055	5	7	1.25
845	3	9	1.00

The results of this single evaluation indicate that all adjacent circumferential tendons can fail (i.e., all tendons anchored on one face of one pilaster, including head region) without reducing the safety factor against failure at 845 psi below 2.0. Liner strains are still compressive.

Of 236 circumferential tendons, about 30 tendons uniformly distributed could be lost before net tensile stresses would occur across the wall section at 845 psig assuming the predicted prestress losses of about 12% have occurred. On this same basis, of the 84 circumferential tendons in the heads, about 6 from each head could be lost.

Crosshead Tendons. All adjacent crosshead tendons on one face of the vessel represent 33% of the total crosshead prestress, or 16 out of 48 tendons. Loss of these adjacent tendons does not unbalance the remaining prestressing forces that help to counteract the cavity pressure applied to the heads because of the 120 degree orientation of the tendons. The large head depth also allows the unbalanced forces, caused by loss of adjacent tendons, to redistribute and still provide an almost uniform prestress force on the inside face of the vessel head.

The overall effect of the crosshead tendons has been demonstrated by overpressure tests on a 1/13 scale model of the PSC-PCRV bottom head. Test pressures of 2400 psi could not cause failure of the heads. Since the crosshead tendons were tensioned to resist only approximately 600 psi of the internal pressure, the complete loss of all of these tendons would not reduce the head capacity below 1800 psig, which is approximately 2.1 times Reference Pressure. Liner strains are still compressive.

These tests are being continued with various combinations of prestress removed in order to establish failure levels in relation to applied prestress.

The above analyses have not taken credit for the restraint provided by adjacent concrete mass or transverse prestress. It has been shown that the loss of a certain number of tendons in each type of adjacent tendons would not cause a hazard with respect to the reduction in the vessel safety factor or the loss of net compression across a section under operating conditions. The number of adjacent nonparallel tendons that could be lost is at least the same as the number of those determined for each individual group. For example, the lost adjacent vertical tendons and the lost circumferential tendons on one pilaster face or in one complete ring do not depend on each other in the analysis performed; i.e., their contribution to restraint is neglected. It is believed that more refined analyses are not justified in view of the large margin of vessel capacity available even with the loss of the significant number of tendons of each type. A representative number of tendons in Model 2 will be unloaded to confirm the above analysis. Adjacent nonparallel tendons in the region of the crosshead tendon anchorages will be unloaded thereby putting all three types of tendons out of service in one region. One Model 2 tendon is approximately equal to four PSC tendons. (Reference Pressure for Model 2 is 704 psig versus 845 psig for PSC-PCRV.)

The reactor will normally be operated with all of the tendons tensioned, and with the tendon loads in the ranges specified by the design. However, it will be possible at all times to operate with any one tendon detensioned and still comply fully with the design criteria for the PCRV. It is expected that operation with one tendon detensioned will occur at times when tendon load cells are being calibrated, and when a tendon is removed for inspection or replacement of the tendon itself, its anchor hardware, or its corrosion protection.

P-86491 Attachment 2

Reference 1

to answer to
Specific Question 1

The information below further supplements the answer given to Question V.5 (Rev. 1), Attachment A, which was contained in Amendment No. 5. Results of the tendon detensioning tests recently completed on Model 2 are given. The information below is also supplemental to the answer to Question D.3, Attachment D, which was contained in Amendment No. 9.

V.5 Question: Submit a summary of the test data and failure mode for Model 2, a similitude study comparing the model and the Fort St. Vrain vessel and predictions of structural performance of the Fort St. Vrain vessel based on the test results from this model.

Supplemental Answer: A series of tests has been made on Model 2 wherein several tendons were fully detensioned and the vessel behavior in the partially detensioned condition was evaluated with internal pressure. These tests were performed to provide experimental confirmation of the approximate analyses used in determining the permissible number of tendons which could fail during operation of the Fort St. Vrain reactor before a hazardous condition would exist. The results of the analyses were given in the answer to Question D.3, Attachment D of Amendment No. 9.

Similar analyses were made on Model 2 to determine the equivalent number and type of tendons that should be detensioned to simulate the Fort St. Vrain PCRV conditions postulated in the answer to Question D.3. Although one Model 2 tendon is approximately equal to four Fort St. Vrain PCRV tendons, the differences in Reference Pressures (705 psig vs 845 psig), effective prestressing forces, and reinforcing steel quantities necessitated a separate analytical evaluation of Model 2. The results of the analyses of Model 2 are summarized as follows:

1. Vertical tendons. Four adjacent vertical tendons out of a total of 36 tendons (11.1% loss) should be fully detensioned to approach zero average stress across the wall at RP = 705 psig.

2. Circumferential tendons. One complete band of circumferential tendons consists of 2 sets of 3 tendons (180° wrap) spaced over a wall height of 18 in. A minimum of 4 out of 6 tendons traverse any 18 in. cross-section. One circumferential tendon should be detensioned to achieve an equivalent 25% loss in one band as postulated for the Fort St. Vrain PCRV.

3. Crosshead tendons. Eight adjacent crosshead tendons on one face of the vessel represent 33% of the total crosshead prestress (8 out of 24 tendons). The four outer crosshead tendons in Model 2 were tensioned to approximately twice the force in the four inner

crosshead tendons. Because of interferences, the inner crosshead tendons are not readily accessible for detensioning. The four outer crosshead tendons could be detensioned and represent a loss of approximately 22% in the crosshead prestressing.

The last test on Model 2 included in the answer to Question V.5, Attachment A, Amendment No. 5 was the overpressure test to 1500 psig (2.13 RP). At the completion of the 1500 psig overpressure test, the vessel was pressurized to its NWP = 585 psig and maintained for a period of time at ambient temperature. When the detensioning tests were initiated, the vessel had been under 585 psig sustained pressure for approximately 5 months.

Detensioning of the tendons was accomplished by rejacking and releasing the residual tendon force. The sequence of detensioning was as follows: 4 crosshead tendons, 1 circumferential tendon, and 4 vertical tendons. The specified tendons detensioned were in a region of the vessel where strain gages in the concrete and the liner were located. The four outer crosshead tendons were located in the bottom head, the circumferential tendon was approximately at the level of the bottom inner crosshead tendon anchor and the four adjacent vertical tendons were located between pilasters in the same face where the crosshead tendons were located. Strain and load measurements were made before and after each tendon was detensioned. Sensor measurements were also taken when the vessel was pressurized to RP = 705 psig, which was done prior to detensioning any tendon and after each group of tendons (i.e., all crosshead tendons) was completely detensioned. After all 9 tendons were fully detensioned, the vessel was subjected to a 48-hr pressure hold test at 705 psig. With the completion of the hold test, the vessel was depressurized and the tendons were retensioned to approximately their residual force prior to detensioning. The 585 psig sustained pressure test at ambient temperature was resumed thereafter.

Data obtained during the detensioning tests have not been fully evaluated. A sampling of concrete and reinforcing steel strains in the vicinity of the detensioned region at various stages of detensioning is given in Table V.5.3. No large strain changes were observed. Detensioning of the 4 vertical tendons caused the major strain increases. Strain reduction was observed in the inner midplane in the circumferential direction (see gages SR 413 and SR 407) after two additional vertical tendons were detensioned, while a strain increase was observed in the outer midplane (see gage SR 823). It appears that bending of the vessel wall is occurring over the region where the vertical prestressing has been drastically reduced by detensioning. Visual examination of the vessel exterior surface during the pressure tests showed no appreciable opening of concrete cracks which had been formed during the previous overpressure tests. Tendon loads monitored by load cells showed little load increases during various stages of detensioning. The major load increase over the residual prestress force was approximately 3600 lb for the circumferential tendons near midplane when the vessel was pressurized to 705 psig with all 9 tendons fully detensioned. This compares with a load increase of about 1400 lb at 705 psig pressure prior to detensioning. The residual prestressing force of the circumferential tendons at midplane is approximately 120,000 lb.

During the 48-hr hold test at 705 psig pressure with all 9 tendons fully detensioned, the vessel behavior was stable. Load cells being monitored during the pressure hold test indicated random load changes with a maximum load increase of about 3%.

Table V.5.3

SAMPLING OF CONCRETE AND REBAR STRAINS IN THE VICINITY OF DETENSIONED REGION AT VARIOUS STAGES OF DETENSIONING

Model 2

Gage No.	Location	Gage Orient.	Strain Due to 705 psig Pressure At Stages of Detensioning* (μin/in)				
			1	2	3	4	5
SR 823	Outer Midplane At Thin-wall Sect.	Circumf.	240	243	259	278	284
SR 894	Outer Midplane At Thin-wall Sect.	Vert.	97	91	85	102	124
SR 413	Inner Midplane At Thin-wall Sect.	Circumf.	180	193	219	237	222
SR 895	Adjacent to Circumf. Tendon Detensioned	Vert.	136	124	139	191	252
SR 820	Adjacent to Circumf. Tendon Detensioned	Circumf.	228	230	244	276	296
SR 896	Near Detensioned Crosshead Tendon Anchor Area	Vert.	27	28	21	26	26
SR 407	Inner Midplane At Pilaster Sect.	Circumf.	215	229	237	274	230
SR 873	Outer Midplane At Pilaster Sect.	Vert.	139	144	137	171	218
SR 881	Inner Bottom Haunch Junction at Pilaster Sect.	Vert.	167	171	178	203	237
SR 851	Inner Bottom Haunch Junction at Pilaster Sect.	Vert.	161	167	167	205	253

*Notes:
1. Prior to tendon detensioning
2. Four tendons detensioned (outer bottom crosshead tendons)
3. Five tendons detensioned (4 crosshead and 1 circumferential tendons)
4. Seven tendons detensioned (4 crosshead, 1 circumferential and 2 vertical tendons)
5. Nine tendons detensioned (4 crosshead, 1 circumferential and 4 vertical tendons)

Reference 3 to Answer to Specific Question ~~5~~1
P-86491 Attachment 3

Public Service Company of Colorado

February 14, 1985
Fort St. Vrain
Unit No. 1
P-85053

Regional Administrator
Region IV
Nuclear Regulatory Commission
611 Ryan Plaza Drive, Suite 1000
Arlington, Texas 76011

Attention: Mr. E. H. Johnson

SUBJECT: FSV - Tendon Requirements
Based on Safety Consideration

Dear Mr. Johnson:

Enclosed is a copy of GA Technologies' analysis entitled "FSV - Tendon Requirements Based on Safety Consideration." This analysis determines the number of tendons required to prevent a breach of the PCRV liner at various PCRV cavity pressures.

Please be aware that this analysis was contracted and performed well in advance of our January 15, 1985 meeting in Arlington, Texas and has been under final review by PSC. Although this analysis was completed prior to receiving your questions in this area, we believe that it does serve to establish the design margins of the prestressing system.

If you have any questions, please contact Mr. M. H. Holmes at (303) 571-8409.

Very truly yours,

D W Warembourg
D. W. Warembourg
Manager, Nuclear
Engineering Division

DWW/MJF/ksc

attachment REVIEWED BY: Scott Hofstetter 2/14/85

~~8502280585~~

GA 1485 (REV. 10/82)

GA Technologies Inc.

ISSUE SUMMARY

2 RELEASED

TITLE	FSV - TENDON REQUIREMENTS BASED ON SAFETY CONSIDERATION	☐ R & D ☐ DV & S ☒ DESIGN	APPROVAL LEVEL 2

DISCIPLINE	SYSTEM	DOC. TYPE	PROJECT	DOCUMENT NO.	ISSUE NO./LTR.
S	11	CFL	1900	907738	N/C

QUALITY ASSURANCE LEVEL	SAFETY CLASSIFICATION	SEISMIC CATEGORY	ELECTRICAL CLASSIFICATION
I	FSV - 1	FSV - 1	N/A

ISSUE	DATE	PREPARED BY	APPROVAL				ISSUE DESCRIPTION/ CWBS NO.
			ENGINEERING	QA	FUNDING PROJECT	APPLICABLE PROJECT	
N/C	DEC 17 1984	T.T.Lee	J-D.Wistrom	for D.Pettycord	R. Rosenberg R.Rosenberg		Original Release 2970.205

CONTINUE ON GA FORM 1485-1

Text 1 - 11 = 11
A1 - A20 = 20
B1 - B80 = 80
C1 - C2 = 2
TOTAL 113

NEXT INDENTURED DOCUMENTS

P.O. N-5159

REV																												
SH																												
REV																												
SH	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
REV																												
SH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

(SR-5022-EC-86-H) ~~8602280588~~

PAGE 1 OF 113

A TECHNOLOGIES INC.

TITLE: FSV - TENDON REQUIREMENTS BASED ON SAFETY CONSIDERATION

	DOCUMENT NO. 907738	**ISSUE NO./LTR.** N/C

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. SUMMARY

The minimum numbers of tendons required for safely supporting the core cavity pressure of 845 psig (Reference Pressure, RP) and 1268 psig (1.5 RP) without breaching the liner of the Fort St. Vrain PCRV have been determined for: 1) circumferential tendons in the PCRV wall and 2) crosshead and circumferential tendons in the heads of the PCRV. Hand calculations based on the concept of ultimate load analysis are used. No calculation is performed for the vertical tendons in this study. Per Ref. 1, the PCRV can resist up to 1515 psig cavity pressure with only the rebars acting, i.e., without reliance on any vertical prestress.

The results are given in Table 1 and Figs. 1 and 2. These results indicate that the core cavity pressure of 1.0 RP can be safely resisted with considerably less number of tendons than is actually provided. With 1.5 RP, the number of head tendons required is still less than that actually provided. The difference, however, is small if no vertical tendons exist as assumed in the analysis. Existence of vertical tendons will require less number of head tendons to resist 1.0 and 1.5 RP.

The procedure used in the study is described in the following sections. Detailed calculations are given in the appendices.

2. MATERIAL PROPERTIES

Material properties used in this analysis are (Ref. 1):

Concrete:

Compressive strength $f'_c = 6000$ psi

Liner:

Material = SA 537, Gr. B

Yield strength $f_{sy} = 60,000$ psi (at 0.2% offset)

Tensile strength $f'_s = 80,000$ psi (Ref. 2)

Failure strain $\varepsilon' = 18\%$ (Ref. 2)

Modulus of elasticity $E = 29 \times 10^6$ psi

Tendon Wires:

Tensile strength $f'_s = 240,000$ psi

Yield strength $f_{sy} = 204,000$ psi (at 1% strain)

Failure strain $\varepsilon' = 4\%$

Modulus of elasticity $E = 27 \times 10^6$ psi

Rebars:

Material = A432

Tensile strength $f'_s = 90,000$ psi

Yield strength $f_{sy} = 60,000$ psi

Failure strain $\varepsilon' = 7\%$

Modulus of elasticity $E = 29 \times 10^6$ psi

3. DEFINITION OF NUMBERS OF TENDONS

The Fort St. Vrain PCRV has, in addition to 90 vertical tendons with 169 1/4-in. diameter wires each, 210 circumferential tendons with 152 1/4-in. diameter wires each, 100 circumferential tendons with 169 1/4-in. diameter wires each, and 48 crosshead tendons with 169 1/4-in. diameter wires each.

All 210 152-wire circumferential tendons are in the barrel section. Of the 100 169-wire circumferential tendons, 34 are in the top head (the top 15'-6" section), 34 in the bottom head (the bottom 15'-6" section), and 16 each in the barrel sections adjacent to the top and bottom heads. Each head has 24 crosshead tendons.

All circumferential tendons are 180° tendons rather than full circle tendons (see Fig. E.15-2, Ref. 1). Because of the arrangement of these tendons, of the 18 circumferential (180°) tendons in a typical five-foot high wall section, a minimum of 12 pass any cross section. Hence 18 actual circumferential tendons provide 12 "effective" circumferential tendons. Similarly in the top or bottom head, 34 actual circumferential tendons provide 22 effective circumferential tendons.

The following definitions are used in this report:

N_b = Number of effective circumferential tendons in a 5-foot high wall section (12 in existence).

N_c = Number of effective circumferential tendons in the top or bottom head (22 in existence).

N_x = Number of crosshead tendons in the top or bottom head (24 in existence).

It is assumed that there is no broken wire in any tendon and that the required tendons in each group are uniformly distributed.

4. CIRCUMFERENTIAL TENDONS IN PCRV WALL

For the determination of the required number of circumferential tendons in the PCRV wall a typical five-foot high wall section was considered. It is assumed that ultimate conditions are reached at 1.0 RP or 1.5 RP for the purpose of this analysis. The core cavity liner is anchored to the concrete by means of studs welded to the liner and embedded in the concrete. The stud spacings are 7-1/2 in. in both circumferential and axial directions. It is assumed that, at ultimate, radial concrete cracks would develop at stud anchor locations and that resistance to the core cavity pressure is provided by the steel elements acting as multiple structural rings. The steel elements include the liner, and circumferential tendons and rebars at various radial locations. With the liner and rebar cross-sectional areas known, the number of tendons required to provide a total pressure resistance capacity for the core cavity pressure of 1.0 RP or 1.5 RP, and meeting the selected limit criteria can be determined from equilibrium and strain compatibility.

The tendon prestress loss at end of life is assumed to be 13.5% (Ref. 1), and the friction loss is assumed to be 11.5% (Ref. 3) in these calculations.

Two limit criteria are used in this case:

1) Liner stress = 0.9 f_{sy},

Tendon stresses $\leq f'_s$, and

Rebar stresses $\leq f'_s$

2) Maximum tendon stress = f'_s,

Liner stress < f'_s, and

Rebar stresses $\leq f'_s$

Obviously the first criterion is the more stringent and results in a larger number of tendons being required. The required numbers of circumferential tendons in the PCRV wall for the above two limit conditions are shown in Table 1.

5. TENDONS IN PCRV TOP AND BOTTOM HEADS

The required number of crosshead and circumferential tendons in the PCRV top and bottom heads to safely support 1.0 RP and 1.5 RP without breaching of the liner boundary are determined by ultimate load analysis of the bottom head.

Four quasi-analytical solutions were originally used in assessing the ultimate capacity of the Fort St. Vrain PCRV heads (Ref. 1). These are: 1) bottom head yield line failure analysis, 2) bottom head punching shear failure analysis, 3) bottom head concrete ligament compressive failure analysis, and 4) top head analysis by grid system simulation. In the case of 34 circumferential and 24 crosshead tendons in each head and 90 vertical tendons, the yield line analysis provided the lowest estimate of the ultimate pressure capacity, while the concrete ligament compressive failure analysis provided the highest, about three times as high as the lowest estimate. The top head grid analysis requires use of a computer program.

Based on the above observations it was decided to use the yield line failure analysis method for the ultimate load analysis in the current study, and to check the results using the punching stress failure analysis.

The assumptions and detailed procedure used in the bottom head yield line analysis follow those used in Ref. 1. Based on an assumed number of crosshead tendons the resultant pressure which must be resisted by the bottom head (cavity pressure reduced by the cavity pressure equivalent of crosshead tendons, Ref. 1) is first calculated. By assuming formation of a plastic hinge at the head-to-wall junction (signified by 0.003 in/in maximum concrete strain and/or yielding of liner and majority of rebars in tension), and a yield line pattern (generally radial along concrete ligaments) the unit yield line moment required to prevent this particular yield line mode of failure under the given cavity pressure (1.0 RP or 1.5 RP) can be determined. The number of circumferential tendons required to provide an ultimate moment capacity along the yield line which is larger than the required unit yield line moment is then established. The ultimate moment capacity of the bottom head is defined by the following stress limits (Ref. 1):

Maximum rebar stress $\leq 0.9\ f_{sy}$,

Maximum tendon stress $\leq 0.9\ f_{sy}$, and

Maximum compressive concrete stress $\leq 0.85\ f'_c$

The tendon prestress losses at end of life are assumed to be 12% for both crosshead and circumferential tendons (Ref. 1) and the friction losses are assumed to be 10% and 11.5%, respectively for these two types of tendons (Ref. 3). The yield line failure analysis in the current study is based on the assumption that no vertical tendons exist.

The required number of tendons based on the results of the yield line failure analysis are shown graphically in Figs. 1 and 2.

For the punching shear failure analysis of the bottom head the failure plane is assumed to be the one formed by the concrete ligaments connecting the steam generator penetrations (Ref. 1). Reference 4 provides an equation to estimate the ultimate shearing strength of PCRV heads as a function of span/depth ratio and radial prestress. Based on this equation and the number of head tendons required as determined by the yield line failure analysis, it is found that the punching shear stress is not critical for either the 1.0 RP or the 1.5 RP cases.

6. CONCLUSIONS

The required numbers of circumferential tendons in the Fort St. Vrain PCRV wall to safely support the cavity pressure of 1.0 RP and 1.5 RP are given in Table 1. The corresponding required numbers of crosshead and circumferential tendons in either top or bottom head of the PCRV, derived under a conservative assumption of no vertical prestress, are given in Figs. 1 and 2.

From Fig. 2, it appears that under 1.5 RP the permissible reduction in the numbers of crosshead and circumferential tendons in the heads is small if no vertical prestressing tendons exist.

7. REFERENCES

1. "Fort St. Vrain Nuclear Generating Station. Updated Final Safety Analysis Report."

2. ASTM, "Specification for Carbon-Manganese-Silicon Steel Plates, Heat Treated for Pressure Vessels. SA-537."

3. Lee, T. T. and Cheung, K. C., "FSV - PCRV Tendon Evaluation," GA Document 907441/A, April 30, 1984.

4. Garas, F. K. and Trowsdale, D. R., "Overload Behavior and Shear Failure Mechanisms of Model No. 2 of the Bottom Head of the Fort St. Vrain Prestressed Concrete Reactor Vessel," Report 14H/69/1411, Taylor Woodrow Construction, Ltd., September 1969.

5. Bresler, B., "Reinforced Concrete Engineering," Vol. 1 Materials Structural Elements, Safety, John Wiley & Sons, New York, 1974.

6. "PCRV Bottom Head, Reinforcing Plan, Sheet 1," Drawing 3614, B-36/J, Sargent & Lundy, March 1969.

7. "PCRV Bottom Head, Reinforcing Schedule and Details, Sheet 1," Drawing 3614, B-37/E, Sargent & Lundy, October 1969.

8. "PCRV Bottom Head, Reinforcing Plan, Sheet 2," Drawing 3614, B-38/K, Sargent & Lundy, April 1969.

9. "PCRV Bottom Head, Reinforcing Schedule & Details, Sheet 2," Drawing 3614, B-39/E, Sargent & Lundy, December 1968.

10. "PCRV Bottom Head, Reinforcing Schedule & Details, Sheet 3," Drawing 3614, B-40/D, Sargent & Lundy.

11. "PCRV Bottom Half Vertical Section," Drawing 3614, B-35/S, Sargent & Lundy, December 1969.

12. "PCRV Bottom Head, Tendon Tubes Details," Drawings 3614, B-21/E and B-22/D, Sargent & Lundy, October 1969.

NOTE: References 5 through 12 are cited in the appendices.

TABLE 1

MINIMUM NUMBERS OF CIRCUMFERENTIAL TENDONS IN WALL SECTION

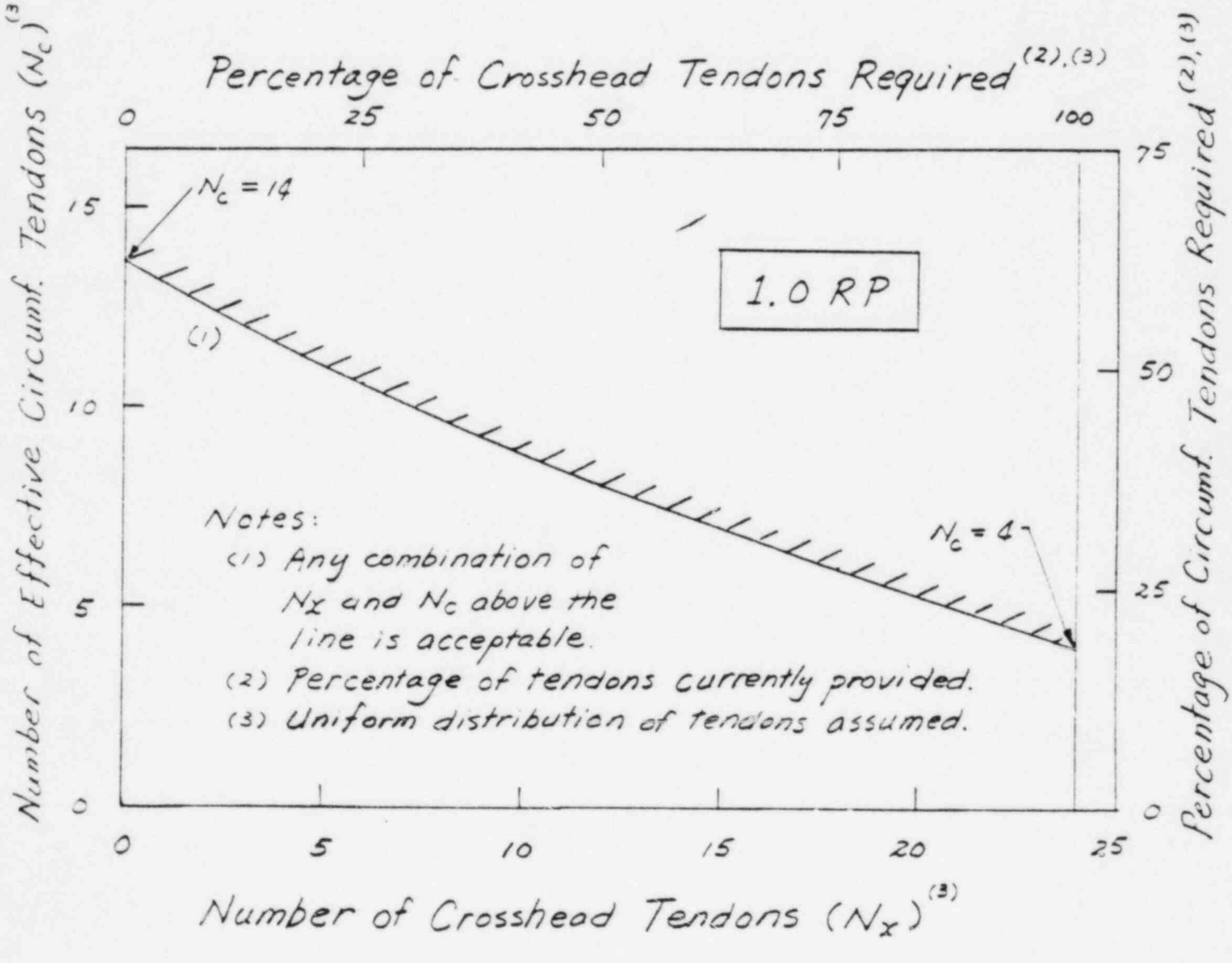
	Number of Tendons Required (N_b)(1)		Percentage of Tendons Required(2)	
Criterion	1.0 RP(3)	1.5 RP	1.0 RP	1.5 RP
Liner Stress = 0.9 f_{sy}	5	9	42%	75%
Max. Tendon Stress = f'_s (4)	3	5	25%	42%

(1) Number of effective tendons required per 5-foot high section. See the text for definition of N_b.

(2) Percentage of tendons currently provided in any region of the PCRV wall. It is assumed that the required tendons are located uniformly in the region under consideration.

(3) 1.0 RP = 845 psig.

(4) The liner strain is 0.046 in./in. when the maximum tendon stress is f'_s.



Notes:

(1) Any combination of N_x and N_c above the line is acceptable.

(2) Percentage of tendons currently provided.

(3) Uniform distribution of tendons assumed.

Figure 1. Number of Head Tendons Required in Each Head to Support 1.0 RP

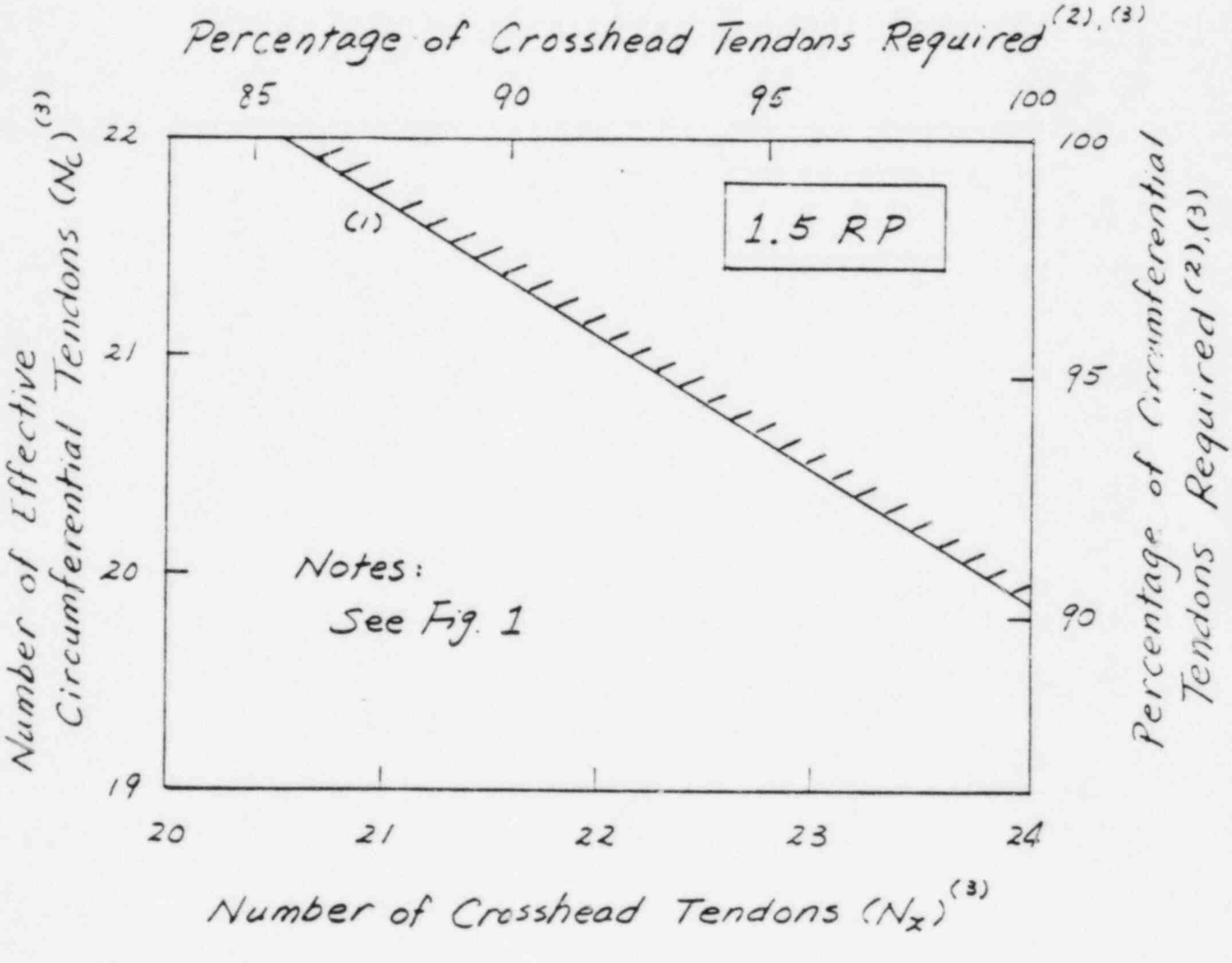


Figure 2. Number of Head Tendons Required in Each Head to Support 1.5 RP

APPENDIX A

NUMBER OF CIRCUMFERENTIAL TENDONS IN THE PCRV WALL

TABE OF CONTENTS - APPENDIX A

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR		
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C — PAGE A3 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:
CHECKED BY	DATE	

A.1 Cases Considered

1) Core cavity pressure = Reference Pressure

= 1.0RP = 845 psig

2) Core cavity pressure = 1.5RP = 1268 psig

A.2 Location of Steel Components

For a 5'-0" barrel section

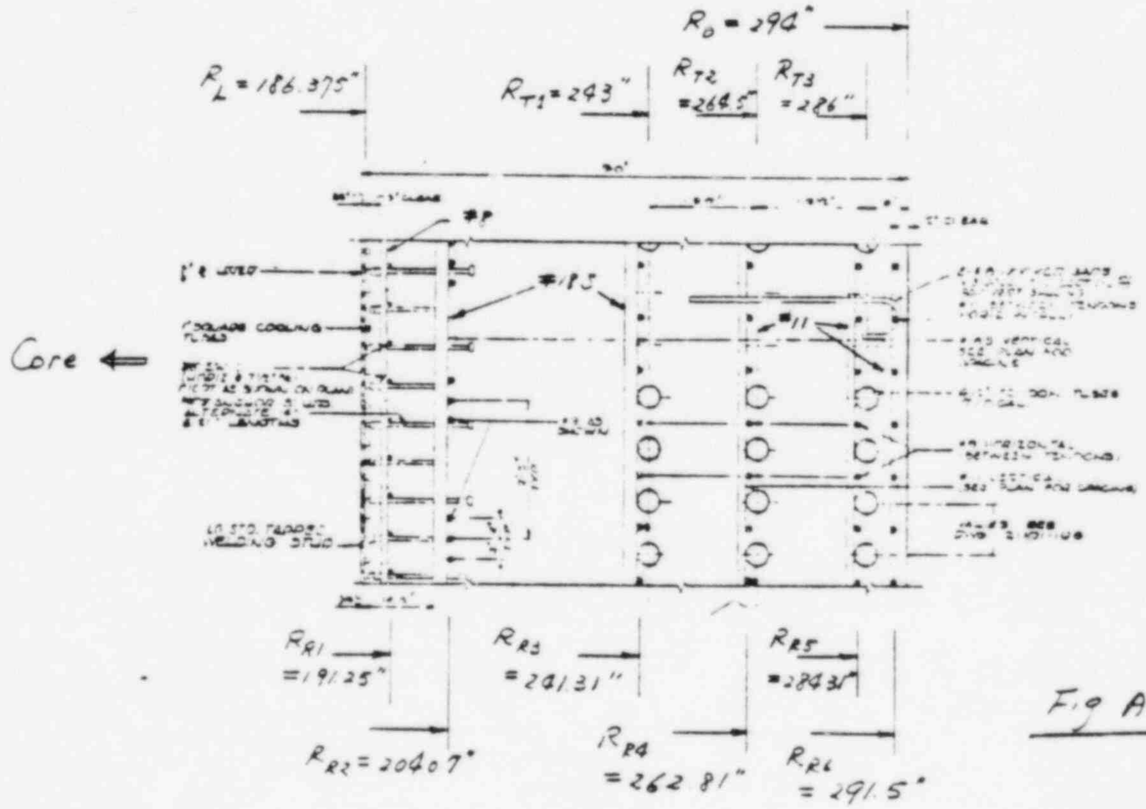


Fig A-1

(Ref 1. FSAR Fig E.15-6)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 807738 N/C

PAGE A4 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Rebar Dimensions:

Table A-1

Bar Size	Diam. (in.)	Area (in²)
#8	1.000	0.79
#9	1.128	1.00
#11	1.410	—
#18S	2.257	—

Rebar Groups: Table A-2

Group	R_R (in.)	Rebars	Number per 5 ft.	Total Area (in²)
R1	191.25	#8 @ 7.5"	8	6.32
R2	204.07	3-#9 @ 27"	6	6.00
R3	241.31	#9 @ 10"	6	6.00
R4	262.81	#9 @ 10"	6	6.00
R5	284.31	#9 @ 10"	6	6.00
R6	291.50	#8 @ 10"	6	4.74

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A5 OF
PREPARED BY T. T. Lee	DATE 11/19/86	REF. DOCUMENTS:	
CHECKED BY	DATE		

Liner: 3/4 in thick at $R_L = 186.375$ in

Tendons: 152 - 1/4 in diam wires → Area = 7.463 in²
169 - " " " → Area = 8.298

- 3 groups of 6 tendons each (total of 18) for each 5 ft. section, located at R_{T1}, R_{T2} & R_{T3}
- Minimum of 12 tendons pass any 5 ft section

A.3 Material Properties

Rebars A432 (A305-56T. Deformation)

f_{sy} = Minimum guaranteed yield strength
(at 0.5 % total extension)
= 60 Ksi (FSAR. App. E Section E.1)

f_s' = Minimum guaranteed tensile strength
= 90 Ksi (FSAR. Section E.1)

ϵ' = Minimum quanteed strain at failure
= 7 % in 8 in (FSAR. Section E.1)

E = Modulus of elasticity = 29.0×10³ Ksi
(FSAR Sec E.10.3

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A6 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Liner: SA 537, Grade B (Quenched & tempered)
(Ref. 1)

f_{sy} = 60 ksi (at 0.2% offset) (FSAR, E.1.
(FSAR. E.10

f_s' = 80 ksi

ϵ' = 18%

} (ASTM Spec. SA 537. Ref. 2)

E = 29.0 x 10^3 ksi (FSAR Sec. E.10.3)

Tendons:

Tendon wires: f_s' = 240 ksi

f_{sy} = 204 ksi at 1% strain

ϵ' = 4%

See Fig. 4 (From FSAR Fig 5.6-1)

E = 27 x 10^3 ksi (Table 5.6-5)
FSAR

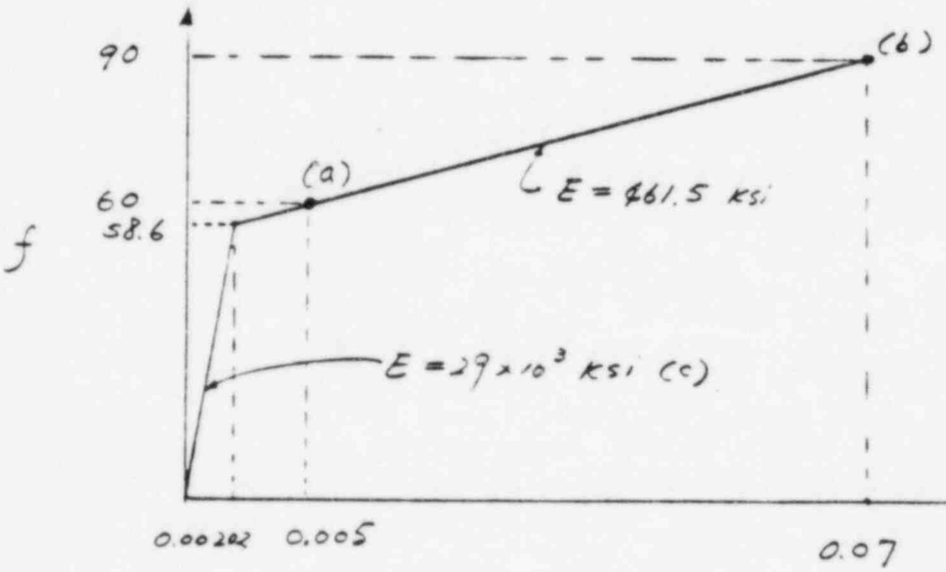
GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A7 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Stress - Strain Curves:

Rebars:



Based on (a), (b) and (c)

Fig. A-2

$$\text{Use}\begin{cases} f = 90 - (0.07 - \epsilon) \times 461.5, & \epsilon \geq 0.00202 \\ f = 29.0 \times 10^3 \epsilon, & \epsilon \leq 0.00202 \end{cases}$$

Liner:

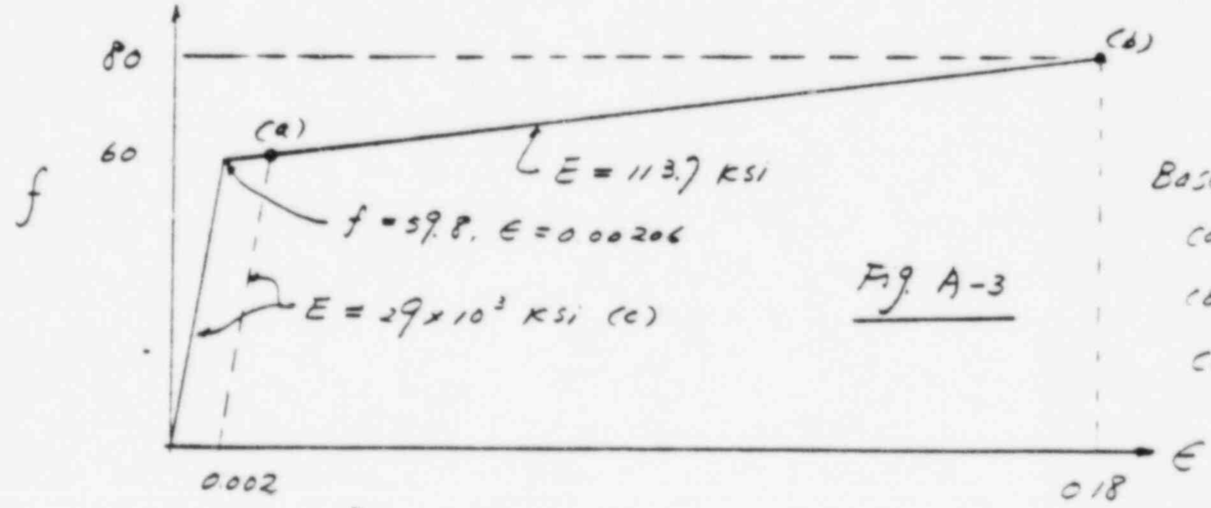


Fig. A-3

Based on (a) (b), & (c)

$$\text{Use}\begin{cases} f = 80 - (0.18 - \epsilon) \times 113.7, & \epsilon \geq 0.00206 \\ f = 29.0 \times 10^3 \epsilon, & \epsilon \leq 0.00206 \end{cases}$$

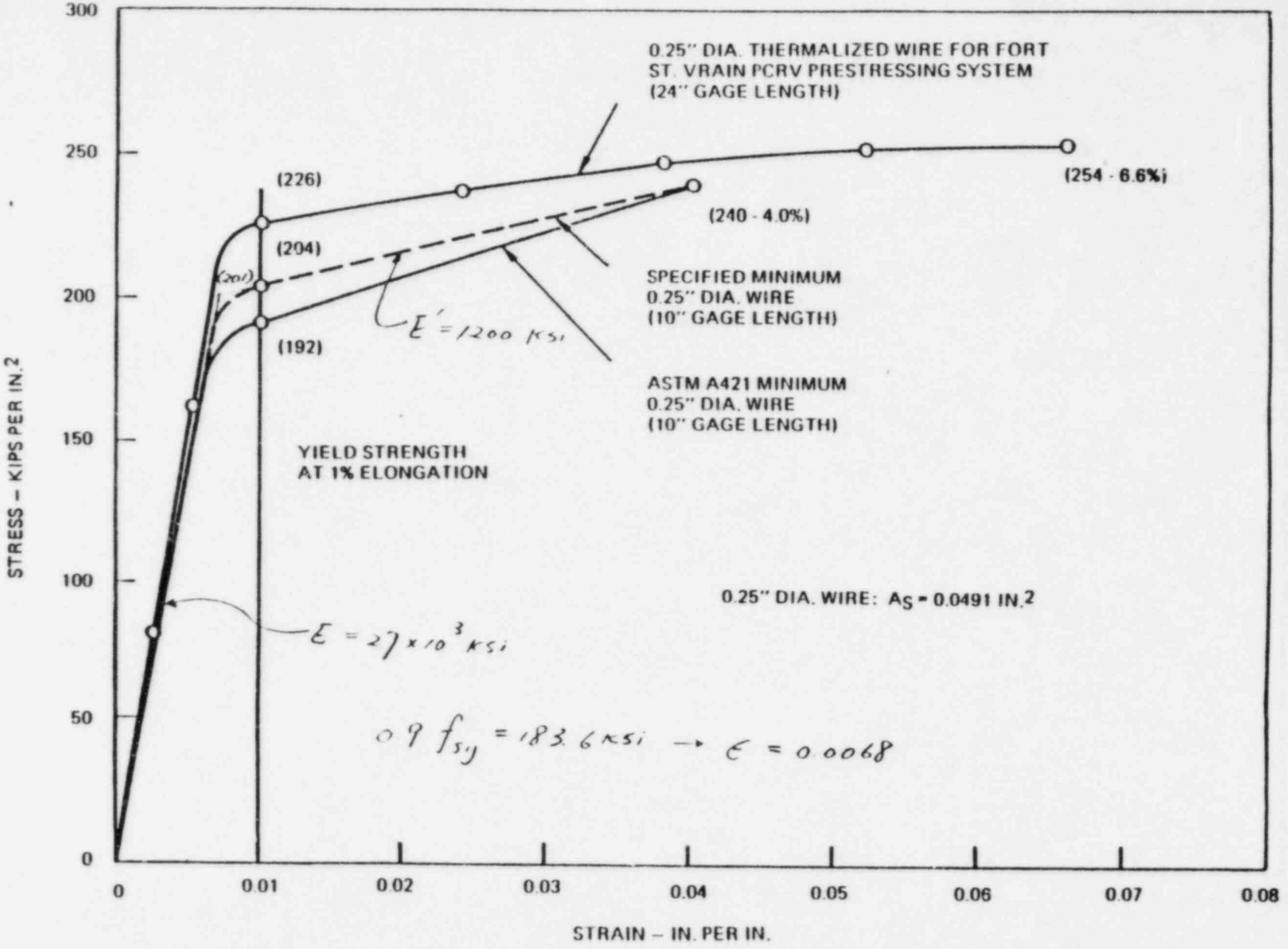


Figure A-4 Typical Stress-Strain Curve of Wire

– T. Lee 11/19/84 -07738 N/C

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A9 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

A.4 Assumptions

(1) Based on the discussion on the crack propagation given in FSAR, Section E 8.2.3.1 it is assumed that radial cracks develop at the locations of stud anchors. Hence concrete does not participate in resisting the core cavity pressure. It does transmit the pressure radially

(2) Each steel component (liner, rebar and tendon) acts as a ring and contributes in resisting the core cavity pressure

(3) On account of the extensiveness of the concrete crack the bond between rebars and concrete is essentially non-existing and the strain in a given rebar is essentially

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A10 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

constant (Ref. 5, p 175).

(4) The prestress loss at end of life is 13.5 % (FSAR. Table 5.6-4) The friction loss is 11.5 % (Ref. 3)

(5) Radial shortening of concrete is negligible Hence the radial displacements of all steel components are the same

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A 11 OF

PREPARED BY T T Lee

DATE 11/19/84

REF. DOCUMENTS.

CHECKED BY

DATE

A.5 Compatibility

Assuming that each steel component displaces radially the same amount (Assumptions) the strains in various components are related as follows:

$$\epsilon_L R_L = \epsilon_{Ri} R_{Ri} = (\Delta\epsilon_{Ti})\ R_{Ti}$$

where ϵ = strain

R = radial distance from the center of core cavity

$\Delta\epsilon_{Ti}$ = additional tendon strain for Group i tendon
= total tendon strain − strain due to prestress

The subscripts are:

L = liner

R = a rebar group

T = a tendon group

i = group number

The strain due to prestress ≅ 0.00476 in/in (Fig. A-4

based on $f = 0.7 f_s' \times (1 - \overset{\text{Loss}}{0.135}) \times \overset{\text{Friction}}{0.885} = 128.6$ ksi

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A 12 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

A.6 Contribution to Pressure Capacity

Let f = stress (psi)

A_s = total steel area (in²)

p' = pressure capacity if the pressure is applied to the steel component (psi)

p = contribution to the core cavity pressure capacity (psi)

Liner:

$$\frac{p'_L R_L \cdot 60}{A_{s,L}} = f_L \rightarrow p'_L = \frac{3/4 \times 60}{186.375 \times 60} f_L = 4.024 \times 10^{-3} f_L$$

$$p_L = p'_L = 4.024 \times 10^{-3} f_L$$

Rebar Groups:

$$\frac{p'_{Ri} R_{Ri} \, 60}{A_{s,Ri}} = f_{Ri} \rightarrow p'_{Ri} = \frac{A_{s,Ri}}{60 \cdot R_{Ri}} f_{Ri}$$

$$p_{Ri} = p'_{Ri} \frac{R_{Ri}}{R_L} = \frac{A_{s,Ri}}{60 \; R_L} f_{Ri}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A13 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

For R1: $$p_{R1} = \frac{6.32}{60 \ 186.375} f_{R1} = 0.565 \times 10^{-3} f_{R1}$$

For R2 ~ R5:

$$p_{Ri} = \frac{6.00}{6.32} \ 0.565 \times 10^{-3} f_{Ri} = 0.536 \times 10^{-3} f_{Ri}$$

For R6: $$p_{R6} = \frac{4.74}{6.32} \cdot 0.565 \times 10^{-3} f_{R6} = 0.424 \times 10^{-3} f_R$$

Tendon Groups

$$\frac{p'_{Ti} R_{Ti} 60}{A_{s,Ti}} = f_{Ti} \longrightarrow p'_{Ti} = \frac{A_{s,Ti}}{60 R_{Ti}} f_{Ti}$$

$$p_{Ti} = p'_{Ti} \frac{R_{Ti}}{R_L} = \frac{A_{s,Ti}}{60 R_L} f_{Ti}$$

$$= \frac{N' \cdot 7.463}{60 \cdot 186.375} f_{Ti} = 0.667 \times 10^{-3} N'_i f_{Ti} \quad \text{(152-wire}$$

$$= \frac{N' \cdot 8.298}{60 \cdot 186.375} f_{Ti} = 0.742 \times 10^{-3} N'_i f_{Ti} \quad \text{(169-wire}$$

where N'_i = Minimum number of tendons passing any 5 ft Section

(for each group, maximum is 4)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A-14 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

A.7 Calculation of Minimum Tendons Required

(1) Select a limit criterion in terms of ϵ

(2) Calculate strains for all steel components using the compatibility relations. Check $\epsilon \le \epsilon$

(3) Calculate f_L, f_{Ri} and f_{Ti} (Figs. A-2 ~ A-4)

(4) Calculate p_L, p_{Ri} and p_{Ti}

(5) Calculate the total pressure capacity to be contributed by tendons:

$$\left(\sum_{i=1}^{3} p_{Ti}\right)_{req'd} = \underset{(\text{or } 1268)}{845} - \left(p_L + \sum_{i=1}^{6} p_{Ri}\right)$$

(6) Calculate the total number of tendons required, using the middle row as an average:

$$N_b = \sum_{i=1}^{3} N_i' = \frac{\left(\sum p_{Ti}\right)_{req'd}}{\underset{(\text{or } 0.742)\sim(169\text{-wire tendons})}{\overset{(152\text{-wire})}{0.667}}\ f_{T2}}\ , \quad f_{T2} \text{ in ksi}$$

Or $N = \dfrac{18}{12} \sum_{i=1}^{3} N_i'$

where N is the actual total number of tendons required to provide $\sum_{i=1}^{3} N_i$ effective number of tendons in any 5 ft sectio

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A15 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

IRP Case

Table A-3.

Criterion: Liner Stress at 0.9 f_{sy} = 54 ksi

Component	R. (in)	$\frac{R_L}{R}$	$\Delta\epsilon_{Ti}$	ϵ	f (ksi)	P (psi)
Liner	186.38	1		0.00186	54.0	27.3
R1	191.25	0.975		0.00181	52.5	29.7
R2	204.07	0.913		0.00170	49.3	26.4
R3	241.31	0.772		0.00144	41.8	23.6
R4	262.21	0.709		0.00132	38.3	20.5
R5	284.21	0.656		0.00122	35.4	19.0
R6	291.50	0.639		0.00119	34.5	14.6
T1	243.00	0.767	0.00143	0.00619		
T2	264.50	0.705	0.00131	0.00607	Average → 164	109 for each
T3	286.00	0.652	0.00121	0.00597		

$845 - (P_L + \Sigma P_{Ri}) = 845 - (351.1) = 493.9$ psi

$\sum_{i=1}^{3} N_i = \frac{493.9}{109} = 4.53$ $\rightarrow N = 6.80$

For $N = 7$ $P = 351 + 109 \times 7 \times \frac{2}{3} = 860$ psi

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A 16 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

1RP case   Table A-4

Criteria 2:

Tendons at R = 243 in have $\epsilon = \epsilon'$

Component	R (in)	$\frac{R_{T1}}{R}$	$\Delta\epsilon_{T2}$	ϵ	f (ksi)	p (psi)
Liner	186.38	1.30		0.0458	64.7	260.5
R1	191.25	1.27		0.0447	78.3	44.2
R2	204.07	1.19		0.0419	77.0	41.3
R3	241.31	1.01		0.0356	74.1	39.7
R4	262.81	0.925		0.0326	72.7	39.0
R5	284.31	0.855		0.0301	71.6	38.4
R6	291.50	0.834		0.0294	71.3	30.2
T1	243.00	1	0.0352	0.04	240	160.0 ea
T2	264.50	0.919	0.0324	0.0372	236.6	157.8 eoc tend
T3	286.00	0.850	0.0200	0.0347	233.6	155.8 ec

$845 - (p_L + \Sigma p_{Ri}) = 845 - (493) = 352$

$\sum_{i=2}^{5} N_i' = 352/157.8 = 2.23$ $\rightarrow N = 3.35$

For $N = 4$ $p = 493 + 4 \times 157.8 \times \frac{2}{3} = 914$ psi

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A17 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

1RP Case   Table A-5

Criterion 3:

Rebars at R = 191.25 in have $\epsilon = \epsilon'$

Component	R (in)	$\frac{R_{R1}}{R}$	$\Delta\epsilon_{Ti}$	ϵ	f (ksi)	p (psi)
Liner	186.38	1.03		0.072	67.7	272.5
R1	191.25	1		0.07	90.0	50.9
R2	204.07	0.937		0.0656	87.8	47.2
R3	241.31	0.793		0.0555	83.3	44.6
R4	262.81	0.728		0.0509	81.2	43.5
R5	284.31	0.673		0.0471	79.4	42.6
R6	291.50	0.656		0.0459	78.9	33.4
T1	243.00	0.787	0.0551	0.0599		0
T2	264.50	0.723	0.0506	0.0554	> 4% = ϵ'	0 eac forc
T3	286.00	0.669	0.0468	0.0516	Failed	0

$845 - (p_L + \sum p_{Ri}) = 845 - (535) = 310$

$\sum_{i=1}^{3} N_i' = N.A$ $\rightarrow N = N.A$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A18 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Tables A-3 through A-5 are for tendons with 152 wires. For tendons with 169 wires, still for 1RP, using the data in Tables A-3 and A-4:

Criterion 1 $f_T = 164$ ksi $\rightarrow \frac{P_{Ti}}{N_i} = 121.7$ p:

$$\Sigma N_i = \frac{4939}{121.7} = 406$$ vs 453 for 152-wir tendon:

Criterion 2 $f_T = 236.6 \longrightarrow \frac{P_{Ti}}{N_i} = 1756$

$$\Sigma N_i = \frac{352}{1756} = 200$$ vs 223 for 152-wir tendon.

→ Use the same number of tendons as in the 152-wire tendon case

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE A 19 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

1.5 RP Case

Data in Tables A-3 and A-5 still apply. The required pressure capacity is 1268 psig instead of 845 psig.

Based on Table A-3:

$P_L + \sum P_{Ri} = 351.1$ psi

Tendons must supply 1268 − 351.1 = 9169

$$\sum_{i=1}^{3} N_i' = \frac{9169}{109} = 841 \longrightarrow N = 12.6$$

Use $N = 13 \longrightarrow P = 3511 + 109 \times 13 \times \frac{2}{3} = 1296$ p

Criterion 2: <u>Tendons at R = 243 in. have ε = ε'</u>

$$\sum_{i=1}^{3} N_i = \frac{1268 - 493}{1578} = 491 \rightarrow N = 7.37$$

Use $N = 8 \rightarrow P = 493 + 8 \times 157.8 \times \frac{2}{3} = 1335$ p

Criterion 3: <u>Rebars at R = 191.5 in have ε = ε'</u>

Tendon strain > 4 % $P = 535$ psig

N. G

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE A20 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

A.8 Summary of Calculated Results

Table A-6

Minimum Number of Circumferential Tendons

Required per 5 ft High Wall Section

Limit Criteria	Required 1.0 RP		Required 1.5 RP		Number currnt Provided	
	Actual	Effective	Actual	Effective	Actual	Effecti
Liner Stress $= 0.9 f_{sy}$	7	5	13	9	18	12
Max. Tendon strain $= \epsilon'$	4	3	8	5	18	12

APPENDIX B

NUMBER OF PCRV HEAD TENDONS

TABLE OF CONTENTS - APPENDIX B

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR		
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C · PAGE B3 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:
CHECKED BY	DATE	

B.1 Yield Line Mode of Failure

The analysis is performed for the bottom head subjected to 1 RP or 1.5 RP cavity pressure. Calculational steps parallel those used in the FSAR Update, Section E.11.2.2 (Ref. 1).

B.1.1 Basic Assumptions

See Ref 1, Section. E.11.2.2

Additional assumptions

1) No vertical tendons

2) Number of crosshead and circumferentia tendons in the heads are to be reduce (Original design has 24 crosshead tendons and 24 circumferential tendons.)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B4 OF
PREPARED BY T T Lee	DATE 11/19/86	REF. DOCUMENTS:	
CHECKED BY	DATE		

B. 1.2 Calculational Procedure

1) Calculate the net head pressure load.

(Cavity pressure - cavity pressure equivalent of crosshead tendons

This is done for an assumed N_x (§B.1.3)

2) Calculate the net tensile force (or boundary force) transmitted through the intersection of the PCRV wall and the bottom head (§B.1

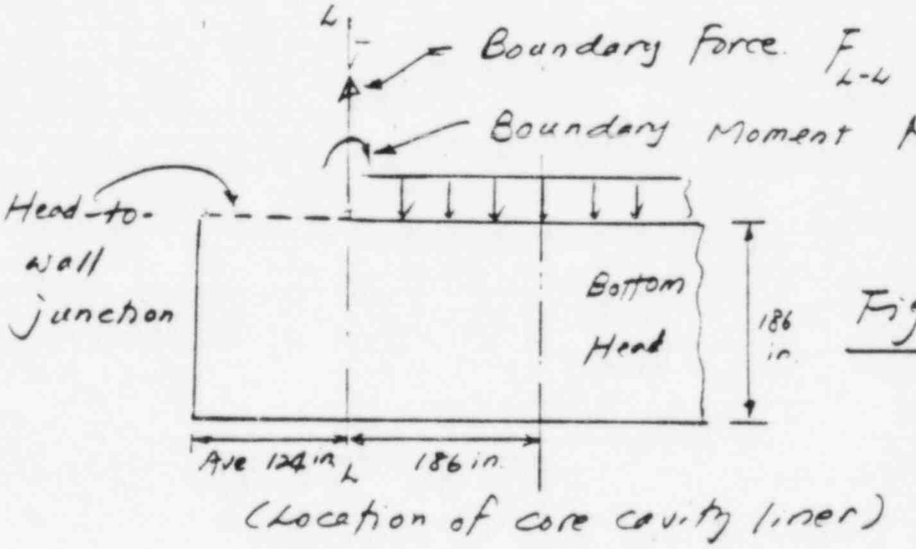


Fig. B-1

3) Assuming that a plastic hinge forms at the head-to-wall junction, calculate the boundary moment corresponding to F_{L-L} (§B.1

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B5 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

4) Assuming a yield pattern for the head, calculate the unit yield line moment required to balance the net pressure. F_{L-L} and M_{L-L}. (§ B.1.6)

5) Calculate the number of circumferential (head) tendons required to provide a unit moment capacity along the yield equals to or larger than the required unit yield line moment. (§B.1.7. B.1.8)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B6 OF
PREPARED BY T. T. Lee	DATE 11/19/82	REF. DOCUMENTS:	
CHECKED BY	DATE		

B.1.3 Net Head Pressure Load

The pressure load on the heads is resisted in part by the crosshead tendons. The vertical component of the crosshead tendons is:

$$F_v = (2 N_x)(A_t)(f_t) \sin \alpha$$

where: N_x = Number of crosshead tendons

A_t = X-sectional area of a tendon = 8.35 in²

f_t = tendon stress

α = average inclination of the tendons = 36° 45'

Allowing $f_t = 0.7 f_s' \underset{\text{loss (Ref. 1, Table 5.6-4)}}{(1-0.12)} \underset{\text{friction (Ref. 3)}}{(0.9)} = 0.554 f_s' = 1$

$$F_V = 2 N_x (8.35)(133{,}000) \sin 36° 45$$

$$= 1{,}329{,}000\ N_x \text{ lbs}$$

Cavity pressure equivalent of crosshead tendons is assumed constant over the cavity.

$$p_x = \frac{F_V}{3.14 \times 186^2} = 12.23\ N_x \text{ psig}$$ (cavity rad = 186

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 87 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE /		

The net pressure load is:

p = Actual cavity pressure − 12.23 N_x

Table B-1 Net Pressure and Boundary Force

N_x	1.0 RP		1.5 RP	
	Net pressure (psi)	F_{L-L} (k/in. of liner)	Net pressure (psi)	F_{L-L} (k/in of liner)
0	845	786	1268	1179
6	772	71.8	1194	111.1
12	698	64.9	1120	1042
18	625	58.1	1046	97.3
24	551	51.3	972	90.4

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B8 OF

PREPARED BY T. T. Lee

DATE 11/19/86

REF. DOCUMENTS:

CHECKED BY

DATE

B 1.4 Boundary Force

Since there is no vertical tendons the net pressure load must be resisted by the vertical rebars liners and concrete. The net tensile force per circumferential inch at the head-to-wall junction is:

$$F_{L-L} = \frac{\pi\,(186)^2\,(\text{Net pressure in psi})}{2\pi\,(186)\,(1000)} \quad \text{k/in of liner.}$$

$\llcorner$ core cavity radius

See Table B-1.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 89 OF

PREPARED BY T. T. Lee

DATE 11/19/86

REF. DOCUMENTS:

CHECKED BY

DATE

B.1.5 Boundary Moment

Boundary moment at the head-to-wall junction is determined by establishing a strain diagram which is consistent with the plastic hinge condition and which will result in a net cross-sectio resistance force equals to F_{L-L}

A plastic hinge is considered formed when,

Max. concrete strain = 0.003

or

Max steel strain (rebar) = 0.07 = ϵ

Liner contribution is neglected in this analysis

Fig B-2 shows the location of rebars strain diagram, etc for a case in which the two limits given above occur simultaneously

T. T Lee 11/19/86

907738 N/C

310

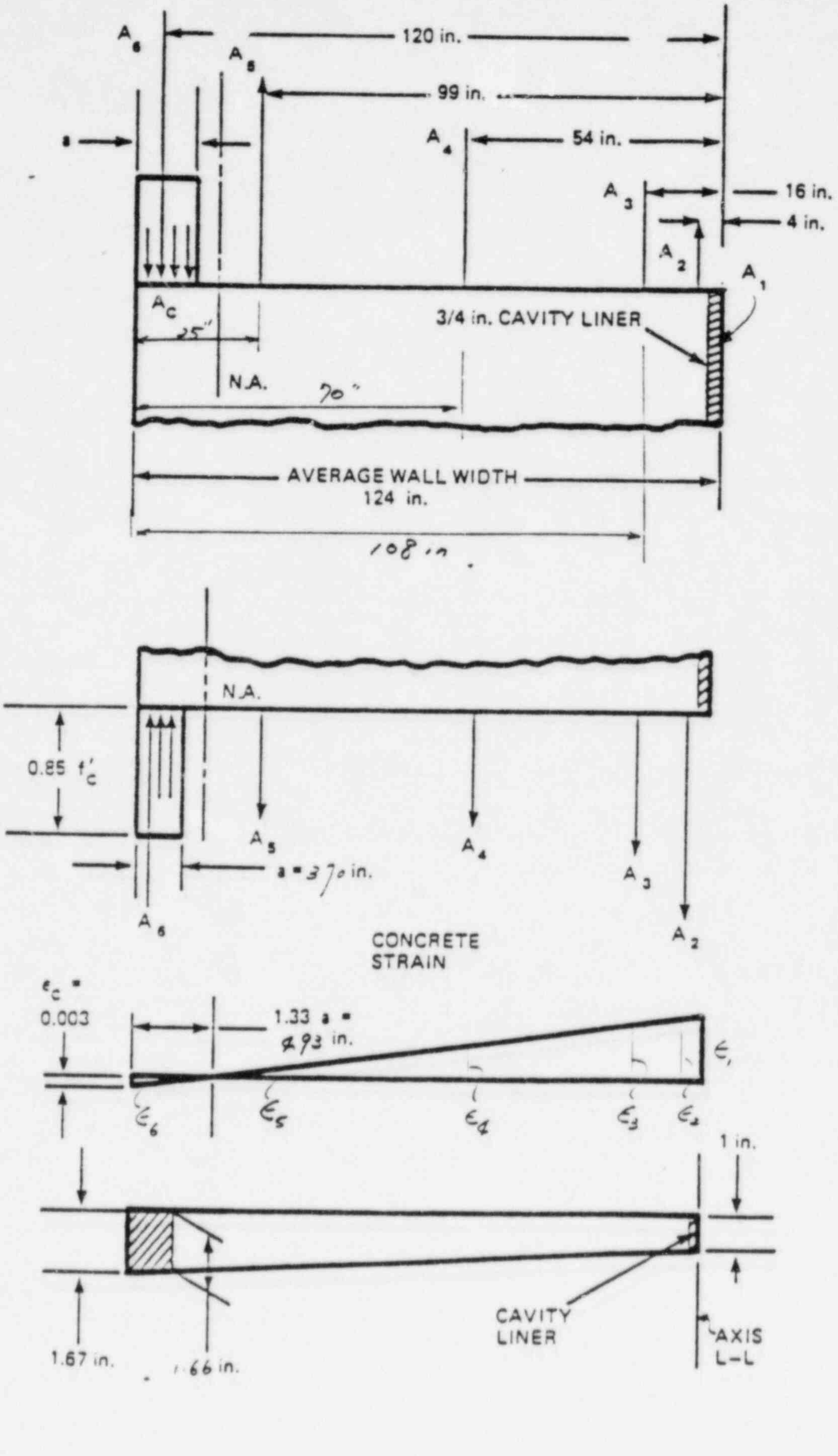


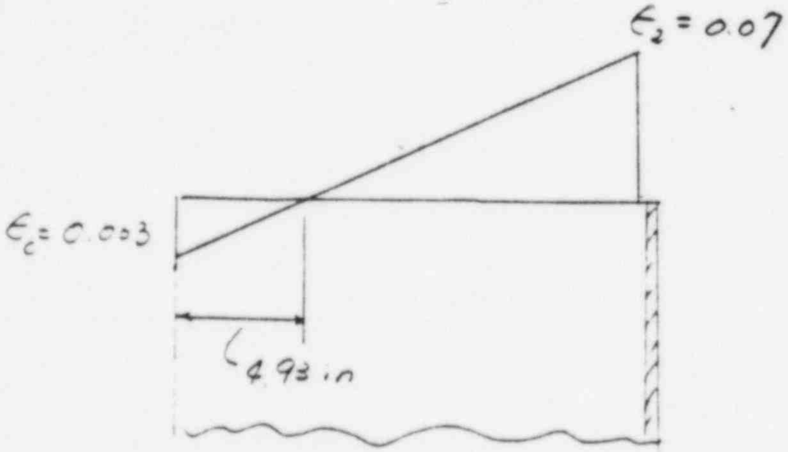
Figure B-2

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B 11 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

A balanced case:

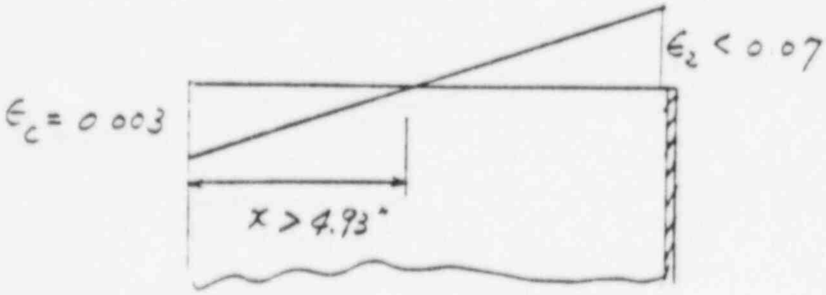


Referring to Fig B-2 and Table B-2:

$F_{L-L} = 76.6$ k/in of line

$M_{L-L} = 1616.06$ k-in./in line.

For $F_{L-L} < 76.6$ k/in:



Case 1

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B12 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Table B-2

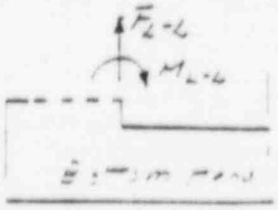
Wall Moment about Liner Axis L-L

Element	Area[(a)] (in²/in)	Strain[(b)] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist. from L-L[(a)] (in.)	Moment ab L-L (k-in)
A_1	0.75		~	~	0	~
A_2	0.27	0.07	90.	24.30	4.0	97.20
A_3	0.29	0.063	86.640	25.126	16.0	402.02
A_4	0.21	0.040	75.969	15.953	54.0	861.46
A_5	0.77	0.012	63.331	48.765	99.0	4827.74
A_6	0.38	-0.001	-16.412	-6.236	120.0	-748.32
A_c		0.003		-31.306	122.15	-3824.03

(a) Those for A_2 through A_6 are from Ref. 1, Table E.1-1

(b) Based on $x = 4.93$ in
$\epsilon_c = 0.003$

$F_{L-L} = 76.602$ (ks), $M_{L-L} = +1616.06$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 813 OF

PREPARED BY T. T. Lee

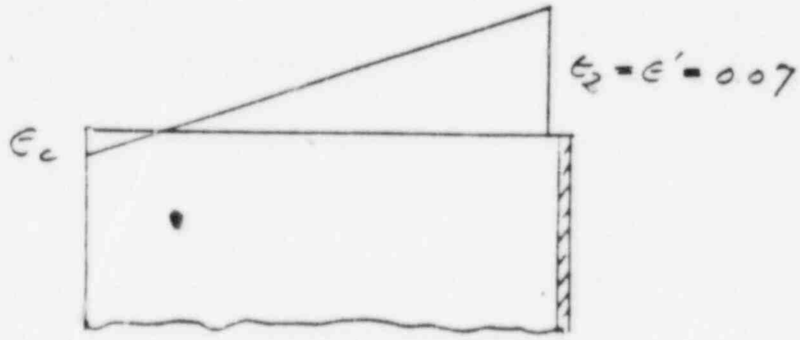
DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

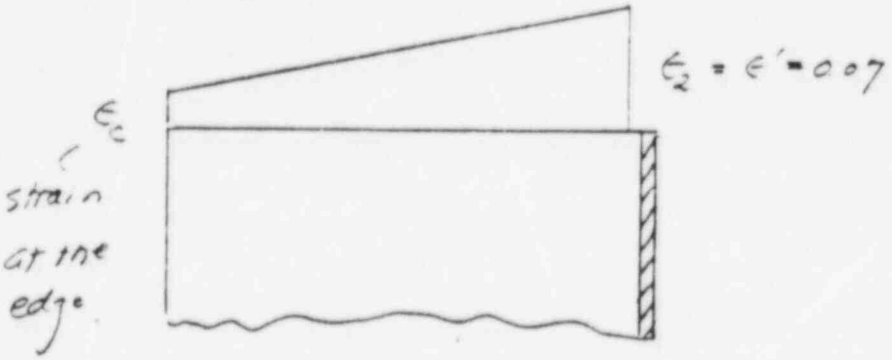
DATE

For $F_{L-L} > 76.6$ k/in

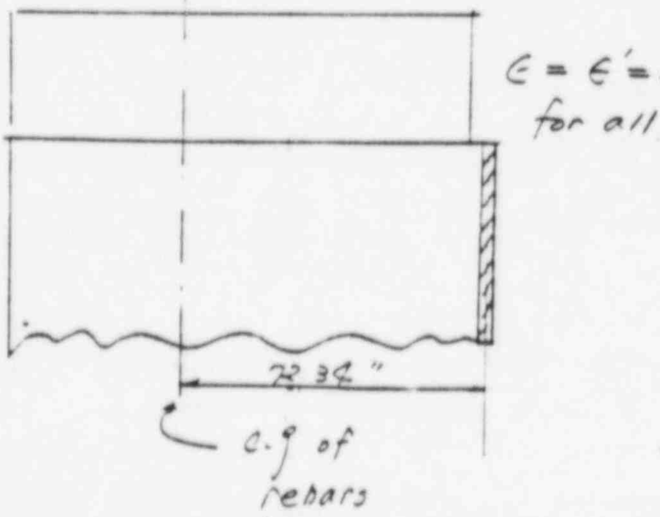


Case 2

Larger F_{L-L} ↓



Larger F_{L-L} ↓



$F_{cg} = f_s' \Sigma A_s$

$= 90 \times 1.92$

$= 172.80$ k/i

$M_{c.g} = 0$

$F_{L-L} = 172.80$

$M_{L-L} = +12500$ k-in/in.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO. | PROJ. | CALC. NO. 907738 N/C | PAGE 8 14 OF

PREPARED BY T. T. Lee | DATE 11/19/84 | REF. DOCUMENTS:

CHECKED BY | DATE

For Case I, $F_{L-L} < 766$ k/in:

From the force equilibrium:

$$\sum_{i=2}^{5} F_i - F_6 - F_c = F_{L-L} = \text{Boundary Force}$$

Note. Liner force not included

Strains:

$$\epsilon_1 = \frac{0.003(124 - x)}{x} = \frac{0.372}{x} - 0.003$$

$$\epsilon_2 = \frac{0.003(120 - x)}{x} = \frac{0.36}{x} - 0.003$$

$$\epsilon_3 = \frac{0.003(124 - 16 - x)}{x} = \frac{0.003(108 - x)}{x} = \frac{0.324}{x} - 0.$$

$$\epsilon_4 = \frac{0.003(124 - 54 - x)}{x} = \frac{0.003(70 - x)}{x} = \frac{0.21}{x} - 0.0$$

$$\epsilon_5 = \frac{0.003(124 - 99 - x)}{x} = \frac{0.003(25 - x)}{x} = \frac{0.075}{x} - 0$$

$$\epsilon_6 = \frac{0.003(x - 4)}{x} = 0.003 - \frac{0.012}{x} \quad \text{(Comp)}$$

Stress:

Let f_i be the stress in element i.

$f_i = 90 - (0.007 - \epsilon_i) \times 4615$ if $\epsilon_i \geq 0.00202$

$i = 2 \sim 6$ (Fig A-2)

$f_6 = 29000\, \epsilon_6$ if $\epsilon_6 \leq 0.00202$ (Fig. A-3)

$f_c = 0.85 f_c' = 5.1$ ksi

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B15 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Forces:

$$F_i = f_i \times A_i \qquad i = 2, \cdots, 6$$

$$F_c = f_c \times A_c$$

where $A_c = (0.75\,x)$(Ave width of conc compression zone)

$$= (0.75\,x)(\bar{w}_c)$$

$$\bar{w}_c = \frac{1}{2}\left(1.67 + 1.67 - 0.67\,\frac{0.75\,x}{124}\right)$$

$$= 1.67 - 0.00203\,x$$

use $\bar{w}_c = 1.66 \qquad x \le 7.39"$

$\bar{w}_c = 1.65 \qquad x \le 12.31"$

$\bar{w}_c = 1.64 \qquad x \le 17.24"$

$F_c = 6.35\,x$ if $x \le 7.39"$

$= 6.31\,x$ if $x \le 12.31"$

$= 6.27\,x$ if $x \le 17.24"$

Distance from i.i. for A_c

$$124 - \frac{0.75\,x}{2} = 124 - 0.375\,x$$

Calculation of $M_{i.i}$ using the above formulas and other needed relations are done in tabular form.

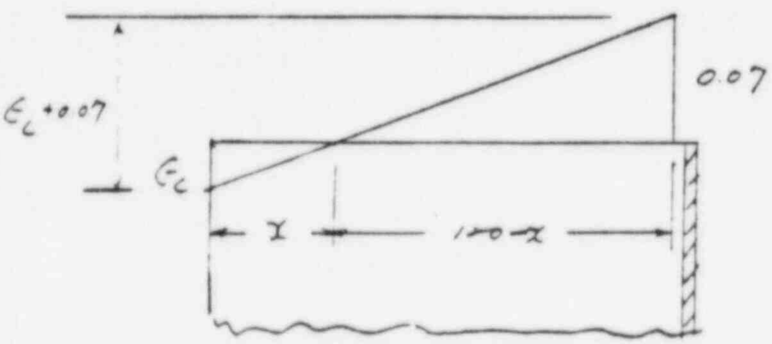
GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B16 OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Case 2: For $F_{L.L} > 76.6$ k/in



$$\epsilon_3 = 0.07 - (\epsilon_c + 0.07)\frac{12}{120} = 0.0630 - 0.1\,\epsilon_c$$

$$\epsilon_4 = 0.07 - (\epsilon_c + 0.07)\frac{50}{120} = 0.0408 - 0.4167\,\epsilon_c$$

$$\epsilon_5 = 0.07 - (\epsilon_c + 0.07)\frac{95}{120} = 0.0146 - 0.7917\,\epsilon_c$$

$$\epsilon_6 = 0.07 - (\epsilon_c + 0.07)\frac{116}{120} = 0.0023 - 0.9667\,\epsilon_c$$

$$x = \frac{120\,\epsilon_c}{0.07 + \epsilon_c}$$

Use $F_c = 6.35x$

& arm = $124 - 0.375x$ } For $\epsilon_c \geq 0.001$

(i.e, assume $0.85 f_c'$ rect. block)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B17 OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

To avoid a tedious iteration process, calculatio of M_{L-L} for various F_{L-L} given in Table B-1 is done as follows:

1) Compute a series of F_{L-L}, M_{L-L} pairs for selected values of z or ϵ.
Use formulas for Case 1 or Case 2, as need
(Tables B-2 through B-13)

2) Interpolate to obtain M_{L-L} for various F_{L-L} of interest
(Table B-14)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 818 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-3 Boundary Force and Moment about Liner Axis L-L

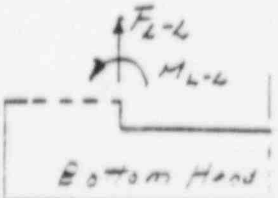
Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment ab L-L (k-in)
A_1	0.75	0.051	—	—	0	—
A_2	0.27	0.049	80.389	21.705	4.0	86.820
A_3	0.29	0.044	77.981	22.614	16.0	361.832
A_4	0.21	0.027	70.356	14.775	54.0	797.839
A_5	0.77	0.008	61.327	47.222	99.0	4674.972
A_6	0.38	0.001	-36.565	-13.895	120.0	-1667.374
A_c		0.003		-43.815	121.413	-5319.687

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 48.61$ $M_{L-L} = -1065.63$

(b) Based on $x = 6.9$ in

$\epsilon_c =$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B19 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-4 Boundary Force and Moment about Liner Axis L-L

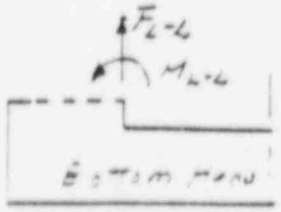
Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment abt L-L (k-in/in)
A_1	0.75	0.055	—	—	0	—
A_2	0.27	0.053	82.270	22.213	4.0	88.851
A_3	0.29	0.048	79.674	23.105	16.0	369.680
A_4	0.21	0.030	71.453	15.005	54.0	810.282
A_5	0.77	0.009	61.719	47.523	99.0	4704.817
A_6	0.38	0.001	-32.625	-12.398	120.0	-1487.700
A_c		0.003		-40.640	121.6	-4981.824

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 54.85$ $M_{L-L} = -455.894$

(b) Based on $x = 6.4$ in

$\varepsilon_c =$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B20OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

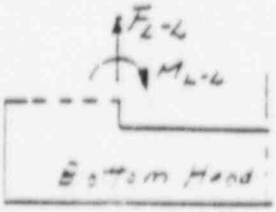
Table B-5 Boundary Force and
Moment about Liner Axis L-L

Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist. from L-L[a] (in.)	Moment ab L-L (k-in/
A_1	0.75	0.060	—	—	0	—
A_2	0.27	0.058	84.375	22.781	4.0	91.125
A_3	0.29	0.052	81.568	23.655	16.0	378.477
A_4	0.21	0.032	72.681	15.263	54.0	824.206
A_5	0.77	0.010	62.157	47.861	99.0	4738.244
A_6	0.38	0.001	-28.216	-10.722	120.0	-1286.659
A_c		0.003		-37.592	121.78	-4577.954

$F_{L-L} = 61.25$ $M_{L-L} = 167.439$

(a) Those for A_2 through A_6
are from Ref. 1, Table E.11-1

(b) Based on $x = 5.92$ in
$\varepsilon_c =$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR		
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C — PAGE B-21 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:
CHECKED BY	DATE	

Table B-6 Boundary Force and Moment about Liner Axis L-L

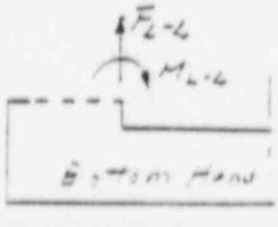
Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist. from L-L[a] (in.)	Moment ab L-L (k-in/in)
A_1	0.75	0.065	—	—	0	—
A_2	0.27	0.062	86.52	23.36	4.0	93.4
A_3	0.29	0.056	83.50	24.21	16.0	387.4
A_4	0.21	0.035	73.93	15.53	54.0	838.4
A_5	0.77	0.011	62.60	48.20	99.0	4772.3
A_6	0.38	-0.001	-23.73	-9.02	120.0	-1082.0
A_c		0.003		-34.92	121.94	-4258.7

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 67.36$ $M_{L-L} = +750.8$

(b) Based on $x = 5.5$ in

$\epsilon_c = 0.003$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B.22 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-7 Boundary Force and Moment about Liner Axis L-L

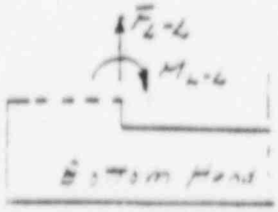
Element	Area[a] (in²/in)	Strain[b] (in./in)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment ab L-L (k-in/in)
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	4.0	97.2
A_3	0.29	0.0627	86.64	25.12	16.0	402.0
A_4	0.21	0.0296	75.97	15.95	54.0	861.5
A_5	0.77	0.0123	63.37	48.80	99.0	4830.8
A_6	0.38	-0.0005	-14.60	-5.55	120.0	-665.7
A_c		0.0029		-30.29	122.21	-3701.7

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 78.3$ $M_{L-L} = 1824.1$

(b) Based on $I = 477$ in

$\varepsilon_c = 0.0029$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B23 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-8 Boundary Force and Moment about Liner Axis L-L

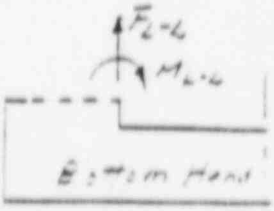
Element	Area[a] (in²/in)	Strain[b] (in/in)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment ab L-L (k-in/
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	4.0	97.2
A_3	0.29	0.0628	86.66	25.13	16.0	402.1
A_4	0.21	0.0398	76.08	15.98	54.0	862.8
A_5	0.77	0.0128	63.59	48.97	99.0	4847.7
A_6	0.38	0.0001	2.22	0.84	120.0	101.3
A_c		0.0023		-24.24	122.57	-29710

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 90.98$ $M_{L-L} = 33400$

(b) Based on $x = 2.82$ in

$\epsilon_c = 0.0023$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR		
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C — PAGE B-24 OF
PREPARED BY T. T. Lee	DATE 1/19/84	REF. DOCUMENTS.
CHECKED BY	DATE	

Table B-9 Boundary Force and Moment about Liner Axis L-L

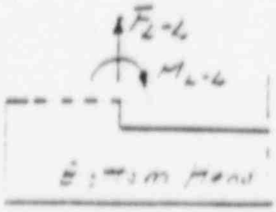
Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment a. L-L (k-in)
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	4.0	97.2
A_3	0.29	0.0628	86.68	25.14	16.0	402.2
A_4	0.21	0.0400	76.14	15.99	54.0	863.4
A_5	0.77	0.0130	63.70	49.05	99.0	4856.0
A_6	0.38	0.0004	11.60	4.41	120.0	529.0
A_c		0.002		-21.17	122.75	-2598.6

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

(b) Based on $x = 3.33$ in

$\epsilon_c = 0.002$

$F_{L-L} = 97.72$ $M_{L-L} = 4149.2$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 v/c

PAGE B25 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS.

CHECKED BY

DATE

Table B-10 Boundary Force and
Moment about Liner Axis L-L

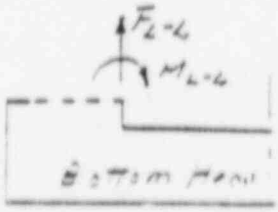
Element	Area[(a)] (in²/in)	Strain[(b)] (in/in)	Stress (ksi)	Force (k/in liner)	Dist from L-L[(a)] (in.)	Moment a L-L (k-in/
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	4.0	97.2
A_3	0.29	0.0628	86.69	25.14	16.0	402.2
A_4	0.21	0.0401	76.20	16.00	54.0	864.1
A_5	0.77	0.0133	63.81	49.14	99.0	4864.9
A_6	0.38	0.0007	19.04	7.24	120.0	1047.6
A_c		0.0017		-18.07	122.9	-2221.4

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

(b) Based on $x = 2.84$ in

$\varepsilon_c = 0.0017$

$F_{L-L} = 103.75$ $M_{L-L} = 5058.1$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B26 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-11 Boundary Force and Moment about Liner Axis L-L

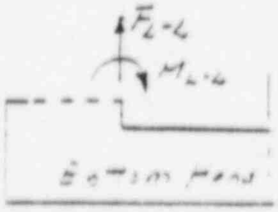
Element	Area[(a)] (in²/in)	Strain[(b)] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist from L-L[(a)] (in.)	Moment ab L-L (k-in/
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	40	972
A_3	0.29	0.0629	86.71	25.14	16.0	402.3
A_4	0.21	0.0403	76.27	16.02	54.3	869.9
A_5	0.77	0.0136	63.96	49.25	99.0	4875.5
A_6	0.38	0.0010	30.26	11.50	120.0	1379.6
A_c		0.0013		-13.89	123.18	-1710.9

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 112.32$ $M_{L-L} = -5908.6$

(b) Based on $x = 2.19$ in

$\epsilon_c = .0013$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B27 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

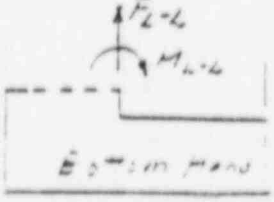
Table B-12 Boundary Force and Moment about Liner Axis L-L

Element	Area[a] (in²/in)	Strain[b] (in./in)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment ab L-L (k-in/in)
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90.0	24.3	4.0	97.2
A_3	0.29	0.0629	86.723	25.15	16.0	402.4
A_4	0.21	0.0404	76.34	16.03	54.0	865.7
A_5	0.77	0.0138	64.07	49.33	99.0	4883.9
A_6	0.38	0.0013	37.7	14.33	120.0	1719.1
A_c		0.001		−10.73	123.37	−1323.7

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 117.65$ $M_{L-L} = 6644.6$

(b) Based on $x = 169$ in, $\varepsilon_c = 0.001$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B28 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Table B-13 Boundary Force and Moment about Liner Axis L-L

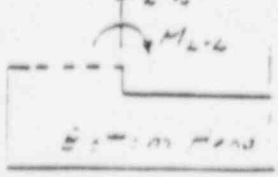
Element	Area[a] (in²/in)	Strain[b] (in./in.)	Stress (ksi)	Force (k/in liner)	Dist from L-L[a] (in.)	Moment a. L-L (k-in/
A_1	0.75		—	—	0	—
A_2	0.27	0.07	90	24.3	4.0	97.2
A_3	0.29	0.0630	86.77	25.16	16.0	402.6
A_4	0.21	0.0408	76.52	16.07	54.0	867.8
A_5	0.77	0.0146	64.43	49.61	99.0	4911.7
A_6	0.38	0.0023	58.76	22.33	120.0	2679.3
A_c						

(a) Those for A_2 through A_6 are from Ref. 1, Table E.11-1

$F_{L-L} = 137.47$ $M_{L-L} = 8950.6$

(b) Based on $x =$ in

$\epsilon_c = 0$



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B29 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS.

CHECKED BY

DATE

Table B-14 M_{L-L} Values by Interpolation

Calculated (See Tables) F_{L-L} vs M_{L-L}		Interpolated F_{L-L} vs M_{L-L}	
F_{L-L}	M_{L-L}	F_{L-L}	M_{L-L}
48.61	-1065.6		
		51.3	-802.8
54.85	-455.9		
		58.1	-139.4
61.25	167.4		
		64.9	515.9
67.36	750.8		
		71.8	1166.6
76.60	1616.1		
78.30	1824.1	78.6	1860.0
90.98	3340.0	90.4	3270.7
97.72	4149.2	97.3	4098.8
103.75	5054.1	104.2	5099.0
112.32	5908.6	111.1	5787.0
117.65	6644.6		
		117.9	6573.8
137.47	8958.6		

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B30 OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

B.1.6 Unit Yield Line Moment

Consider two failure modes as shown in Fig. B-3. For each mode, calculate the unit yield line moment required to maintain equilibrium.

Forces acting on each segment of slab bounded by the yield lines and the boundaries are

1) Net cavity pressure
2) Boundary forces and moments
3) Yield line moment

Equilibrium of these forces are established by computing their moments about Line C-C' (or E-E') shown in Fig. B-4.

The following calculation is performed for the case of 1.0 RP with $N_x = 0$. Unit yield moments for other cases are done by proportion from this basic case (Tables B-15 ~ B-18.

T. T. Lee 11/19/84

907738 N/C

B 31

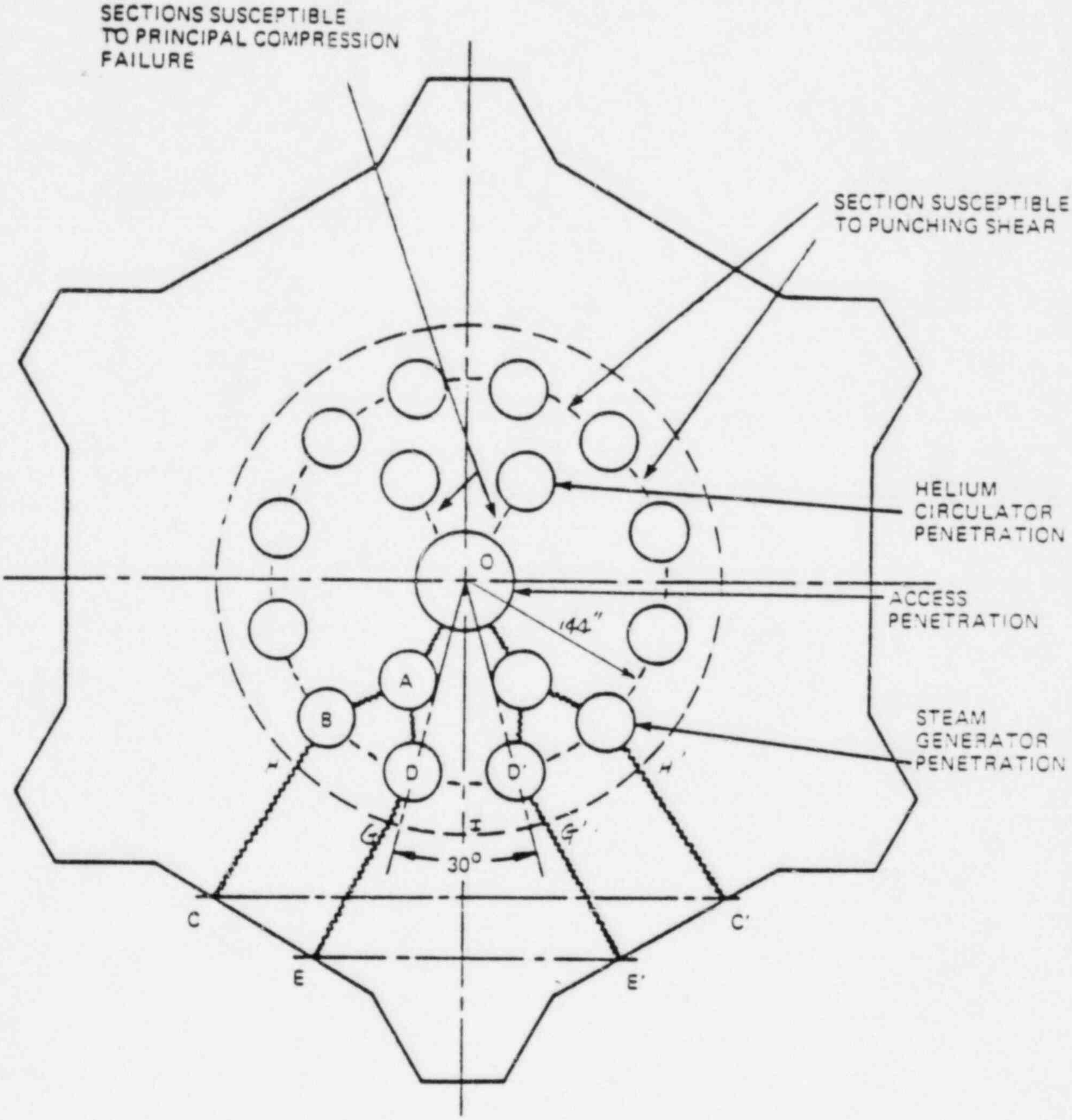


Figure B-3 Arrangement of Lower Head Penetrations and Potential Failure Modes

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B32 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

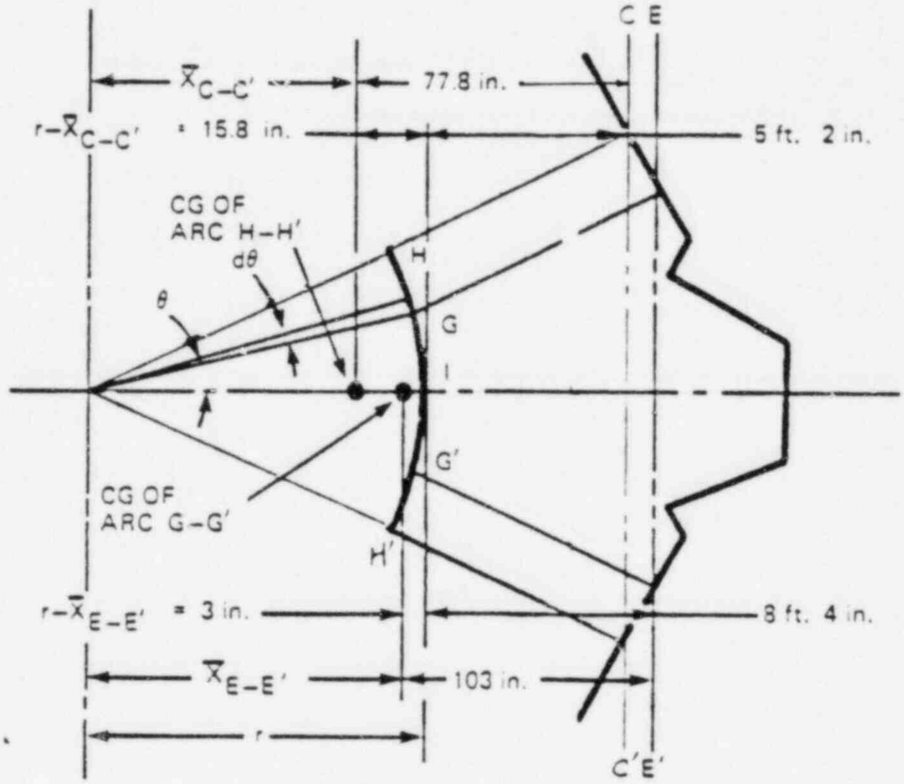


Fig. B-4

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B33 OF
PREPARED BY T. T. Lee	DATE 11/19/86	REF. DOCUMENTS:	
CHECKED BY	DATE		

Yield pattern O-A-B-C (See Fig. B-3):

Referring to Fig. B-5, the moment about Line A-A' due to the uniform distributed moment m is:

$$M_{A-A'} = 2\int_0^{\theta_1} mr\cos\theta \, d\theta = 2mr\left[\sin\theta\right]_0^{\theta_1}$$

$$= 2mr\sin\theta_1$$

For this case, $\theta_1 = 41°30'$ (Fig. B-6)

Hence, due to M_{L-L} (See Table B-14):

$$M_{C-C'} = M_{H-H'} = 2(1860\times1000)(185)\sin 41°30'$$

$$= 0.458\times10^9 \text{ lbs-in}$$

Due to F_{L-L} over H-H':

$$M_{C-C'} = 78.6\times10^3 \times \frac{2\times41.5\times\pi}{180}\times185\times77.8$$

$$= 1.648\times10^9 \text{ lbs-in}$$

where 77.8 in. is the distance between the c.g. of F_{L-L} over H-H' and Line C-C' (See Fig. B-4).

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 83 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

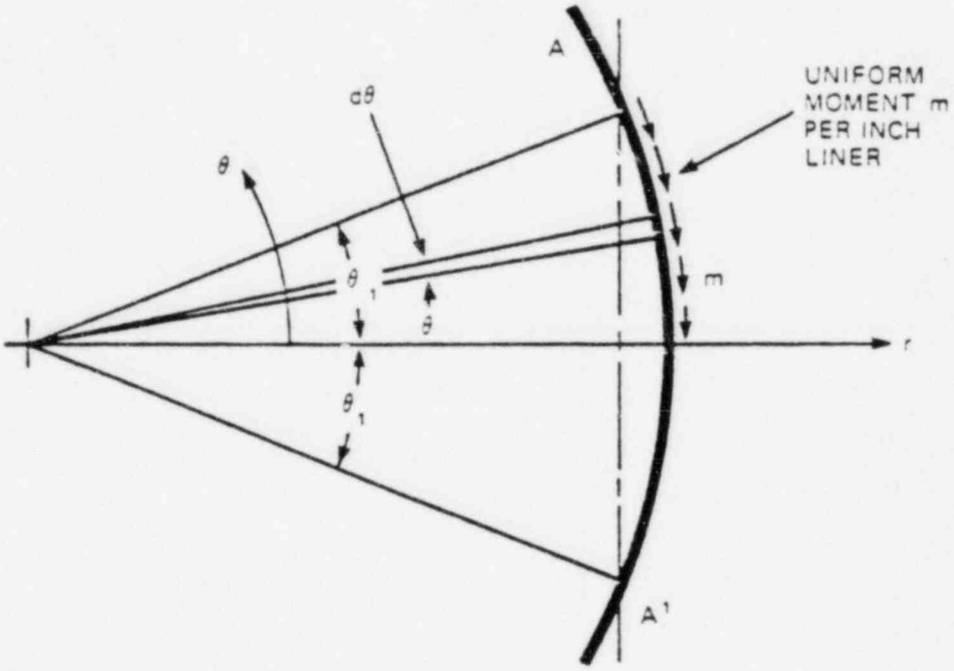
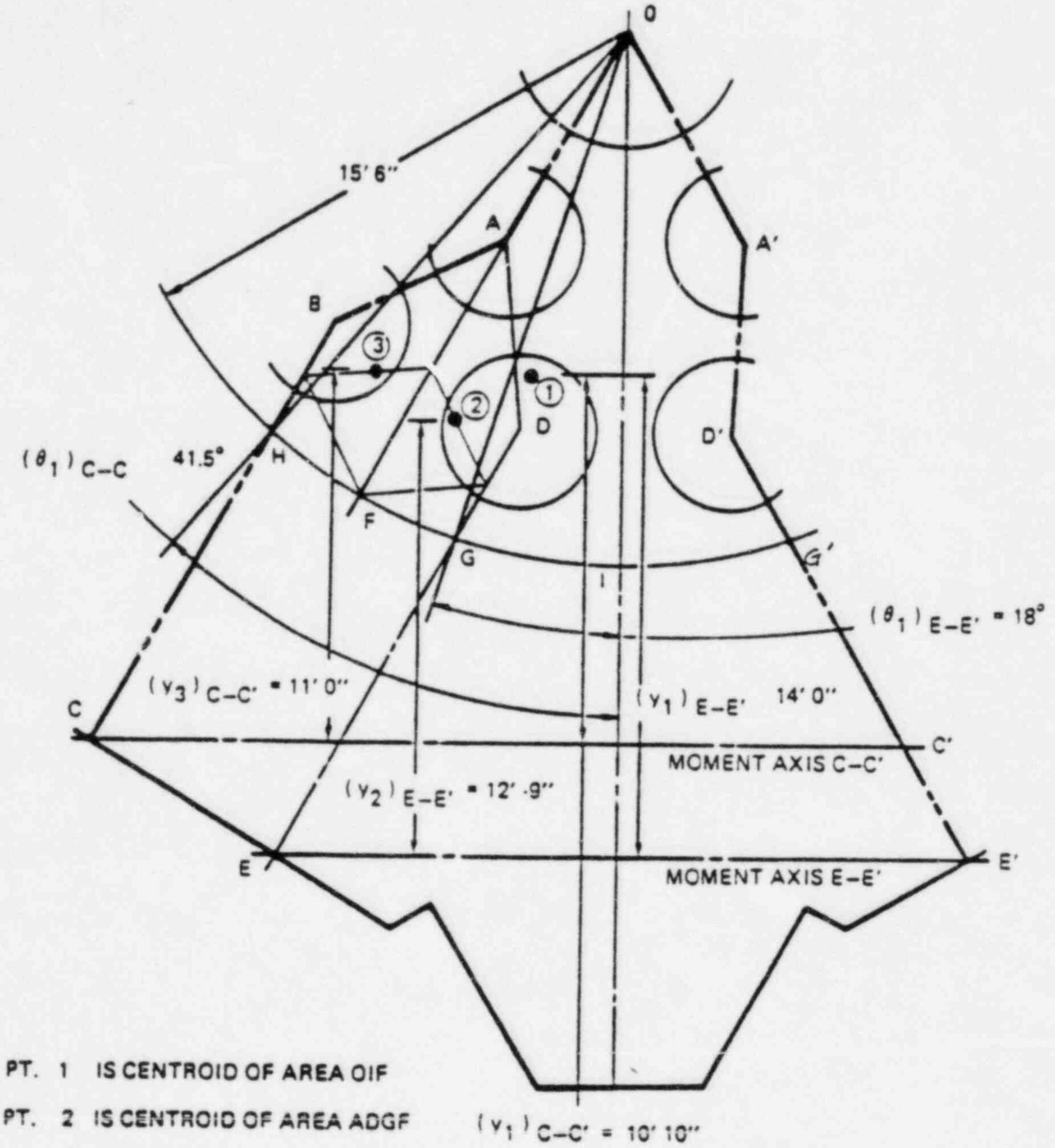


Fig. B-5

T. T. Lee 11/19/84 907738 N/C



NOTE: PT. 1 IS CENTROID OF AREA OIF

PT. 2 IS CENTROID OF AREA ADGF

PT. 3 IS CENTROID OF AREA ABHF

Fig. B-6

Potential Failure Mode

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B36 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Referring to Fig. 10, and Ref. 4 p. E.11-7.

Area OAFI $= \frac{1}{12}\pi(186)^2 = 9050 \text{ in}^2$

Centroidal dist. from C-C' = 10'10" = 130

Area ABHI $= \frac{1}{2}(102 + 42) \times 38 = 2736 \text{ in}^2$

Centroidal dist from C-C' = 11' = 132 in

Hence moment about C-C', due to the cavity pressure on (OABHI) × 2 is:

$$M_{c-c'} = 2p[(9050 \times 130) + (2736 \times 132)]$$

$$= 3.076\, p \times 10^6 \text{ lbs-in}$$

$$= 3.076 \times 845 \times 10^6 = 2.599 \times 10^9 \text{ in}$$

Total moment about C-C' to be resisted by the yield lines O-A-B-C is:

$$M_{c-c'} = (2.599 - 1.648 + 0.458) \times 10^9$$

$$= 1.410 \times 10^9 \text{ lbs-in}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B37 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Let m_{B-C} be the unit yield line moment for all segments along O-A-B-C

The components of total yield line moments for individual segments in the C-C' direction is (See Fig B-7):

$$2\left(17\, m_{B-C} \cdot \frac{9}{17} + 14\, m_{B-C} \cdot \frac{13}{14} + 142\, m_{B-C} \cdot \frac{72}{142}\right)$$

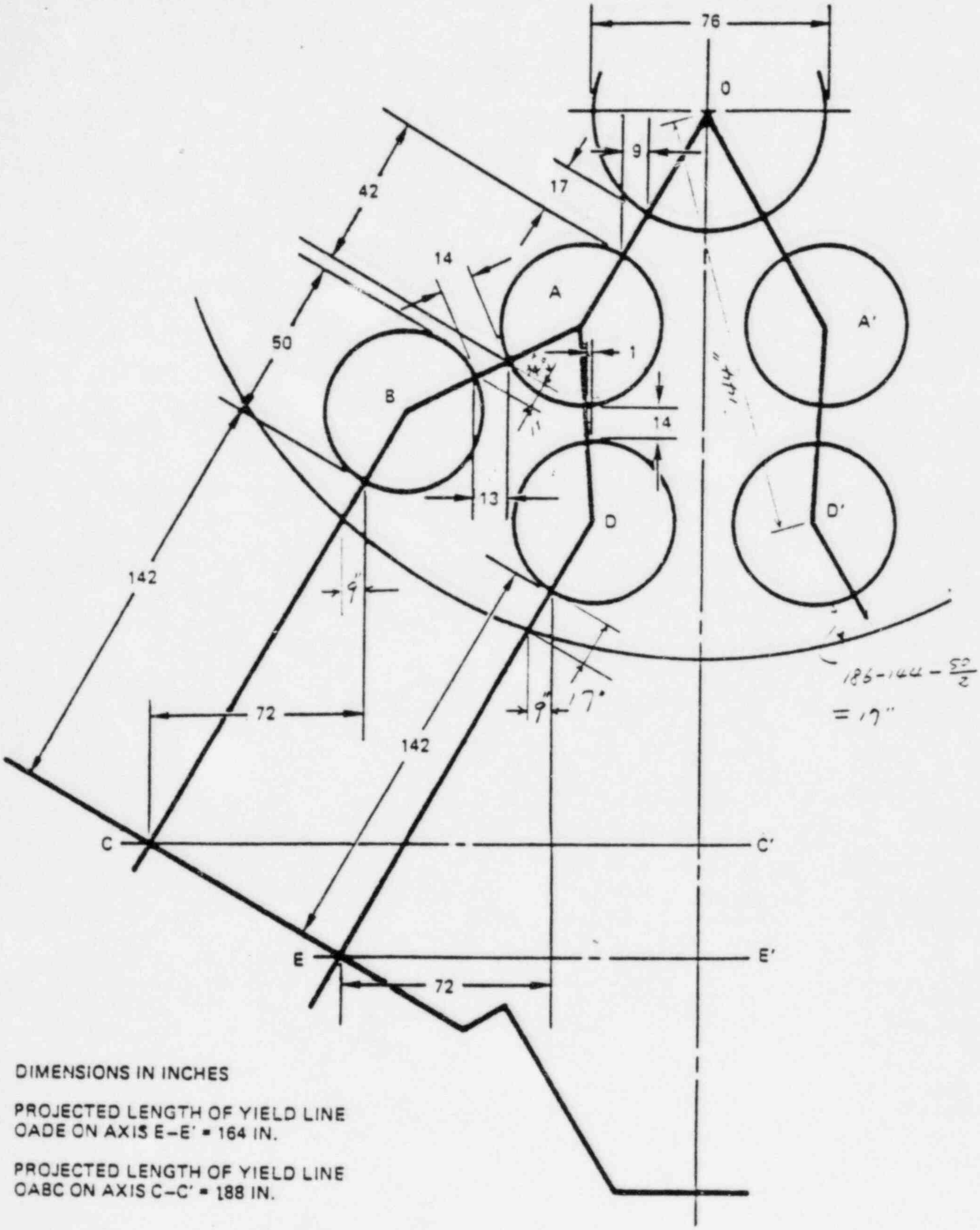
$$= 188\, m_{B-C}$$

This balances the $M_{C-C'}$ total, hence

$$m_{B-C} = \frac{M_{C-C'}\ \text{total}}{188} = \frac{1.410 \times 10^{9}}{188} = 7.50 \times 10^{6}\ \text{lb-}$$

T. T. 'ee 11/19/84

907738 N/C B38



$186 - 144 - \frac{50}{2}$

= 17"

DIMENSIONS IN INCHES

PROJECTED LENGTH OF YIELD LINE
OADE ON AXIS E–E' = 164 IN.

PROJECTED LENGTH OF YIELD LINE
OABC ON AXIS C–C' = 188 IN.

Figure B-7 Projected Length of Yield Line

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 839 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Yield pattern O-A-D-E:

Repeating the similar calculation done for yield pattern O-A-B-C.

Due to M_{L-L} over G-G'.

$$M_{E-E'} = 2(1860 \times 1000)(186) \sin 18^\circ = 0.214 \times 10$$

lbs-in

Due to F_{L-L} over G-G'.

$$M_{E-E'} = (78.6 \times 1000) \times \frac{2 \times 18 \times \pi}{180} \times 186 \times 103$$

$$= 0.946 \times 10^9 \text{ lbs-in}$$

Due to cavity pressure over (OADGI)×2:

$$M_{E-E'} = 2p[(9050 \times 168) - (2736 \times 153)]$$

$$= 2.204\, p \times 10^6 \text{ lbs-in}$$

$$= 2.204 \times 845 \times 10^6 = 1.862 \times 10^9 \text{ lbs-in}$$

Total to be resisted by the yield lines O-A-D-E is:

$$M_{E-E'} = (1862 - 0946 + 0.214) \times 10^9$$

$$= 1.130 \times 10^9 \text{ lbs-in.}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B40 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Let m_{D-E} be the unit yield line moment for all segments along O-A-D-E

The components of total yield line moments for individual segments along the E-E' axis is (Fig. B-7):

$$2(9\, m_{D-E} + m_{D-E} + 72\, m_{D-E})$$

$$= 164\, m_{D-E}$$

This balances the $M_{E-E'}$ total, hence

$$m_{D-E} = \frac{M_{E-E', total}}{164} = \frac{1.130 \times 10^9}{164} = 6.89 \times 10^6$$

lbs-in/in

The m_{B-C} of 7.50×10^6 lbs-in/in and the m_{D-E} of 6.89×10^6 " computed for the case of 1 RP and $N_x = 0$ are used as the basis for proportioning in the following tables.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 84 OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Table B-15

Unit Yield Line Moments

for Yield Pattern 0-A-B-C, 1 RP

N_x		0	6	12	18	24
M_{L-L}		18600	11666	5159	-1394	-8028
F_{L-L}		78.6	71.8	64.9	58.1	51.3
Resul. Cavity Pressure		845	772	698	625	551
$M_{c-c'}$ Due to (10^9 lb-in)	M_{L-L} *	0.458	0.287	0.127	-0.034	-0.198
	F_{L-L} *	-1.648	-1.505	-1.361	-1.218	-1.076
	Press. *	2.599	2.374	2.147	1.922	1.695
Total $M_{c-c'}$		1.410	1.156	0.913	0.670	0.421
m_{B-C} * (10^5 lb-in/in)		7.50	6.15	4.86	3.56	2.24

Note: For Tables B-15 and B-17

↑ Base case

* Numbers in these rows are computed by proportion from the base case in Table

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B42 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Table B-16

Unit Yield Line Moments for Yield Pattern O-A-D-E, 1 RP

N_x		0	6	12	18	24
M_{L-L}		1860.0	1166.6	515.9	-139.4	-802.8
F_{L-L}		786	718	649	581	513
Resul. Cavity Pressure		845	772	698	625	551
$M_{E-E'}$ Due To (10^9 lb-in)	M_{L-L} **	0.214	0.134	0.059	-0.016	-0.092
	F_{L-L} **	-0.946	-0.864	-0.781	-0.699	-0.617
	Press. **	1.862	1.701	1.538	1.377	1.214
Total $M_{E-E'}$		1.130	0.971	0.816	0.662	0.505
m_{D-E} ** (10^6 lb-in/in)		6.89	5.92	4.98	4.04	3.08

Note: (For Tables B-16 B-18)

Base Case

** Numbers in these rows are computed by proportion from the base case in Table B-16.

GA 258 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B43 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Table B-17

Unit Yield Line Moments

for Yield Pattern 0-A-B-C, 1.5 RP

N_x		0	6	12	18	24
M_{L-L}		6673.8	5787.0	5099.0	4098.8	3270.7
F_{L-L}		117.9	111.1	104.2	97.3	90.4
Resul. Cavity Pressure		1268	1194	1120	1046	972
$M_{C-C'}$ Due to (10^9 lb-in)	M^*_{L-L}	1.643	1.425	1.256	1.009	0.805
	F^*_{L-L}	-2.472	-2.329	-2.185	-2.040	-1.895
	Press.*	3.900	3.672	3.445	3.217	2.990
Total $M_{C-C'}$		3.071	2.768	2.516	2.186	1.900
m^*_{B-C} (10^6 lb-in/in)		16.34	14.72	13.38	11.63	10.11

m_{B-C} = 11.27

if N_x = 19.42 by interpo- [illegible]

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B44 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Table B-18

Unit Yield Line Moments for Yield Pattern O-A-D-E, 1.5 RP

	N_x	0	6	12	18	24
	M_{L-L}	6673.8	5787.0	5099.0	4098.8	3270.7
	F_{L-L}	117.9	111.1	104.2	97.3	90.4
	Resul. Cavity Pressure	1268	1194	1120	1046	972
M_{E-E} Due to (10^9 lb-in)	M_{L-L}^{**}	0.768	0.666	0.587	0.472	0.376
	F_{L-L}^{**}	-1.419	-1.337	-1.254	-1.171	-1.088
	Press.**	2.794	2.631	2.468	2.305	2.142
	Total M_{E-E}	2.143	1.960	1.801	1.606	1.430
	m_{D-E}^{**} (10^6 lb-in/in)	13.07	11.95	10.98	9.79	8.72

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B45 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

B.1.7 Moment Capacity Along Yield Lines

Moment capacity in the hoop direction provided by the circumferential tendons, circumferential rebars and concrete is established for a cross section with unit width along a radial yield line.

Criteria:

1) Maximum tendon stress = 0.9 f_{sy} (Ref 1)

2) Maximum concrete strain ≤ 0.003

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.
PROJ.
CALC. NO. 907738 N/C
PAGE 8 46 OF
PREPARED BY T T Lee
DATE 11/19/84
REF. DOCUMENTS:
CHECKED BY
DATE

Circumferential Rebars:

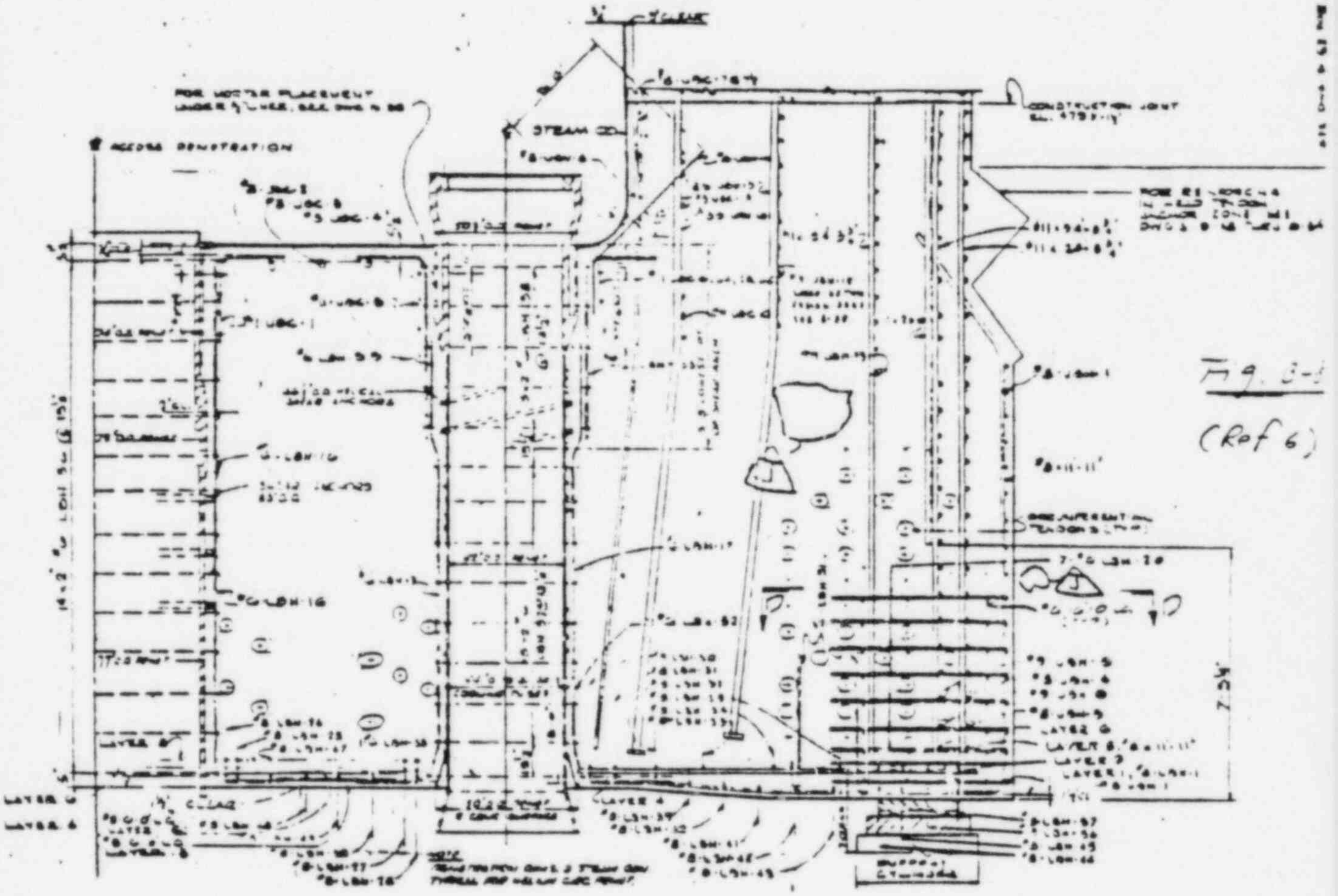


Fig. 8-8
(Ref 6)

For 17" long concrete ligament between O. and A (Fig. 8-7):

$$6 - \#8 \text{ bars} \rightarrow \frac{6 \times 0.79}{17} = 0.28 \text{ in}^2/\text{in}$$

For 14" long concrete ligament between A and D:

$$6 - \#8 \text{ bars} \longrightarrow 0.28 \text{ in}^2/\text{in}$$

For 142" length between D + E:

$$22 - \#8 \text{ bars} \rightarrow \frac{22 \times 0.79}{142} = 0.12 \text{ in}^2/\text{in}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B47 OF

PREPARED BY T T Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Rebars: LBH - 30 (2) , -31(2) , -32(2)

(Fig. B-8) LBH - 33 (1) , -34(1), -35(1)

LBH - 40 (1) , -41(1), -42(1)

LBH - 43 (1). -44(2). -45(2)

LBH - 56 (2). -57(2)

Each contains three sections, forming a complete circle

Use A_r = 0.12 in²/in in the following calculatio

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.
PROJ.
CALC. NO. 907738 N/C
PAGE 848 OF
PREPARED BY T. T. Lee
DATE 11/19/84
REF. DOCUMENTS:
CHECKED BY
DATE

Effect of Internal Pressure within Penetration:

For concrete compression zone

$$p_c \times X \times \frac{\text{Sum of pen. I.D over on yield line}}{\text{Total yield line length}}$$

$$= 0.722\, p_c\, x = 0.722 \times 845\, x = 610\, x$$

where p_c = cavity pressure.

x = height of compression zone

0.722 is from Ref. 1 p E11-10

For tension zone:

Stress in penetration is

$$\frac{p_c \cdot r}{h} = \frac{845 \times 21}{1} = 17.700 \text{ psi.} < f_{sy}.$$

r = radius of penetration = 21 in
h = thickness of penetration = 1 in } (Ref

Hence this effect is applied to compressio

zone only in the calculation of moment capac

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 849 OF

PREPARED BY T. T. Lee

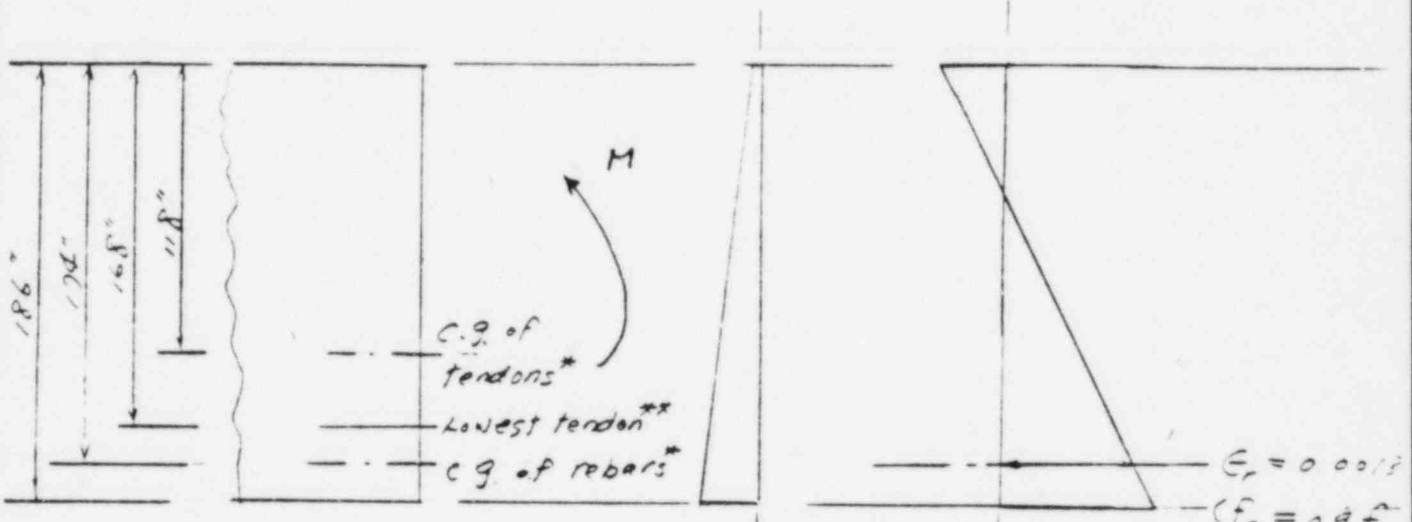
DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Moment Capacity Per Unit Width Along Yield Line:

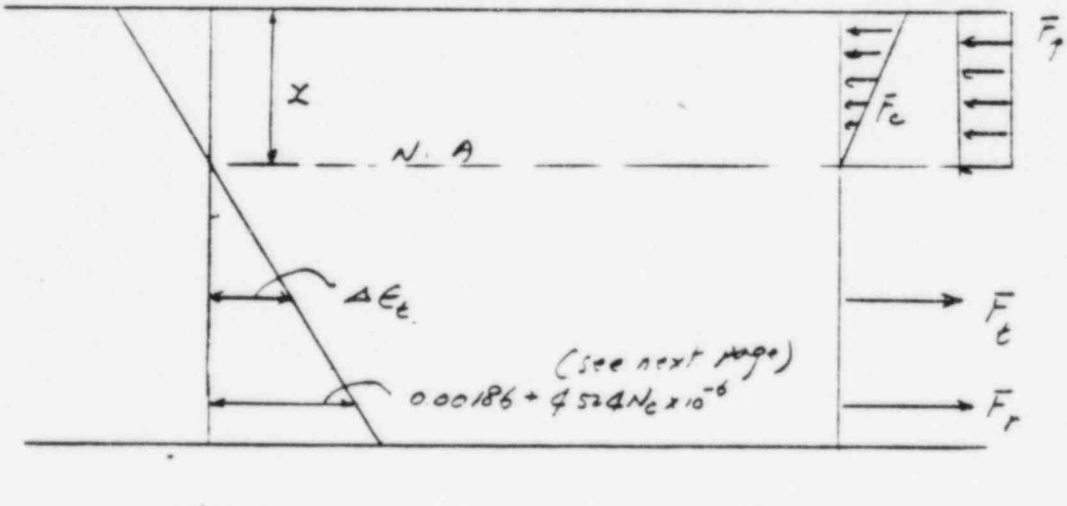


(1) strain due to prestress

(2) Strain at limit

* Ref. 1, Fig. E11-7

** Ref. 5.



strain due to moment

Forces due to moment + prestress

Fig. B-

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B50 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Due to prestress:

Tendon stress at end of life:

$$0.7 f_s'(1-0.12)(0.885) = 0.545 f_s' = 130.8 \text{ ksi}$$

Loss (Ref. 1, Table 5.6-4), Friction effect (Ref 3)

corresponding strain in tendon is.

0.00484 in/in (Fig 4)

Prestress in concrete:

Total tendon force at end of life:

$$F_{t,e} = \frac{2}{3} N_c' \times 8.35 \times 130.8 / 294$$

$$= 2.477 N_c' \text{ kip/in width}$$

Concrete stresses: N_c' = actual number of circ. head tendons.

Top (of bottom head): $\frac{2.477 N_c}{186} - \frac{(2.477 N_c')(118-}{\frac{(1)\,186^2}{6}}$

$$= 0.0133 N_c' - 0.0107 N_c' = 0.0026 N_c' \text{ k/in}$$

Bottom $= 0.0133 N_c + 0.0107 N_c' = 0.024 N_c'$ k/in

Concrete strains:

$E_c = 5.0 \times 10^6$ psi (Ref. 1, §5.4.1)

$\epsilon_{top} = 0.52 N_c \times 10^{-6}$ in/in, $\epsilon_b = 4.8 N_c \times 10^{-6}$ in/

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 85 / OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Concrete strains.

at rebar location:

$$\left[48 - \frac{48 - 0.52}{186} \cdot 12\right] N_c \times 10^{-6} = 4.524 N_c \times 10^{-6}$$

Due to Moment.

Limit. Max. rebar stress $= 0.9 f_{sy} = 54$ ksi.

Rebar strain at limit.

$$\frac{54}{29000} = 0.00186 \text{ in./in}$$

Rebar strain due to moment: $\epsilon_r = 0.00186 + 4.524 N_c'$

With $N_c' = 34$ (Max). additional ϵ_r over 0.001

is 0.000154 or about 8 % of 0.00186.

For simplicity and conservatism. assume

$$\epsilon_r = 0.00186 \text{ in./in}$$

This gives.

f_r = rebar stress = 54 ksi

$F_r = 0.12 \times 54{,}000 = 6480$ lbs/in

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B 52 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Tendons

$$\Delta \epsilon_t = \frac{118 - x}{174 - x} \cdot 0.00186$$

$$f_t = 130.8 + \Delta \epsilon_t \cdot 27000 = 130.8 + \frac{118 - x}{174 - x} \cdot 50 \div$$

(ks

$$F_t = \frac{2}{3} N_c' \times 835 \times f_t / 294$$

$$= 18.9 \; \underset{(\text{in } ksi)}{f_t} \; N_c' \quad (\text{lbs/in})$$

Concrete

Max. strain: $\frac{x}{174 - x} \epsilon_r = \epsilon_c = \frac{x}{174 - x} \; 0.00186$

Max. stress: $f_c = E_c \epsilon_c = 5 \times 10^6 \times \frac{x}{174 - x} \times 0.00186$

$$= \frac{9300 x}{174 - x} \quad (\text{psi})$$

Total force in concrete

$$F_c = \frac{1}{2} x \; f_c = \frac{4650 x^2}{174 - x} \quad (\text{lbs/in})$$

Effect of pressure inside penetration.

$$F_p = 610 \; x \quad (\text{lbs/in})$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 85 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Equation of equilibrium:

$$F_c + F_p = F_t + F_r$$

$$\frac{4650x^2}{174-x} + 610x = 18.9 N_c \left[130.8 + \frac{118-x}{174-x} \cdot 50.28 \right]$$

$$+ 6480$$

$$4650x^2 + 610x(174-x) = 18.9 N_c' \cdot 130.8 (174-x)$$

$$+ 18.9 N_c' (118-x) 50.28$$

$$+ 6480 (174-x)$$

$$(4650-610)x^2 + (610 \cdot 174 + 18.9 \cdot 130.8 N_c'$$

$$+ 18.9 \cdot 50.28 N_c' + 6480) x$$

$$- (18.9 N_c' \times 130.8 \times 174 + 18.9 N_c' \, 118 \times 50.2$$

$$+ 6480 \times 174) = 0$$

$$\underbrace{4040}_{a} x^2 + \underbrace{(112620 + 3422 N_c')}_{b}$$

$$- \underbrace{(1127,520 + 542283 N_c')}_{c} = 0$$

$$x = \frac{1}{2a} \left(-b + \sqrt{b^2 + 4ac} \right)$$

Capacity: $M = \frac{2}{3} x F_c + 305 x^2 + F_t (118-x) + F_r (174-x)$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 85 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS.	
CHECKED BY	DATE		

Table B-19 Moment Capacity

N'_c	34	32	30	28	
a					
b					
c					
N. A x (in.)	46.80	45.52	44.18	42.78	
$f_{c,max}$ (psi)	3422	3295	3165	3031	
$\overline{F}_c$ (lbs/in.)	80070	74988	69914	64854	
f_t (ksi)	158.94	159.16	159.39	159.62	
$\overline{F}_t$ (lbs/in.)	102138	96263	90375	84472	
F_r (lbs/in.)	6480	6480	6480	6480	
M (10^6 lbs-in) per in.	11.27	10.72	10.17	9.61	

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 855 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Table B-19 Moment Capacity (Continued)

N_c'	24	22	20	16	
a					
b					
c					
N. A. x (in.)	39.78	38.17	36.46	32.73	
$f_{c,max}$ (psi)	2756	2613	2465	2155	
F_c (lbs/in.)	54823	49877	44942	35261	
f_t (ksi)	16010	16035	16061	161.15	
F_t (lbs/in.)	72622	66674	60710	48731	
F_r (lbs/in.)	6480	6480	6480	6480	
M (10^6 lbs-in) per in.	8.49	792	7.34	6.17	

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 856 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Table B-9 Moment Capacity (Continued)

N_c'	14	12	10	8	6
a					
b					
c					
N. A x (in.)	3066	2843	2600	2333	2035
$f_{c,max}$ (psi)	1989	1816	1634	1440	1232
F_c (lbs/in.)	30495	25819	21239	16798	12533
f_t (ksi)	161.44	161.74	162.06	162.39	162.75
F_t (lbs/in.)	42716	36682	30628	24554	18456
F_r (lbs/in.)	6480	6480	6480	6480	6480
M (10^6 lbs-in per in)	557	4.96	4.35	3.73	309

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B57 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

<u>Effect of pressure inside penetration</u> – a check

If $F_p = 610\,x$ is neglected, the equation of equilibrium becomes:

$$F_c = F_l + F_r$$

$$4650\,x^2 + (6780 + 3422\,N_c') - (1127{,}520 + 542{,}$$

$$= 0$$

$$x = \frac{1}{2a}\left(-b + \sqrt{b^2 + 4ac}\right)$$

$$M = \frac{2}{3}x\,F_c + F_t\,(118 - x) + F_r\,(174 - x)$$

Check $N_c' = 34 \rightarrow x = 5299$

$$M = 11.19 \times 10^6$$

If F_p is included $x = 46.80$, $M = 11.27 \times$

$$\frac{11.27 - 11.19}{11.19} = 0.01 \quad \text{off}$$

. Thus F_p effect is small

Also, if $N_c' = 0 \rightarrow M = 1.095 \times 10^6$ vs 1.10×10^6

(No F_p) (with F_p)

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B58 OF
PREPARED BY T. T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

B. 1.8 Required Number of Head Tendons

Table B-20

N_x	1.0 RP			1.5 RP		
	Unit Yield Line Moment Req'd	N_c' Req'd(1)	N_c Req'd(1)	Unit Yield Line Moment Required	N_c' Req'd(1)	N_c Req'd
	lb-in/in			lb-in/in		
0	7.50×10^6	20.55	13.70	16.34×10^6	(2)	—
6	6.15×10^6	15.93	10.62	14.72×10^6	(2)	—
12	4.98×10^6	12.07	8.05	13.38×10^6	(2)	—
18	4.04×10^6	9.00	6.00	11.63×10^6	$34^{(3)}$	22.6
24	3.08×10^6	6.00	4.00	10.11×10^6	29.79	19.86
Source	Tables B-15, B-16	Table 19 by interpolation	$N_c' \times \frac{2}{3}$	Tables B-17, B-18	Table 19 by interpolation	$N_c' \times \frac{2}{3}$

(1) Required to provide (See Fig. 1) (See F
a moment capacity equal to the unit yield line moment.

(2) Not possible.

(3) Corresponds to $N_x = 19.42$. Max N_c' is 34 $N_x = 18$ req'd $N_c' > 34$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738, N/C

PAGE B59 OF

PREPARED BY T T Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

The calculated effective number of circumferential head tendons and the corresponding number of crosshead tendons required are shown graphically in Figs. 1 and 2, main text.

As a further conservatism, the curve for 1.5 Rt (Fig. 2) is truncated at $N_c = 22$ since in each head, the minimum N_c passing any section is 22, out of 34 actual number of tendons currently provided.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B60 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

B. 2 Potential Failure Mode with Yield Line at Edge of Core Cavity

N_c, N_x requirements were determined from consideration of yield patterns O-A-B-H-C and O-A-D-G-E (See Fig B-3).

Potential yield line failure along the yield pattern O-A-B-H-I and O-A-D-G-I are checked to assure that any of these will not be critical (See Fig. B-3)

Four N_x, N_c' combinations representing the extreme conditions in Figs. 1 and 2 are checked They are

$N_x = 0$, $N_c' = 20$ $(N_c = 13)$ } Fig. 1

$N_x = 24$, $N_c' = 6$ $(N_c = 4)$

$N_x = 21$, $N_c' = 33$ $(N_c = 22)$

$N_x = 24$ $N_c' = 30$ $(N_c = 20)$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 86/ OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

<u>Bottom Rebars for Bottom Head</u> (Ref. 7)

Layer #1 : All #8. A432

LBH-1, 2, ..., 9 = 102

LBH-10, 11, 12, 13, 14 = 72

} $184 \times (0.79) = 145.3$ in²

Layers #3, 5, 7 All #8. A432

LBH-18.	64
LBH-21	32
11'-11" LG.	24
11'-2" ..	36
12'-9" ..	24
7'-6" ..	12

} $192 \times (0.79) = 151.68$ in²

Total in radial dir. = 297.04 in²

Or. $\frac{297.04}{2\pi \cdot 186} = 0.254$ in²/in liner

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 362 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Top Rebars for Bottom Head

Diagonal Bars (Refs. 8 & 10) A431. #11

$12 \times 16 \times (1.56) \times \cos 19°50' \times \cos 45°$

#11 (plan) (Elevation)

$= 192 \times 1.56 \times \cos 19°50' \times \cos 45°$

$= 299.52\ in^2 \times \cos 19°50' \times \cos 45°$

(19.83°)

$= 199.23\ in^2$ total in radial direction

Radial Bars (Refs. 8 and 9) A431. #14s

(Area)

UBH-5. 5A. 6. 6A: $8 \times 2.25 \times \cos 27.5° \times \cos 9° =$ 15.77

UBH-7, 7A. 8. 8A: $8 \times 2.25 \times \cos 27.5° \times \cos 18° =$ 15.18

UBH-9. 9A. 10. 10A $8 \times 2.25 \times \cos 27.5° \times \cos 25° =$ 14.47

UBH-11. 11A. 12 12A $8 \times 2.25 \times \cos 27.5 \times \cos 33° =$ 13.39

UBH-17. 17A. 18. 18A. $16 \times 2.25 \times \cos 28° \times \cos 9° =$ 31.39

UBH-19. 19A. 20. 20A. $16 \times 2.25 \times \cos 28° \times \cos 18° =$ 30.23

UBH-21, 21A. 22, 22A. $16 \times 2.25 \times \cos 28° \times \cos 25° =$ 28.8

UBH-23, 23A. 24. 24A. $16 \times 2.25 \times \cos 28° \times \cos 33° =$ 26.1

UBH-33. 33A. 34. 34A: $96 \times 2.25 \times \cos 27.5° \times \cos 27°15' =$ 170.

Total in radial dir. = 346.23

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

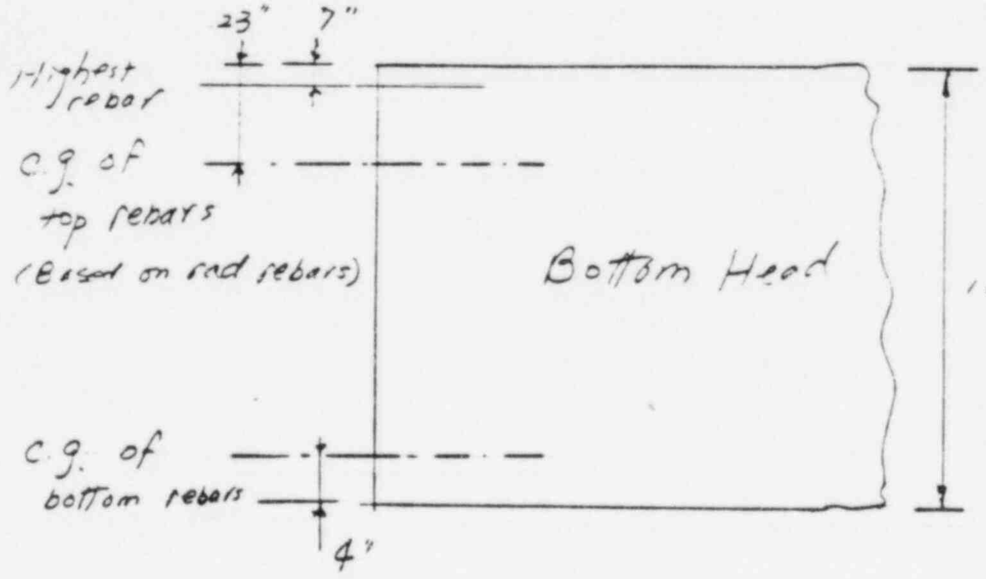
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE B63 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Total in radial dir. = 199.23 + 346.23 = 545.46

Or $\frac{545.46}{2\pi \cdot 186} = 0.467$ in²/in.

<u>Location of Rebars</u>

(Refs. 8 and 11)



GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 864 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Radial Prestress due to Crosshead Tendons

Referring to Ref. 10,

Of 24 tendons, 12 are essentially radial at the edge of core cavity, and 12 are inclined about 30° w.r.t the radial direction. Vertically, the largest inclination is 43°. Hence the prestress force is

$$2 \cdot \frac{N_x}{2} (1 + \cos 30°) \cos 43° \times 8.35 \times f_x$$

(stress in X-head tendons.)

$$= 2 \times 5.698 \; f_x N_x \quad \text{kips} \qquad (f_x \text{ in ksi})$$

or $$\frac{2 \times 5.698 \; f_x N_x}{2 \pi \cdot 186} = 9.75 f_x N_x \quad \text{lbs/in.}$$

(f_x in ksi.)

From Ref. 11, the location of crosshead tendons at the edge of core cavity is about 8 ft from the top of bottom head

GA 258 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B65 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Moment Capacity Along a Radial Yield Lines

Same as before (See § B.1.7) except

use $F_t = 18.9\ (130.8)\ N_c = 2472\ N_c^{*}$

$F_c + F_p = F_t + F_r$

$\frac{4650\ x^2}{174 - x} - 610\ x = 2472\ N_c - 5480$

$4650\ x^2 + 610x\ (174 - x) = (2472\ N_c + 6480)\ (174-x$

$4040 x^2 + (610 \cdot 174 - 2472\ N_c + 6480) x$

$- 174 (2472 N_c + 6480) = 0$

$\underset{a}{\underline{4040}}\ x^2 + \underset{b}{\underline{(112620\ - 2472\ N_c)}} x - \underset{c}{\underline{(1127,520 + 43}}$ $= c$

$x = \frac{1}{2a} \left(-b + \sqrt{b^2 + 4ac} \right)$

$M = \frac{2}{3} x F_c + 305 x^2 + F_t\ (118 - x) + F_r\ (174 - x)$

* The increase in prestress due to further extension of tendons is ignored.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 866 OF

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Table B-21 Moment Capacity

Along a Radial Yield Line

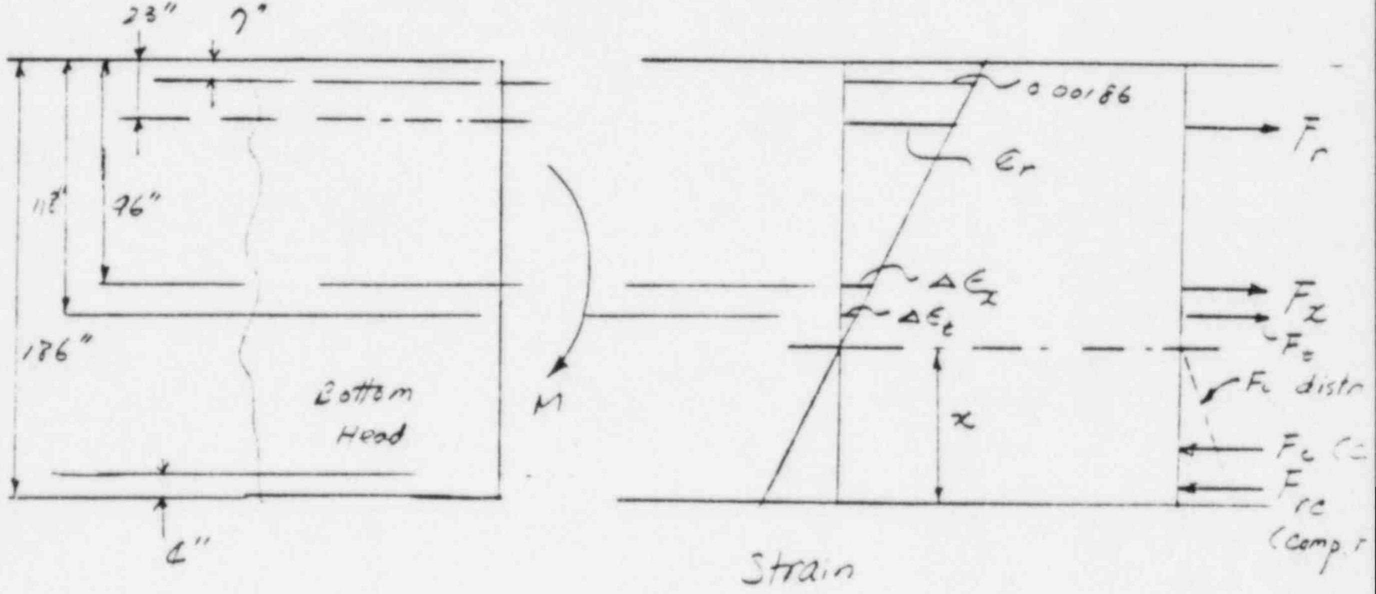
N_c'	20	6	33	30
a	4040	4040	4040	4040
b	162060	127182	194196	186780
c	9,730,080	3,708,288	15,321,744	14,031,360
N.A. x (in.)	32.96	18.40	42.07	40.19
$f_{c,max}$ (psi)	2173	1100	2966	2793
F_c (lbs/in)	35817	10118	62386	56128
f_t (ksi)	130.8	130.8	130.8	130.8
F_t (lbs/in)	49440	14832	81576	74160
F_r (lbs/in.)	6480	6480	6480	6480
M (10^6 lbs-in per in)	6.24	2.71	9.34	8.63

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 867 OF
PREPARED BY T. T. Lee	DATE 11/19/86	REF. DOCUMENTS:	
CHECKED BY	DATE		

Moment Capacity Along a Hoop Yield Line



Strain
due to moment
(≈Strain at
limit)

Fig. B-10

$$\text{Max. rebar strain} = \frac{54}{29000} = 0.00186$$

$$\text{Ave. rebar strain} = \frac{186-23-x}{186-7-x} \cdot 0.00186 = \frac{163-x}{179-x} \cdot 0.0$$

Total rebar force (tensile):

$$F_r = \underset{(\text{Area}/\text{in.})}{0.467} \times \frac{163-x}{179-x}(0.00186)(29{,}000{,}000)$$

$$= 25190 \times \frac{163-x}{179-x} \quad \text{lbs/in}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO. | PROJ. | CALC. NO. 907738 N/C | PAGE B68 OF

PREPARED BY T. T. Lee | DATE 11/19/84 | REF. DOCUMENTS:

CHECKED BY | DATE

Total rebar force (compressive):

$$\text{Strain: } 0.00186 \frac{x-4}{179-x}$$

$$F_{rc} = 0.00186 \frac{x-4}{179-x} \cdot 29{,}000{,}000 \times 0.254$$

(Area/in)

$$= 13700 \frac{x-4}{179-x} \quad \text{lbs/in}$$

Crosshead tendons

$$\Delta\epsilon_x = \frac{186-96-x}{179-x} \cdot 0.00186 = 0.00186 \frac{90-x}{179-x}$$

Stress at end of life

$$0.7 f_s' \underset{\text{loss}}{(1-0.12)} \underset{\text{friction}}{(0.9)} = 0.554 f_s' = 133 \text{ ksi}$$

f_x = Stress in X-head tendons

$$= 133 + \Delta\epsilon_x \cdot 27{,}000 = 133 + \frac{90-x}{179-x} \times 50.28 \quad (\text{k}$$

$$F_x = 9.75 \underset{(\text{in ksi})}{f_x} \cdot N_x \quad (\text{lbs/in})$$

Concrete

$$\text{Max. strain} - \epsilon_c = 0.00186 \frac{x}{179-x}$$

$$f_{c(max)} = E_c f_c = 5 \times 10^6 \times 0.00186 \frac{x}{179-x} = \frac{9300x}{179-x} \quad (\text{p}$$

$$F_c = \frac{1}{2} x f_c = \frac{4650x^2}{179-x}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B60

PREPARED BY T. T. Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

(ksi)

$$F_t = \frac{2}{3} N_c' (8.35) \cdot f_t / 22.17 \times 12 = 20.9\, f_t\, N_c'$$

↳ Ave. radius of cir. tendon

Use $f_t = 130.8$ ksi (Inc. in f_t due to $\Delta\epsilon_t$ ignor

$$F_t = 20.9 \times 130.8\, N_c = 2734\, N_c$$

Equilibrium:

$$F_r + F_x + F_t = F_c + F_{rc}$$

$$25190 \frac{163-x}{179-x} + 9.75 \left(133 + \frac{90-x}{179-x} 50.28\right) N_x$$

$$+ 2734\, N_c = \frac{4650 x^2}{179-x} - 13700 \frac{x-4}{179-x}$$

$$25190 (163-x) + 9.75 (133)(179-x) N_x + 9.75 (90-x)$$

$$+ 2734\, N_c (179-x) = 4650\, x^2 - 13700 (x-4)$$

$$4650 x^2 + (13700 + 25190 + 9.75 \times 133 N_x + 9.75 \times 50.28 N_x +$$

$$- (13700 \times 4 + 25190 \times 163 + 9.75 \times 133 \times 179 N_x + 9.75 \times 90 \times 50.28$$

$$+ 2734 \times 179 N_c) = 0$$

$$\underbrace{4650}_{a} x^2 + (\underbrace{38890 - 1787 N_x + 2734 N_c}_{b}) x$$

$$- (\underbrace{4{,}160{,}770 + 276{,}239 N_x + 489{,}386 N_c}_{c}) = 0$$

$$x = \frac{1}{2a} \left(-b + \sqrt{b^2 + 4ac}\right)$$

$$M = F_r (163-x) + F_x (90-x) + F_t (68-x) + F_c \left(\tfrac{1}{3} x\right) +$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR		
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C — PAGE 870 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:
CHECKED BY	DATE	

Table B-22 Moment Capacity Along a Hoop Yield Line (At R = 186 in)

N_x	0	24	21	27	
N_c'	20	6	33	30	
x (in)	45.62	44.79	57.13	58.47	
F_r (lbs/in)	22168	22187	21828	21846	
f_x (ksi)	—	14994	145.95	14615	
F_x (lbs/in)	0	35085	29883	34200	
$\hat{T}_t$ (ksi)	130.8	130.8	130.8	130.8	
F_t (lbs/in)	54680	16404	90222	82020	
f_c (psi)	3181	3104	4588	4512	
F_c (lbs/in)	72556	69507	135621	131894	
F_{rc} (lbs/in)	4275	4164	6301	6191	
M (lbs-in/in)	6.21	6.83	9.68	9.62	

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PREPARED BY T T Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Yield Line Pattern OADGI

Referring to Fig B-6. the forces acting on the slab section bounded by OADGIG'D' consist of the effective pressure on the surface vertical force (F_{L-L}) along GIG'. shearing for along OADG and OA'D'G'. moment along the two radial yield lines (OADG and OA'D'G'), and moment along the hoop yield line GIG'. For simplicity ignore the shear along OADG. & OA'D'G'.

From equilibrium the moment of the effective pressure and F_{L-L} about any horizon axis must be balanced by the moments along all yield lines. For convenience, use E-E' as the axis to compute the moment due to pressure and F_{L-L}.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 872 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Check 1 RP. $N_x = 0$ $N_c' = 20$ Case

From Table B-16.

(1) $M_{E-E'}$ due to pressure $= 1.862 \times 10^9$ lb-in

(2) " " " F_{L-L} $= -0.946 \times 10^9$ lb-in

Sum $= 0.916 \times 10^9$

$= 916 \times 10^6$ lb-in

Resisting Moment

(3) Along OADG & OA'D'G' $= 2 \times \underbrace{6.24 \times 10^6}_{} \times \underbrace{(9+1+9)}_{}$

(Table B-21)*

(See Fig. B-7)

$= 237 \times 10^6$

(4) Along GIG' $= 2 \times \underline{6.21 \times 10^6} \times \underline{186 \times 5\text{in}}$

*(Table B-24)

(See Fig. B-

$= 714 \times 10^6$

Sum $= 951 \times 10^6$ lb-in

$> 916 \times 10^6$ lb-in

∴ This yield line failure mode does not contr

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 873 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Check 1 RP. $N_x = 24$. $N_c' = 6$ Case

$M_{E-E'}$ due to pressure $= 1.214 \times 10^9$

" " " $F_{L-L} = -0.617 \times 10^9$

$\text{Sum} = 0.597 \times 10^9$

$= 597 \times 10^6$ lb-in.

Resisting Moment

Along OADG & OA'D'G' $= 2 \times 2.71 \times 10^6 \times 19 = 103 \times 10$

Along GIG' $= 2 \times 683 \times 10^6 \times 1.86 \times \sin 18°$

$= 785 \times 10^6$

$\text{Sum} = 888 \times 10^6$ lb-in

$> 597 \times 10^6$ lb-in

O.K

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 874 OF
PREPARED BY T. T. Lee	DATE 11/19/86	REF. DOCUMENTS:	
CHECKED BY	DATE		

Check 1.5 RP, $N_x = 21$. $N_c' = 33$ Case

From Table B-18.

$M_{E-E'}$ due to pressure $= 2.224 \times 10^9$ (by interpolat

" " " F_{L-L} $= -1.130 \times 10^9$ (by interpolo

Sum $= 1.094 \times 10^9 = 1094 \times 10^6$ lb-

Resisting moment

Along OADG, OA'D'G' $= 2 \times 9.34 \times 10^6 \times 19 = 355 \times 10^6$

Along GIG' $= 2 \times 9.68 \times 10^6 \times 188 \times \sin 18° = 1113 \times 10$

Sum $= 1468 \times 10^6 > 1094 \times 10^6$ lb-in

O.K

Check 1.5 RP, $N_x = 24$. $N_c' = 30$ Case

$M_{E-E'}$ due to pressure $= 2.142 \times 10^9$

" " " F_{L-L} $= -1.088 \times 10^9$

Sum $= 1.054 \times 10^9 = 1054 \times 10^6$ lb-.

Resisting moment

along OADG, OA'D'G' $= 2 \times 8.63 \times 10^6 \times 19 = 328 \times 10^6$

along GIG' $= 2 \times 9.62 \times 10^6 \times 188 \times \sin 18°$

$= 1106 \times 10^6$

Sum $= 1434 \times 10^6 > 1054 \times 10^6$ lb-.

O.K

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE B75 OF

PREPARED BY T. T. Lee

DATE 11/19/86

REF. DOCUMENTS.

CHECKED BY

DATE

Yield Line Pattern OABHI

Refer to Fig. B-6

Check 1.0 RP, $N_x = 0$, $N_c' = 20$ case

From Table B-15.

$M_{c-c'}$ due to pressure = 2.599×10^9

" " " F_{L-L} = -1.648×10^9

Sum = 0.951×10^9

= 951×10^6 lb-in

Resisting moment

along OABH, OA'B'H' = $2 \times 6.24 \times 10^6 \times (9+13+9) = 387 \times$

along HIH' = $2 \times 6.21 \times 10^6 \times 186 \times \sin 41.5° = 1531 \times 10^6$

Sum = 1918×10^6 lb-in > 951×10

O.K.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.

PROJ.

CALC. NO. 907738 N/C

PAGE 87 OF

PREPARED BY T T Lee

DATE 11/19/84

REF. DOCUMENTS:

CHECKED BY

DATE

Check 1.0 RP, $N_x = 24$ $N_c' = 6$ Case

$M_{c-c'}$ due to pressure $= 2.374 \times 10^9$

" " " $F_{x-x} = -1.505 \times 10^9$

Sum $= 0.869 \times 10^9 = 869 \times 10^6$ 16-

Resisting moment

along OABH, OA'B'H' $= 2 \times 2.71 \times 10^6 \times (31) = 168 \times 10^6$

along HZH' $= 2 \times 6.83 \times 10^6 \times 186 \times \sin 41.5^\circ = 1684 \times$

Sum $= 1852 \times 10^6 > 869 \times 10^6$ 16-

OK

Check 1.5 RP. $N_x = 21$, $N_c' = 33$ Case

$M_{c-c'}$ due to pressure $= 3.106 \times 10^9$

" " " $F_{x-x} = -1.968 \times 10^9$

Sum $= 1.136 \times 10^9 = 1136 \times 10^6$ 16

Resisting moment

along OABH, OA'B'H' $= 2 \times 9.34 \times 10^6 \times 31 = 579 \times 10^6$ 16

along HZH' $= 2 \times 9.68 \times 10^6 \times 186 \times \sin 41.5^\circ = 2386 \times 10^6$

Sum $= 2965 \times 10^6 > 1136 \times 10^6$ 16-

OK

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 87 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

Check 1.5 Rp $N_x = 24$, $N_c' = 30$ Case

$M_{c-c'}$ due to pressure = 2.990×10^9

" " " F_{L-L} = -1.895×10^9

Sum = $1.095 \times 10^9 = 1095 \times 10^6$ lb-in

Resisting moment:

along OABH, OA'B'H' = $2 \times 263 \times 10^6 \times 21 = 535 \times 10^6$

along HIH' = $2 \times 962 \times 10^6 \times 186 \times \sin 41.5° = 2371 \times 10^6$

Sum = $2906 \times 10^6 > 1095 \times 10^6$ lb-in

OK

Conclusion (§B.1.9)

Yield line failure along OABHI or OADGI will not develop, if N_x, N_c shown in Table B-20 (or Figs 1 and 2) are used. Hence Table B-20, Figs 1 and 2 remain valid

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 878 OF
PREPARED BY T. T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

B. 3 <u>Punching Shear Mode of Failure</u>

(Bottom Head)

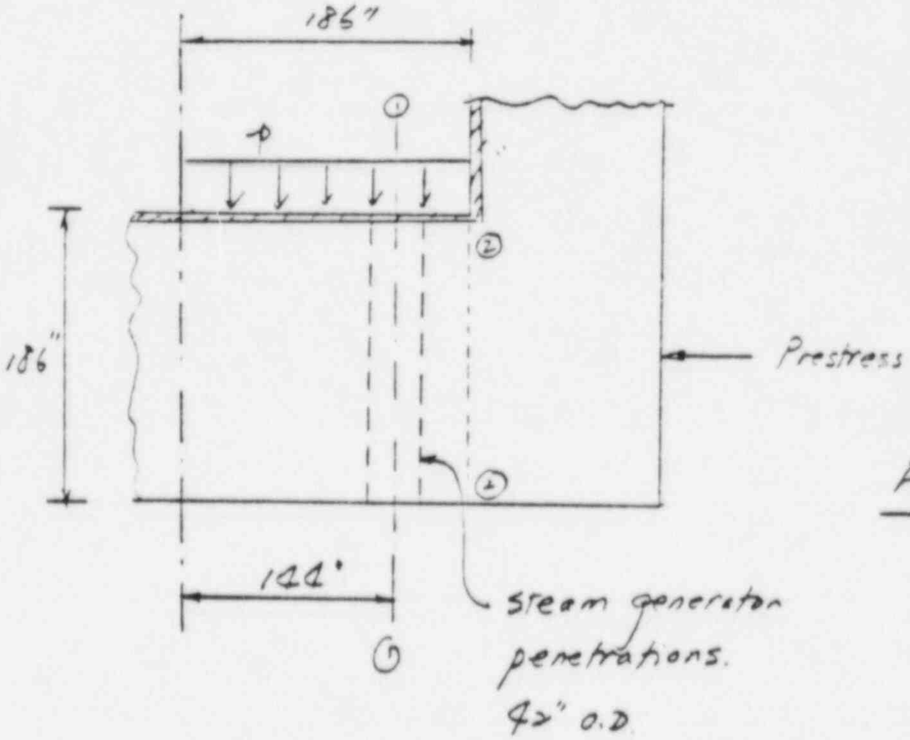


Fig B-11

Section susceptible to punching shear failure is the one connecting the S.G. penetrations, Fig. B-11, ①-①. See Fig. B-3 also.

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR

EQUIP. NO.	PROJ.	CALC. NO. 907738 N/C	PAGE 879 OF
PREPARED BY T. T. Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

The punching shearing stress is :

$$\frac{p\,\pi\,(144)^2}{\left[2\pi(144)-12(42)\right]\cdot 186} = 0.874\,p = f_v$$

Ref. 4 gives

$$p = \frac{d}{D}\left(0.842\,f_c' - 0.1676\,f_t\right)$$

where p = ultimate pressure (psi)

d = slab thickness = 186 in

D = pressurized diameter in inches = 288 in

f_c' = concrete strength = 6000 psi

f_t = prestress (psi)

From this, the shear allowable is

$$\frac{p\,\frac{\pi D^2}{4}}{\pi D\cdot d} = \frac{pD}{4d} = f_{v,\,allowable}$$

GA 268 (REV. 4/82)

CALCULATION SHEET

CALCULATIONS FOR			
EQUIP. NO.	PROJ.	CALC. NO. 9C7738 N/C	PAGE 320 OF
PREPARED BY T T Lee	DATE 11/19/84	REF. DOCUMENTS:	
CHECKED BY	DATE		

$$f_{v,\ allowable} = \frac{1}{4}(0842 f_c' - 0.1676 f_t)$$

$$= 0.210 f_c' + 0.0419 f_t$$

$$= 1260 - 0.0419 f_t$$

For $\underset{(1.0RP)}{p = 845 \text{ psig}}$. $f_v = 738$ psi

$\underset{(1.5RP)}{p = 1268 \text{ psig}}$, $f_r = 1108$ psi

Both are smaller than 1260 psi, the allowable ignoring the constraining effect of the radial prestress

Check Section ②-② (Fig. B-11):

Allowable $p = \frac{186}{2 \times 186}(0.842 f_c' + 0.1676 f_t)$

$= 2526 + 0.0838 f_t$

Actual p = 845 and 1268 psig. < 2526 psi

Hence. punching shear is not a problem

APPENDIX C

CALCULATION REVIEW REPORT

GA1543(REV. 11/80)

907738 N/C 7 c2

CALCULATION REVIEW REPO

TITLE: FSV - Tendon Requirements Based on Safety Consideration

APPROVAL LEVEL 2

QAL LEVEL I

DISCIPLINE	SYSTEM	DOC. TYPE	PROJECT	DOCUMENT NO.	ISSUE NO./LTR.
S	11	CFL	1900	907738	N/C

INDEPENDENT REVIEWER:

NAME Arnold A. Schwartz

ORGANIZATION Structural Design and Analysis

REVIEWER SELECTION APPROVAL: BR MGR DATE 10.29.84

REVIEW METHOD:	YES	NO	ERROR DETECTED
ARITHMETIC CHECK		✓	
LOGIC CHECK	✓		No
ALTERNATE METHOD USED		✓	
SPOT CHECK PERFORMED	✓		No
COMPUTER PROGRAM USED		✓	

REMARKS: (ATTACH LIST OF DOCUMENTS USED IN REVIEW)

Calculation 907738

FSV - Structural Dwgs for PCRV

CALCULATIONS FOUND TO BE VALID AND CONCLUSIONS TO BE CORRECT:

INDEPENDENT REVIEWER Arnold A. Schwartz DATE 11/30/84

SIGNATURE

P-86491 Attachment 4

Public Service Company of Colorado

16805 WCR 19 1/2, Platteville, Colorado 80651

January 31, 1985
Fort St. Vrain
Unit #1
P-85039

Final transmitted version

Regional Administrator
Region IV
U. S. Nuclear Regulatory Commission
611 Ryan Plaza Drive, Suite 1000
Arlington, Texas 76011

Attn: Mr. E. H. Johnson

SUBJECT: Interim Fort St. Vrain
Tendon Surveillance
Program

REFERENCES: PSC Letter,
D. W. Warembourg to
E. H. Johnson
12/14/84 (P-84523)

Dear Mr. Johnson:

In response to the concerns expressed by the NRC we are submitting for your evaluation our plans for implementing an interim tendon surveillance program.

The surveillance program will be based on proposed Technical Specification SR 5.2.2 as submitted in Reference 1 and will include those tendons considered accessible in Reference 1.

PSC plans to implement the surveillance program based on information gathered in our original assessment effort and your expressed concerns for determining the present overall level of corrosion and the current rate of corrosion.

The majority of this program has already been started as a continuing effort following completion of tendon testing we had previously committed to perform. The entire program will be implemented by March 1, 1985 and will be based on an eighteen month cycle, as cited in the submitted SRs.

~~8502110689~~

Tendon Surveillance Specification SR 5.2.2 includes five (5) sections which PSC plans to treat as follows during this interim period.

1. SAMPLE WIRES INSERTED INTO TENDONS WITH AREAS OF KNOWN CORROSION

   No action will be initiated during the interim period. The sample wires currently in the tendons are not necessarily in tendons with areas of known corrosion. The tendons with areas of corrosion are currently being identified and supplies of sample wires are currently being investigated.

2. ATMOSPHERIC SAMPLES OF TENDON TUBES

   No action will be initiated during the interim period. Tendon caps have been removed on most tendons for examinations and air, therefore, was introduced into the tubes. The corrosion prevention system has not been finalized as of this date and sampling of the tubes atmosphere would provide no useful information. During the original corrosion determination investigation the atmospheres in 97 tubes were sampled and tested. The results of these tests have been supplied to the NRC.

3. VISUAL EXAMINATION OF ACCESSIBLE TENDONS

   During the interim period PSC will perform this section as it was submitted to the NRC. A visual examination of at least 5% of the accessible ancher assemblies for the top crosshead and circumferential tendons shall be performed. A visual examination of at least 33% of the accessible ancher assemblies for the longitudinal and bottom crosshead tendons shall be performed. This will include re-examination of tendons with areas of known corrosion to obtain information on the current rate of corrosion. In addition to the required percentage of tendons, an additional two repeat tendons will be examined to provide for continuous monitoring of corrosion rate.

4. TENDON LIST OFF TEST

During the interim period PSC will perform this section as it was submitted to the NRC. Lift off test of at least 5% of the accessible top crosshead tendons and circumferential tendons shall be performed. Lift off test of at least 15% of the accessible longitudinal tendons and bottom crosshead tendons shall be performed. In addition to the required percentage of tendons, an additional two repeat tendons will be tested to provide for continuous monitoring of corrosion rate.

5. REPORT OF TENDON EXAMINATION RESULTS

At the end of the interim period a report will be prepared covering the testing done during the interim period. This special report will be submitted to the NRC at that time. If specification SR5.2.2 is formally approved prior to the end of the eighteen month interim period, the special report will be prepared indicating the status at that time.

Please be aware that the Specification SR 5.2.2 submitted in Reference 1 was a preliminary Technical Specification submittal, only for the purpose of presenting our rational for a tendon surveillance program.

We trust this provides the requested commitment to begin an interim tendon surveillance program and satisfies your concerns. If there are any further questions concerning the PCRV tendons please contact me or Mr. Chuck Fuller at (303) 785-2223.

Sincerely,

J. W. Gahm
Manager, Nuclear Production
Fort St. Vrain Nuclear
Generating Station

JWG:AR/djc

P-86491 Attachment 5

Public Service

Public Service
Company of Colorado

16805 WCR 19 1/2, Platteville, Colorado 80651

June 7, 1985
Fort St. Vrain
Unit No. 1
P-85193 10

P DISTRIBUTION

BORST, T. J.
BREY, H. L.
BURCHFIELD, B.
DENVER DOC. CONT.
DOLPHIN, M.
EGGEBROTEN, J.
FULLER, C. H.
GAHM, J. W.
GRAMLING, J.
HOLMES, M. H.
INDEPENDENT REVIEWE
JOHNS, J
JOHNSON, E. H.
KITZMAN, A.
LEE, O. R.
MCBRIDE, L. M.
NFSC CLERK
NIEHOFF, M. E.
NOVACHEK, F.
PLUMLEE (NRC)
PORC CLERK
REESY, J. R.
SINGLETON, L.
TECH SERV. CLERK (3
U.S.N.R.C.
WAGNER, P
WAREMBOURG, D. W.

Regional Administrator
Region IV
U. S. Nuclear Regulatory Commission
611 Ryan Plaza Drive, Suite 1000
Arlington, Texas 76011

Attention: Mr. Eric H. Johnson

Docket No. 50-267

SUBJECT: Fort St. Vrain
Additional Tendon
Inspection

REFERENCES:
1) PSC Letter,
D. W. Warembourg to
E. H. Johnson, dated
5/20/85 (P-85176)

2) I&E Information
Notice 85-10
(G-85053)

3) I&E Information
Notice 85-10
Supplement 1 (G-85098)

Dear Mr. Johnson:

As per Reference 1, ten of the bottom longitudinal tendon end caps were removed for inspection. The visual inspection consisted of examining the tendon end caps, prestressing anchor assembly stressing washer, shims, bearing plate and buttonheads for evidence of general corrosion, concavity, water or apparent failures. The inspection showed no evidence of concavity, cracking, water, or general corrosion. No raised buttonheads were found during this inspection. To insure that there was no cracking similar to that at Farley, five of the anchor assemblies were magnetic particle inspected for cracking. The tendons inspected were VM1, VI3, VI11, VM17, VM18, VM22, VI27, VM31, VI34 and VI38. The tendons which were subjected to the examination were VM1, VM17, VM22, VM31 and VI34.

RECEIVED

JUN 12 1985

M. B. DOLPHIN

~~8506270277~~

Due to bleedout associated with liquid penetrant tests, Public Service Company considers magnetic particle testing to be more sensitive for this application. The magnetic particle tests showed no discontinuities.

During this inspection, no visible evidence of pitting was found in the tendon caps. As per Reference 3, a galvanic cell was established at Farley between their galvanized caps and the stressing washers. The zinc in Farley's prestressing system was essential in the establishment of the galvanic cell, which resulted in stressing washer failure. Since we have no zinc coated components associated with our prestressing system and based on all previous inspections to date, it is Public Service Company of Colorado's conclusion that Fort St. Vrain is not susceptible nor exhibiting evidence of zinc related galvanic cell corrosion.

If you have any further questions, please do not hesitate to contact Mr. M. H. Holmes at (303) 571-8409.

Very truly yours,

D. W. Warembourg

D. W. Warembourg,
Manager, Nuclear Engineering
Division

* Ref. Corrosion Engineering by
Fontana/Greene, 1978.

DWW/MJF/ksc

Attachments

Reviewed by

P-86491 Attachment 6

interim surveillance program description

cc [illegible] Fisher

Public Service
2420 W. 26th Avenue, Suite 100D, Denver, CO 80211

Public Service Company of Colorado
P.O. Box 840
Denver, CO 80201-0840
(303) 571-7511

P DISTRIBUTION

BORST, T. J.
BREY, H. L.
BURCHFIELD, B.
DENVER DOC. CONT.
DOLPHIN, M.
EGGEBROTEN, J.
FULLER, C. H.
GAHM, J. W.
GRAMLING, J.
HOLMES, M. H.
INDEPENDENT REVIEWE
JOHNS, J
JOHNSON, E. H.
KITZMAN, A.
LEE, O. R.
MCBRIDE, L. M.
MILLEN, C. K.
NFSC CLERK
NIEHOFF, M. E.
NOVACHEK, F.
PLUMLEE (NRC)
PORC CLERK
REESY, J. R.
SINGLETON, L.
TECH SERV. CLERK (
U.S.N.R.C.
WAGNER, P
WAREMBOURG, D. W.

March 5, 1985
Fort St. Vrain
Unit No. 1
P-85071

Regional Administrator
Region IV
U.S. Nuclear Regulatory Commission
611 Ryan Plaza Drive Suite 1000
Arlington, Texas 76011

Attn: Mr. Eric Johnson

DOCKET NO. 50-267

SUBJECT: Fort St. Vrain Unit No. 1
Revised Tendon Surveillance
Program

REFERENCES: 1) P-85039, Gahm to Johnson, dated January 31, 1985

2) P-84523, Warembourg to Johnson, dated December 14, 1984

Dear Mr. Johnson:

As a result of our porposal for a PCRV tendon surveillance program presented at the February 20-22, 1985 site meetings and subsequent telephone conversations, we are transmitting herewith our written description of this program.

The basis for our proposal is as follows:

A. Surveillance Frequency and Tendon Population

Our original interim surveillance program as proposed by P-85039, established an 18 month frequency for the visual inspection and liftoff test programs. While it is felt that this program would provide adequate monitoring of the prestressing system, we recognize that the present data base is not sufficient to define a corrosion rate. Based on present information, the corrosion rate appears to be relatively slow, but we feel it is necessary to develop a more sufficient data base. On this basis we have proposed the accelerated inspection/testing program for

~~8503220042~~

the next three (3) year period or until such time that effective corrosion control is established. The program changes the previously proposed 18 month frequency for visual inspection to a six (6) month frequency. The proposed program also establishes a larger control group of tendons to permit a better assessment of corrosion rate.

The liftoff frequency for the new tendon population remains the same as previously proposed; however, a control group has been established to provide a liftoff assessment every six (6) months for tendons in this group.

This substantial increase in the surveillance program together with a very high percentage of tendons that we have already inspected/tested provides the necessary assurance that PCRV prestressing system is capable of performing its design function.

B. Engineering Evaluations/Failed Wire Criteria

As indicated in the proposed surveillance program, we will be continuously assessing the PCRV prestressing system from an engineering viewpoint as data is obtained in the surveillance program. We expect the surveillance program to be continuous over the frequency cycle specified.

Within the proposed program, we did specify a mandatory engineering evaluation based on ≥ 15% failed wires for circumferential barrel tendons and ≥ 20% failed wires for all other tendons. It should be noted that the program outlined on February 22, 1985, during the NRC site meetings established a general criteria of ≥ 20% failed wires for all tendons. That original criteria did not recognize the two sub-groups of circumferential tendons, one of which is the 152-wire circumferential barrel tendons. As a result, this surveillance program has established a ≥ 15% failed wire criteria for the circumferential barrel tendons.

Design Criteria DC-11-1 (FSAR, Appendix E) requires the PCRV be designed to resist a cavity pressure of 2.1 RP (1775 psig) for Limit Condition 2 which is the governing case. The allowable stress/strength limits for this condition are:

Longitudinal tendons - Guaranteed ultimate tensile strength provided that strain compatibility is satisfied.

Circumferential tendons in barrel - Same as above.

Top and bottom head tendons (circumferential and crosshead) - 0.9 fsy where fsy is the minimum guaranteed steel yield strength at 1% elongation, and is equal to 204 ksi (FSAR, Fig. 5.6-1).

In this calculation, in order to assure the participation of rebars, the allowable stress for the longitudinal tendons and the circumferential tendons in the barrel section is limited to fsy.

The PCRV ultimate load analysis (FSAR Section 5.3.3.3 and Appendix E, Section E.10, Figs. E.10-23 through E.10-25) indicates that at a cavity pressure of 1775 psig the stresses in typical tendons are still elastic as given below:

1. Longitudinal tendons: 156 ksi.
2. Circumferential tendons at barrel: 170 ksi.
3. Circumferential tendons at heads: 138 ksi.
4. Crosshead tendons = 139.5 ksi.

These tendon stresses expressed as ratios of the respective allowable stress/strength limits are as follows:

1. Longitudinal tendons: 156/204 = 0.76
2. Circumferential tendons at barrel: 170/204 = 0.83
3. Circumferential tendons at heads: 138/(0.9 x 204) = 0.75
4. Crosshead tendons: 139.5/(0.9 x 204) = 0.76

It follows that the minimum acceptable tendon steel areas to resist the overpressure condition expressed as ratios of original areas specified in design are as follows:

	Area Required	Permissable Loss	Wire Failure Evaluation Criteria
Longitudinal Tendons	76%	24%	20%
Circumferential Barrel	83%	17%	15%
Circumferential Head	75%	25%	20%
Crosshead, Top or Bottom	76%	24%	20%

Based on the above percentages, we established the $\geq$ 15% and $\geq$ 20% wire failure criteria as a conservative point for mandatory engineering evaluation. The conservative nature of the criteria is based on the following:

1. Although the above calculations are based on minimum guaranteed yield strengths, they are also based on a hypothetical reactor vessel pressure of 2.1 Reference Pressure (1775 psig). The plant protective system action which monitors reactor pressure, trips the reactor at 107.5% of the normal working pressure of 688 psig. In addition, two redundant ~~safety relief~~ valves provide overpressure protection with setpoints of ~ 812 psig and 832 psig respectively.

2. The criteria assumes uniform degradation of all tendons. This is obviously not representative of how

corrosion will proceed, and is most certainly ultra conservative based on our inspection findings. The criteria will be utilized to provide a trigger for engineering evaluations on a tendon by tendon basis.

3. The design of the prestressing system (see FSAR Appendix E Section E.14.2.5) permits complete detensioning and removal of a tendon at power operation which represents a 100% loss of wires for that tendon when applied to the prestressing system as a whole. Obviously an evaluation of an individual tendon using the proposed criteria if $\geq$ 15% and $\geq$ 20% is conservative.

4. The inspection findings to date do not reveal any specific tendency for tendon corrosion on a cluster basis. The corrosion is random in nature and there is no immediate concern for cluster failure of several tendons that would result in localized PCRV concrete tension.

C. Overall Conclusion

It is our opinion that the proposed surveillance program will provide adequate monitoring of the PCRV prestressing system to permit assessment of the PCRV integrity on a continuous basis to ensure the health and safety of the public.

Very truly yours,

Don W Warembourg
Don W. Warembourg
Manager Nuclear Engineering Division

DWW:pa

Reviewed By: M. H. Holmes

Fort St. Vrain
PCRV Tendon Surveillance Program

refer to P-85171 dated June 14, '85

actual 3-yr surveillance program began July 21, '85

CONDITIONS

The following PCRV Tendon Surveillance Program is to be implemented, effective April 22, 1985, for a period of three (3) years or until such time that effective tendon corrosion control is established, whichever occurs first. An ongoing PCRV Tendon Surveillance Program will be established thereafter, subject to NRC review and approval.

DEFINITIONS

For the purpose of this surveillance test, the following definitions are applicable:

VISUAL INSPECTION:	Removal of the tendon end cap and an in-place visual examination of the anchor assembly to include tendon wire button heads, anchor/bushing assembly, shims and bearing plates.
LIFTOFF TESTS:	A physical liftoff of the tendon to determine the load being carried by that tendon. Liftoff tests for tendons that have not previously been lifted off would include removal of the shim plates to permit visual examination and as necessary reapplication of grease to the accessible areas of the tendon. Repetitive liftoff tests on the same tendon not in a control group may not include removal of shim plates for visual examination. Liftoff tests for tendons in designated control groups will include removal of shim plates and visual examination.
NEW TENDONS:	A tendon population selected at random for visual inspection or liftoff testing over the next specified surveillance period. Selection shall be such that the total population of accessible tendons in that group shall be inspected/tested before beginning any repeat inspections/tests.

CONTROL TENDONS:	A population of tendons in each tendon group that will be selected and will remain constant for each inspection/test surveillance cycle. The criteria for selection of these tendons shall be to select those tendons which represent conditions in which corrosion is most pronounced tempered by ready accessibility. Selection must necessarily be based on inspection data available on or before April 15, 1985.
TENDON GROUP:	Four tendon population groups defined as 1. Circumferential-----310 ea 2. Top Cross Head------ 24 ea 3. Bottom Cross Head--- 24 ea 4. Longitudinal-------- 90 ea The circumferential tendon group consists of two subgroups consisting of 210 Circumferential Barrel Tendons and 100 Circumferential Head Tendons. In terms of inspection/testing, there will be no attempt to address these subgroups as separate entities in selecting inspection/test population.
NUMBER OF TENDONS:	The number of tendons to be inspected or tested shall represent a predesignated number of tendons in that group. With the exception of the longitudinal tendon group, all tendons designated for inspection or liftoff testing shall be inspected or lifted off to include both end anchor assemblies if accessible. Longitudinal tendons will be inspected and lifted off only from the top end. (Inaccessible tendons have been designated as such in PSC letter P-84523 dated December 14, 1984).
ENGINEERING EVALUATION:	A technical evaluation based on visual examinations, liftoff tests, load cells and other pertinent information to determine tendon acceptability and PCRV performance.

FAILED WIRES: Wires within a tendon bundle that have failed as identified by raised button heads in the anchor assembly or as may have been previously identified as failed by visual inspection.

For tendons which are not accessible on both ends, it shall be assumed that 20% of the number of failed wires identified on the accessible end have failed on the inaccessible end in determining the total population of failed wires.

VISUAL INSPECTION PROGRAM

Once every six (6) months visual inspection shall be performed for the following tendon population.

Tendon Groups	Total Number of Tendons	Total Number of New Tendons	Total Number of Control Tendons
Circumferential	16	13	3
Top Cross Head	2	1	1
Bottom Cross Head	8	6	2
Longitudinal	30	24	6

LIFTOFF PROGRAM

Liftoff tests shall be performed on all "new" tendons once every 18 months and on all control tendons once every six (6) months as follows:

Tendon Group	Total Number of Tendons	Total Number of New Tendons	Total Number of Control Tendons
Circumferential	16	13	3
Top Cross Head	2	1	1
Bottom Cross Head	4	3	1
Longitudinal	15	12	3

ENGINEERING EVALUATION

Engineering evaluations will be made on a continuous basis as the tendon inspection/testing program progresses with the intent of ensuring that the prestressing system is performing its design function. Specific engineering evaluations will be mandatory for any circumferential barrel tendon with $\geq$ 15% failed wires and for any tendon in any of the remaining tendon groups with $\geq$ 20% failed wires.