MPR ASSOCIATES INC.
ENGINEERS

MPR-1820 (NP)
Non-Proprietary Version
Revision 0
August 1997

# Three Mile Island Nuclear Generating Station OTSG Kinetic Expansion Inspection Criteria Analysis

Information Contained Herein is Non-Proprietary

Prepared For

GPU Nuclear Corporation
One Upper Pond Road
Parsippany, NY 07054

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# OTSG Kinetic Expansion
# Inspection Criteria Analysis

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Prepared By:

Reviewed By:

Approved By:

**QUALITY ASSURANCE DOCUMENT**

This document has been prepared, reviewed, and approved in accordance with the Quality Assurance requirements of 10CFR50 Appendix B, as specified in the MPR Quality Assurance Manual.

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Section 1

# INTRODUCTION

## 1.1 PURPOSE

The purpose of this report is to document the evaluations performed to develop proposed tube inspection acceptance criteria for the upper tubesheet kinetic expansion region of the Once-Through Steam Generators (OTSGs) in the Three Mile Island Unit 1 (TMI-1) Nuclear Generating Station.

## 1.2 SCOPE

The inspection acceptance criteria analysis was performed consistent with the requirements of the GPUN Analysis Specification (Reference 1). As discussed in Paragraph 2.1.1 of the specification, a finite-element structural model of the kinetically expanded tube-to-tube sheet joint was developed. Analyses were performed with the model to confirm that the model can capture the following key effects for the joint:

- Residual contact pressure due to kinetic expansion.
- Influence of the "edge" of the expansion in locally reducing contact pressure.
- Reduction of contact pressure from Poisson contraction due to the axial tube load.
- Tightening due to applied pressure.
- Tightening due to differential thermal expansion between the tube and tubesheet.
- Change in contact pressure due to tubesheet bowing.

Kinetic expansion inspection acceptance criteria were developed for the center, mid-radius and outermost tube bundle locations. For each of these locations, inspection acceptance criteria were developed by the following approach:

- Benchmarking the tube/tubesheet finite-element model calculation results against available experimental data for a defect-free tube.

- Introducing a series of circumferential and axial defects into the tube and determining the effect on structural integrity and the resistance of the tube to axial slip.

- Developing criteria to disposition defects with regard to their extent and location.

- Developing criteria for combining multiple defects into one effective size or for treating them separately.

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Section 2

## SUMMARY

Acceptance criteria were developed for use in the inspections of the upper tubesheet kinetic-expansion region of the TMI-1 OTSGs. The acceptance criteria were developed for axial, circumferential and volumetric defects using finite-element and hand-calculation models. Specifically:

- An elastic-plastic finite-element model was developed for the kinetically-expanded tube-to-tubesheet joint. The finite-element model predictions were benchmarked against tube pullout data from the qualification tests which had previously been performed for the kinetic-expansion joint. The model was then used to determine the allowable extent of axial defects in the expansion region.

- Existing hand-calculation model results from GPUN Report No. TDR-421 were used to determine the allowable extent of circumferential defects in the kinetic-expansion region.

Inspection criteria were developed for OTSG tubes at the center, mid-radius and peripheral tube bundle locations. The criteria apply to the fully-expanded region from 0.5-inch to 6 inches above the bottom of the kinetic-expansion joint. For the transition region at the bottom 0.5-inch of the joint, the tube and tubesheet are not in contact and therefore, the flaw acceptance criteria for the tube region between the upper and lower tubesheets from GPUN Report No. TDR-421 are appropriate.

The inspection acceptance criteria developed by this task are provided in Table 3-5 in Section 3 of this report.

Section 3

# DISCUSSION

## 3.1 DESIGN BASIS LOADS

The design basis loads for the OTSG tube-to-tubesheet joint are developed in BAW-10416 (Reference 2). This report provides loads for normal operation and accident conditions from both mechanical (pressure-induced) and thermal (differential expansion-induced) load sources. Reference 2 shows that the largest tube loads occur for accident conditions:

- For a peripheral tube, the maximum tube axial load is 3140 lbs for a main steam line break (MSLB).
- For a center tube, the maximum tube axial load is 1585 lbs for a loss-of-coolant accident (LOCA). For a MSLB, the tube axial load is 1408 lbs.

Note that both the mechanical and thermal loads are conservatively considered to be primary loads in this evaluation although ASME Section III Code guidance suggests that the thermal load could be considered a secondary load.

Note that the loads in Reference 2 are determined from the tube elongations and strains by assuming the tubes are loaded in their elastic range where load is proportional to displacement. The validity of this approach for the loads stated above was evaluated. This evaluation showed that for the MSLB tube elongation case, the minimum yield strength tube (41 ksi per Reference 3) located at the periphery of the tube bundle is loaded beyond its elastic range. For the MSLB tube strain of 0.16 percent, the load for this 41 ksi yield strength tube is calculated to be 2400 lbs, which is less than the 3140 lb load calculated in Reference 2 on a fully-elastic basis.

For a tube at the mid-radius location, the design basis tube load is calculated to be 2380 lbs based on tube deflection information provided in Reference 2.

## 3.2 TUBE PULLOUT LOAD TESTS

Pullout load test data for a kinetically-expanded OTSG tube-to-tubesheet joint is provided in Reference 3. Data are provided for both "prequalification" and "qualification" tests.

Specifically:

- Prequalification tests were performed to determine the expansion length required to provide adequate pullout resistance. Tests were performed with tubes with various yield strengths from approximately 44 to 60 ksi. As indicated in Reference 3, the tubes had a wall thickness of 0.0385-inch which is greater than the minimum wall thickness of 0.034-inch. Expansion lengths of 4, 6 and 8 inches were tested, and 6 inches was selected as the length for the OTSG kinetic-expansion process.

- Qualification tests were performed with the nominal expansion length of 6-inches and with tubes with both low and high yield strengths. As in the prequalification tests, the tube wall thickness was 0.0385 inches.

The pullout load was identified as the load which provides an initial tube slip at the upper end of the expanded tube as detected by a dial indicator.

## 3.3 TUBE-TO-TUBESHEET JOINT ANALYTICAL MODEL

A finite-element analytical model was developed for the OTSG tube-to-tubesheet kinetically-expanded joint. The model has the following features:

- Tube wall thickness and yield strength are selected as appropriate for the analysis case.

- Transition region between the expanded and unexpanded tube sections is specified based on information provided by GPUN from the qualification/prequalification testing.

- Tube behavior in both the elastic and plastic regions are modeled using tube stress versus strain data provided by GPUN.

- Radial interference between the tube and tubesheet can be varied. Also, the coefficient of friction between the tube and tubesheet can be varied.

- The effect of tubesheet bowing (vertical displacement) can be represented by imposing a displacement/strain distribution at the tubesheet boundary.

Table 3-1 identifies how the analytical model addresses the various tube-to-tubesheet joint effects/features which are listed in the GPUN specification (Reference 1) for the analysis task.

## 3.4 PREQUALIFICATION TEST DATA COMPARISON

The tube-to-tubesheet analytical model was benchmarked against the pullout test results obtained in the kinetic expansion qualification tests as documented in Reference 3. The results of the work are shown in Figures 3-1 through 3-8 and in Table 3-3. In addition, Table 3-2 identifies parameter values not indicated directly in the figures.

- Figures 3-1 through 3-4 show the calculated contact pressure distribution between the tube and tubesheet along the expansion region for 4-, 6-, and 8-inch expansion lengths. Results are shown for the case with no axial load and for the load that results in tube slip. Note that the contact pressure is zero over the transition region at the bottom of the expansion. Also, because of the end effects, the contact pressure begins to drop off about 1/4-inch before either end of the expansion region.

- Figures 3-5 through 3-7 show the calculated load history for the applied load and the friction restraint force. Note that as the load is applied and the tube is elongated, the friction force is reduced as a result of the reduction in the tube-to-tubesheet contact pressure. Results are shown for the 4-, 6- and 8-inch expansion length cases.

- Figure 3-8 shows the calculated pullout load versus the expansion length. The figure shows the results from the analytical model and the results obtained in the prequalification tests in Reference 3. The test data points plotted in Figure 3-8 are the lowest measured pullout loads at the 4-, 6- and 8-inch expansion lengths.

- Table 3-3 compares the calculated pullout loads with the actual range of measured pullout loads from the prequalification tests.

Based on the comparison between the analytical results and the prequalification test data, it was concluded that the radial interference of 0.0003-inch and coefficient of friction of 0.2 which were selected for the analytical model provide a reasonable and conservative agreement with the qualification test data. Accordingly, these parameters were selected for the OTSG tube-to-tubesheet joint evaluation calculations.

### 3.5 OTSG PULLOUT LOAD CALCULATIONS

Using the radial interference and coefficient of friction values selected from the prequalification test benchmark work, pullout loads were calculated for the OTSG tubes. For these calculations, a tube minimum wall thickness of 0.034 inches and a minimum yield strength of 41 ksi (per Reference 3) were used. This is the correct and conservative approach since a tube with a greater wall thickness and yield strength will clearly have greater strength and resistance to pullout.

All analyses for the OTSG tubes were performed for the tube and tube-to-tubesheet expansion joint at room temperature. This is considered to be a conservative approach in the determination of the tube pullout load for the following reasons:

- As discussed in Reference 3, there are two effects of temperature on the tube slip load. The first is the "thermal tightening" effect for the joint which results from the different coefficients of thermal expansion for the Inconel OTSG tubing and the alloy steel tubesheet materials. (Inconel has a higher coefficient of thermal expansion than alloy steel.) The second effect is the reduction of yield strength for the Inconel tube temperature with increased temperature. The "thermal tightening" effect results in an increase in the tube slip load while the yield strength effect results in a decrease in the tube slip load. For a tube with material in the elastic range, it is expected that the increase in slip load due to thermal tightening will outweigh the reduction in slip load due to lower yield strength. For a tube with material in the plastic range, this will not be the case.

- In the joint qualification tests discussed in Reference 3, the tube strains measured at the initiation of slippage for the Block G test at 330°F generally exceeded the strains for the qualification blocks which were tested at room temperature. Since the tube slip load is a strain-induced load, this result indicates that it is conservative to analyze the joint at room temperature.

- For tubes with a pullout load which exceeds the tube yield (i.e., the load which results in tube stresses at or beyond the tube yield stress), such as the peripheral OTSG tubes, both the applied load and the slip load decrease as the tube yield strength decreases. As a result, tube slip would occur at about the same applied strain independent of tube yield strength. Note that the qualification block test results discussed above indicate that the pullout strain actually increases with test temperature.

- For tubes with a pullout load which is less than the tube yield load, such as the center or mid-radius tubes, the applied load would decrease with temperature by a small amount because of the small decrease in the elastic modulus. Also, the interface pressure would increase in these tubes due to the "thermal tightening" effect since the tube-to-tubesheet interface strain for these tubes is less than the yield strain (due to the tubesheet bow effect). Therefore, the elevated temperature pullout strain would increase compared with the room temperature strain.

Results are provided in Figures 3-9 through 3-20 and Table 3-4. Note that Table 3-2 identifies parameter values not specifically identified in the figures.

- Figures 3-9 and 3-10 show the calculated contact pressure distribution for the 6-inch expansion length for tube internal pressures of 0 psi and 1000 psi, respectively.

- Figure 3-11 shows the calculated pullout load versus the expansion length. Also shown is the design load of 2400 lbs for the minimum wall thickness, minimum yield strength OTSG tube. Note that this load is based on the tube axial strain of 0.16 percent as calculated in Reference 2. For the 2500 psi tube internal pressure case, the required expansion length to provide the required pullout load of 2400 lbs is determined to be 1.6 inches. Therefore, the allowable flaw length is 4.4 inches.

The results described above are relevant for a peripheral tube in the OTSG which experiences the largest axial force. Additional evaluations were performed for center and mid-radius OTSG tubes which experience a lower axial force but are affected by the axial deflection (bowing) of the tubesheet due to the primary-to-secondary differential pressure and the applied tube loads. Specifically, the tubesheet bowing is assumed to affect the pullout load as follows:

- The bowing produces a bending moment in the tubesheet which is a maximum at the center of the tubesheet.
- The resulting bending stress distribution in the tubesheet causes an expansion (stretching) of the tubesheet in the planes below the midplane (with positive bending stresses) and a contraction in the planes above the midplane (with negative bending stresses).
- The expansion/contraction results in an increase in the tubesheet hole diameter below the midplane and reduction above the midplane.
- The increase in hole diameter causes a reduction or elimination in the tube-to-tubesheet interference and contact pressure below the midplane and an increase above.

The bending stress/strain was calculated assuming the tubesheet deflects as a uniformly-loaded circular plate which is simply-supported at its connection to the OTSG shell. The calculated tubesheet strain distribution was applied at the boundary of the tube-to-tubesheet finite element model and the contact pressure distribution and tube pullout load calculated. The calculated pressure distributions are shown in Figures 3-13 and 3-14 with tube internal pressures of zero and 2500 psi. Two distributions are shown: (1) with only the tubesheet bending strain applied, and (2) with both the bending strain and the axial load applied. The pullout load for the center OTSG tube was calculated to be 2009 lbs (with a 0 psi internal pressure) and 2999 lbs (with a 2500 psi internal pressure) compared with the applied axial load of 1408 lbs, for a center tube as shown in Table 3-4. Note from Figures 3-13 and 3-14 that the contact pressure only exists from 3 to 6 inches above the bottom of the expansion region for the case with the axial load applied.

### 3.6 DEFECT EVALUATIONS

Defect evaluations were performed for both axial and circumferential defects in the 6-inch expansion region. These calculations were performed for a minimum wall thickness (0.034-inch) and minimum yield strength (41 ksi) OTSG tube.

### 3.6.1 Axial Defects

**Peripheral Tubes**

The tube-to-tubesheet finite element model was used to calculate the contact pressure distribution and tube pullout load for the case of a 6-inch long expansion with an axial defect in the middle 2 inches of the expansion region. The resulting contact pressure distribution is shown in Figure 3-12. For this case, the internal pressure in the tube is assumed to be 0 psi. Note that the contact pressure is zero in the defected region as expected since the effect of the axial defect is to relieve the radial interference between the tube and tubesheet. The tube pullout load for this case is 2509 lbs compared with the axial applied load of 2400 lbs. Accordingly, this 2-inch axial defect length is determined to be acceptable with an acceptable margin to resist the design axial load. Also, the following should be noted:

- The pullout load of 2509 lbs is consistent with the pullout load of 2516 lbs given in Figure 3-11 for the case of a 2-inch defect located at the top of the expansion region.
- The tube internal pressure was assumed to be 0 psi for this case. As shown in Figure 3-11, with internal pressures of 1000 and 2500 psi, the contact pressure and pullout load would be greater and would provide a greater margin to resist the design axial load.
- No growth of the axial defect is considered. This is reasonable since the expansion region of the OTSG tube is in a compressive stress state in the hoop direction. Any axial defects which are present in this region were most likely present prior to the performance of the kinetic-expansion repair.
- For the peripheral tubes, there is no tubesheet bow effect. Therefore, the results are applicable for both the 17-inch and 22-inch expansion cases.

**Center and Mid-Radius Tubes**

For the center and mid-radius tubes, calculations were performed for both the 17-inch and 22-inch expansion length geometries. Note for the 17-inch expansion case, the expansion region was assumed to extend from 11 inches to 17 inches below the top face of the upper tubesheet. For the 22-inch expansion case, the expansion region was assumed to extend from 16 inches to 22 inches below the top face of the tubesheet. Results are as follows:

- Center Tube With 17-inch Expansion - Figure 3-15 shows the calculated tube pullout load for various flaw sizes from 1 to 4 inches. It shows that the allowable flaw size is 2.8 inches based on the applied load of 1408 lbs.

- Mid-Radius Tube With 17-inch Expansion - Figure 3-16 shows the calculated tube pullout load for various flaw sizes from 1 to 5 inches. It shows that the allowable flaw size is 3.2 inches based on the applied load of 2380 lbs.

- Center Tube With 22-inch Expansion - Figure 3-17 shows the tube-to-tubesheet contact pressure distribution for cases with no axial load and with the tube slip load applied. The pullout load was calculated to be 225 lbs which is less than the applied load of 1408 lbs.

- Mid-Radius Tube With 22-inch Expansion - Figure 3-18 shows the tube-to-tubesheet contact pressure distribution and Figure 3-19 shows the calculated pullout load for various flaw sizes from zero to 5 inches. These figures show that the pullout load of 2132 lbs (with no flaw) is less than the applied load of 2380 lbs.

**Acceptable Axial Defects**

Figure 3-20 provides a summary of the above analysis results. It shows the allowable flaw size for the center, mid-radius (i.e., at 0.7 times the tube bundle outside radius) and peripheral tubes for the 17-inch and 22-inch expansions. Note that this figure can be used as follows for tube radial positions not specifically considered in the analyses:

- The results for the center tube could be used for the tubes between the center and mid-radius locations and the results for the mid-radius tube could be used for the tubes between the mid-radius and peripheral locations, or,

- The allowable flaw size for any tube location could be determined by interpolation using the results for the center, mid-radius and peripheral locations. For example, a "straight-line" interpolation following this approach is illustrated in Figure 3-20.

### 3.6.2 Circumferential Defects

Evaluation of circumferential defects for the OTSG tube in the tubesheet region was performed in Section VIII-B of Reference 4. Based on tube parting considerations, this evaluation determined that a through-wall circumferential defect is permitted to be 130 degrees in extent (36 percent of the tube circumference is permitted to be flawed) and 230 degrees is required to be intact. This assumes that the defect is at the bottom of the expansion region where the axial force is at its maximum. At higher elevations within the expansion region, part of the axial force is transmitted to the tubesheet by the friction restraining force, thereby reducing the axial force in the tube wall. As a result, the allowable circumferential defect in the higher portions of the expansion region would be greater than 130 degrees. Also, note that in the expansion region, the tube is in a compressive stress state so that no growth of a circumferential defect would be expected.

## 3.7 INSPECTION ACCEPTANCE CRITERIA

Acceptance criteria for the OTSG tube kinetic-expansion region were developed based on the following results from the OTSG tube evaluations discussed in Section 3.6 above:

- For the peripheral tubes (where there is no tubesheet bow effect), the allowable length of a single axial defect in the expansion region is 4.4 inches. Since there is an "edge effect" in the undefected expansion region immediately adjacent to the defect which reduces the contact pressure for an additional length of approximately 1/4-inch, the allowable combined length for multiple axial defects (with additional "edge effects") would be less than 4.4 inches. Also, there is an "edge" effect from each circumferential defect. Note that the 1/4-inch length is equivalent to approximately three times the "decay length" of 0.08-inch for the OTSG tubes (decay length = $0.78\,(Rt)^{1/2}$).

- For the center tubes (where the tubesheet bow effect is most significant), the allowable combined defect length is 2.8 inches for the expansion region from 11 to 17 inches below the top face of the upper tubesheet.

- For the mid-radius tubes (0.7 times the tube bundle outer radius), the allowable defect length is 3.2 inches for the expansion region from 11 to 17 inches below the top face of the upper tubesheet.

- For the center and mid-radius tubes, the required "undefected" length must be located in the expansion region from 11 to 17 inches below the top face of the upper tubesheet.

- For circumferential defects in center, mid-radius or peripheral tubes, the allowable defect length is 130 degrees or 0.64 inches. The flaw combination criteria are based on providing the required shear path between defect elevations to transfer the total load. It is conservative to include total load for shear transfer since membrane transfer also occurs. For multiple circumferential defects in the expansion region, the combined length of the defects would be 0.64 inches if they are closely spaced in the axial direction such that axial load redistribution between the defect planes could not occur. A reasonable separation distance is judged to be 1-inch considering the tube material required to transmit the axial load between the defect planes (note that the required intact tube length is 1.13 inches at each of the circumferential defects and that the applied axial load would be reacted as a vertical shear load between the defect planes). If the circumferential defects are separated by a distance greater than 1-inch, each defect could be 0.64 inches in length.

  Table 3-5 provides inspection acceptance criteria for the center, peripheral and mid-radius tube regions for axial and circumferential defects. For volumetric defects, the criteria for axial defects should be used for the axial length of the volumetric defect and the criteria for circumferential defects used for the circumferential length of the defect.

Table 3-1

**APPROACH TO CONSIDERATION OF TUBE-TO-TUBESHEET JOINT EFFECTS**

| Effect | Approach |
|---|---|
| Residual contact pressure due to kinetic expansion process. | Calculated directly by finite-element tube-to-tubesheet model. |
| Influence of the "edge" of the expansion in locally reducing contact pressure. | Calculated directly by finite-element tube-to-tubesheet model. |
| Reduction of contact pressure from Poisson contraction due to axial tube load. | Calculated directly by finite-element tube-to-tubesheet model. |
| Tightening due to applied tube in internal pressure. | Calculated directly by finite-element tube-to-tubesheet model. |
| Tightening due to thermal expansion between the tube and tubesheet. | Not considered in model/analysis. Since this effect increases the tube pullout load, this approach is conservative. |
| Change in contact pressure due to tubesheet bowing. | Calculated by applying a bending strain distribution to the tubesheet boundary in the model. The effect is greatest for a center tube where bowing is maximum. There is no effect for a peripheral tube. |

Table 3-2

**PARAMETER VALUES FOR FIGURES**

| Figure | Tube Yield Strength (ksi) | Tube Wall Thickness (in) | Coefficient of Friction | Tube-Tubesheet Radial Interference (in) | Tube Internal Pressure (psi) | Tubesheet Bowing |
|---|---|---|---|---|---|---|
| 3-1 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-2 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-3 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-4 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-5 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-6 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-7 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-8 | 57 | .0385 | 0.2 | 0.0003 | 0 | No |
| 3-9 | 41 | .034 | 0.2 | 0.0003 | 0 | No |
| 3-10 | 41 | .034 | 0.2 | 0.0003 | 1000 | No |
| 3-11 | 41 | .034 | 0.2 | 0.0003 | 0, 1000, 2500 | No |
| 3-12 | 41 | .034 | 0.2 | 0.0003 | 0 | No |
| 3-13 | 41 | .034 | 0.2 | 0.0003 | 0 | Yes |
| 3-14 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-15 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-16 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-17 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-18 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-19 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-20 | 41 | .034 | 0.2 | 0.0003 | 2500 | Yes |
| 3-21 | 50 | -- | -- | -- | -- | -- |

Table 3-3

**COMPARISON OF CALCULATED TUBE PULLOUT LOADS WITH PREQUALIFICATION TEST DATA**

| Expansion Length (in) | Pullout Load (lbs) | |
|---|---|---|
| | Calculated by Model | Prequalication Tests |
| 2 | 1750 | No test results |
| 4 | 3260 | 3100-4000 |
| 6 | 4030 | 5000-5600 |
| 8 | 4110 | 5000-5600 |

Notes:

(1) Prequalification test data from Figures 2-5 and 2-6 of Reference 3.

(2) All calculations and tests for tube with 57 ksi yield strength.

Table 3-4

## APPLIED LOAD AND PULLOUT LOAD FOR UNDEFECTED OTSG CENTER , MID-RADIUS AND PERIPHERAL TUBES

| Parameter | Tube Location | | | | |
|---|---|---|---|---|---|
| | Center | | Mid-Radius | | Peripheral |
| | 17-inch Exp. | 22-inch Exp. | 17-inch Exp. | 22-inch Exp. | 17 and 22-inch Exp. |
| Applied Axial Load[(1)] | 1408 | 1408 | 2380 | 2380 | 2400 |
| Pullout Load[(3)] | 2999[(2), (4)] | 225[(2), (4)] | ~3016[(2), (4)] | 2132[(2), (4)] | 3047[(4)] |

(1) For tube and cold yield stress of 41 ksi and wall thickness of 0.034-inch.

(2) Includes tubesheet bowing strain.

(3) For 6-inch expansion length.

(4) With tube internal pressure of 2500 psi.

Table 3-5

## INSPECTION ACCEPTANCE CRITERIA FOR OTSG KINETIC-EXPANSION REGION

| Tube Bundle Location | Defect Type[3][4] | Allowable Defect Length[4][5] |
|---|---|---|
| Periphery [1] | Axial | For single tube defects, allowable defect length is 4.4 inches. For multiple defects, 1/4- inch should be added to the length of each defect, except the first defect, and the combined defect length should be 4.4 inches or less. Also, for each circumferential defect, a defect length of 1/4-inch should be added.<br>Example: Three axial defects are found, with one defect 1-inch long and two defects each 1/2-inch long. The effective length of the 1/2-inch defects is: 1/2-inch + 1/4- inch = 3/4-inch. The combined length of the three defects is: 1-inch + 3/4-inch + 3/4-inch = 2 1/2- inch. This total length is within the allowable length of 4.4 inches. |
| | Circumferential | For single defects, the allowable defect length is 130 degrees or 0.64 inches. For multiple defects:<br>• If separated axially by less than 1-inch, their length should be combined, and the total should be less than 0.64-inch.<br>• If separated axially by more than 1-inch, the individual defects should each be less than 0.64 inch in extent. |
| Mid-Radius[2], [6] | Axial | The combined allowable defect length is 3.2 inches. |
| | Circumferential | Same as for the tube bundle periphery, as specified above. |
| Center[2], [6] | Axial | The combined allowable defect length is 2.8 inches. |
| | Circumferential | Same as for the tube bundle periphery, as specified above. |

Notes:

(1) These criteria are applicable for tubes with an expansion region between 11 and 17 inches below the top face surface of the upper tubesheet and for tubes with an expansion region between 16 and 22 inches below the top face.

(2) These criteria are only applicable for the expansion region between 11 and 17 inches below the upper tubesheet top face.

(3) For volumetric defects, the criteria for axial defects should be used for the axial length of the defect and the criteria for circumferential defects used for the circumferential length of the defect.

(4) These criteria are only applicable for the fully-expanded region from 0.5-inch to 6 inches above the bottom of the kinetic-expansion joint.

(5) The measured defect length should include consideration of the inspection device accuracy/uncertainty.

(6) For the center and mid-radius tubes, the required "undefected" length must be in the expansion region from 11 and 17 inches below the top face of the upper tubesheet.

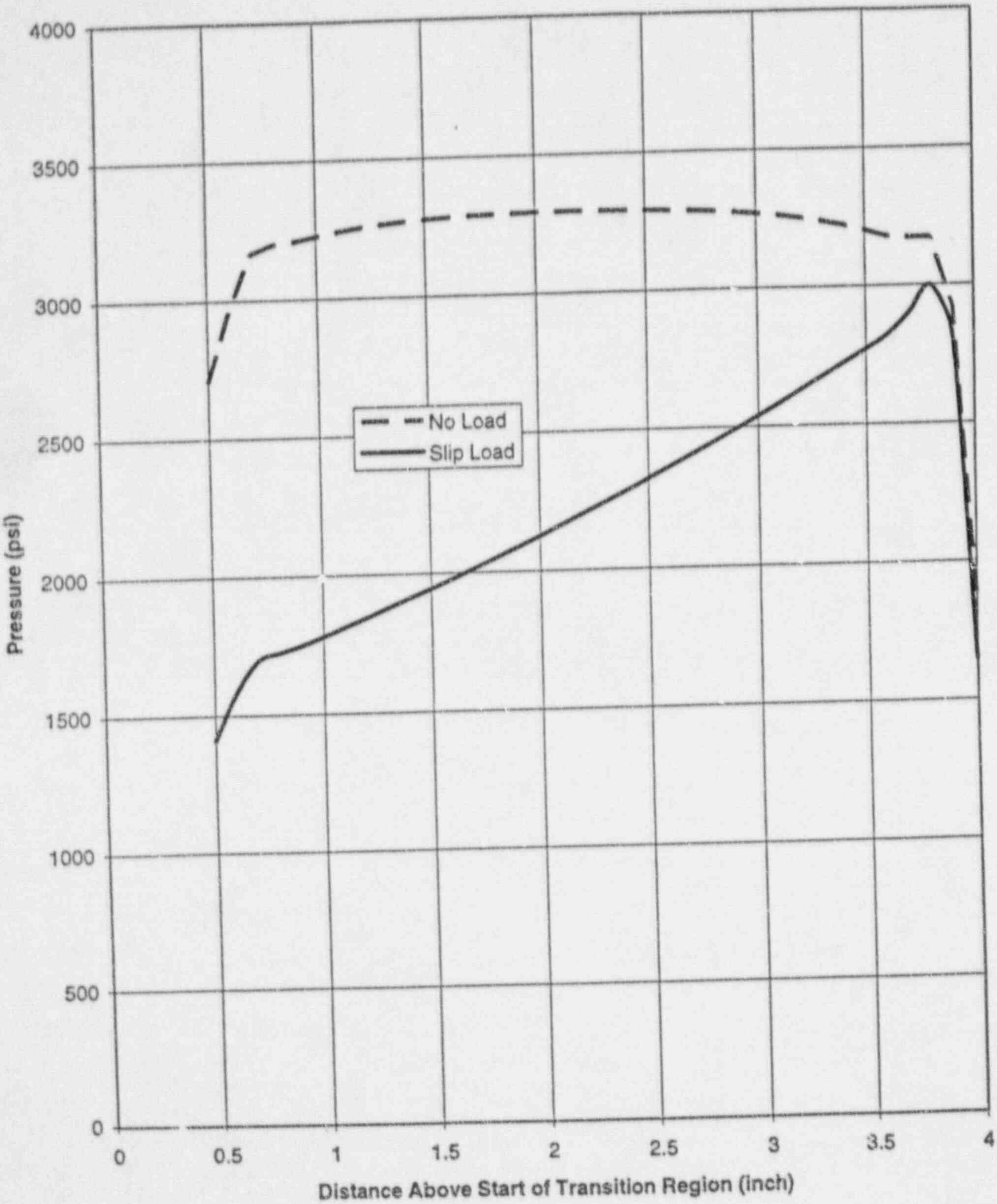



Figure 3-1. Contact Pressure Distribution for 4-inch Long Expansion
(Prequalification Tests)

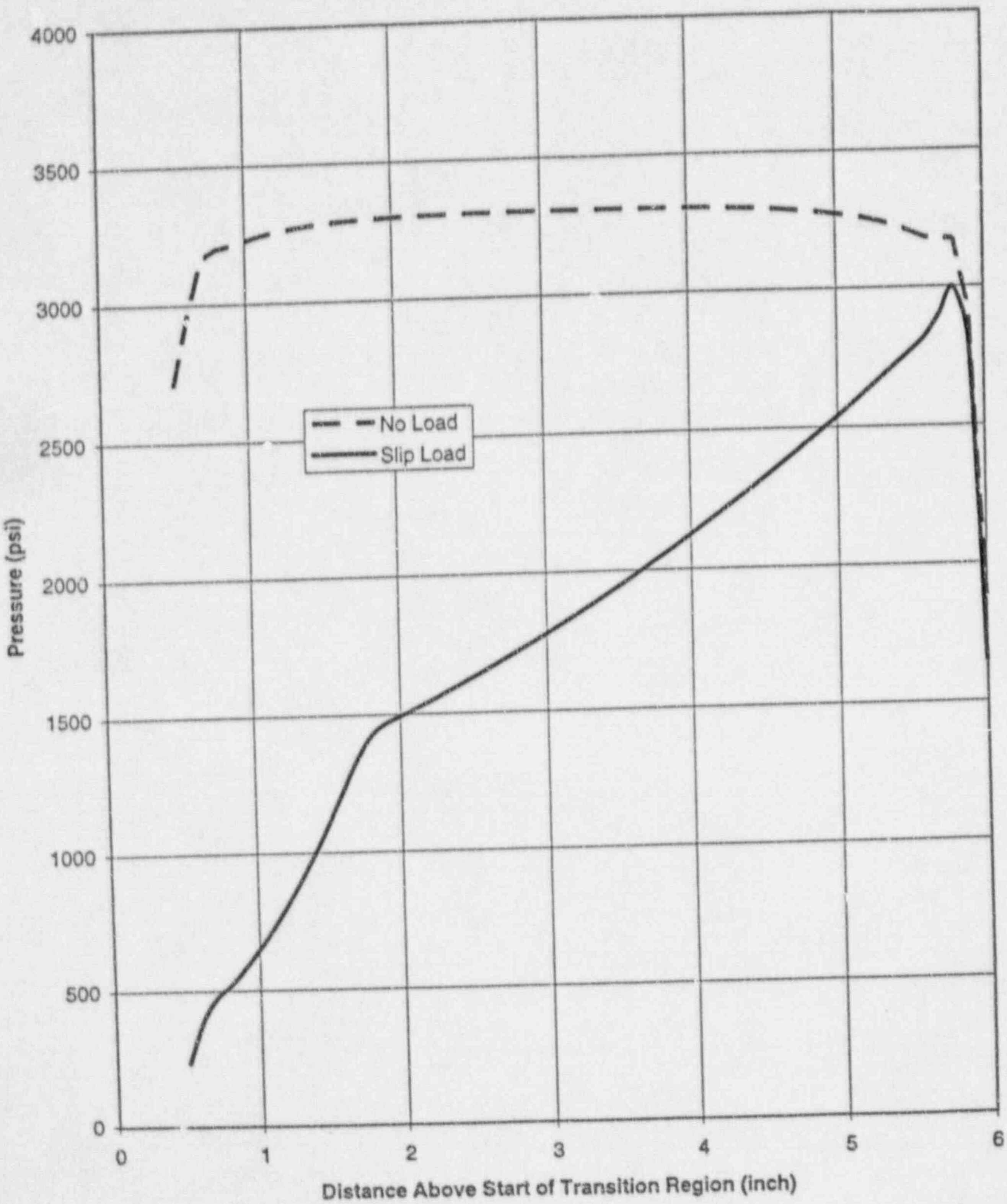



Figure 3-2. Contact Pressure Distribution for 6-inch Long Expansion
(Prequalification Tests)

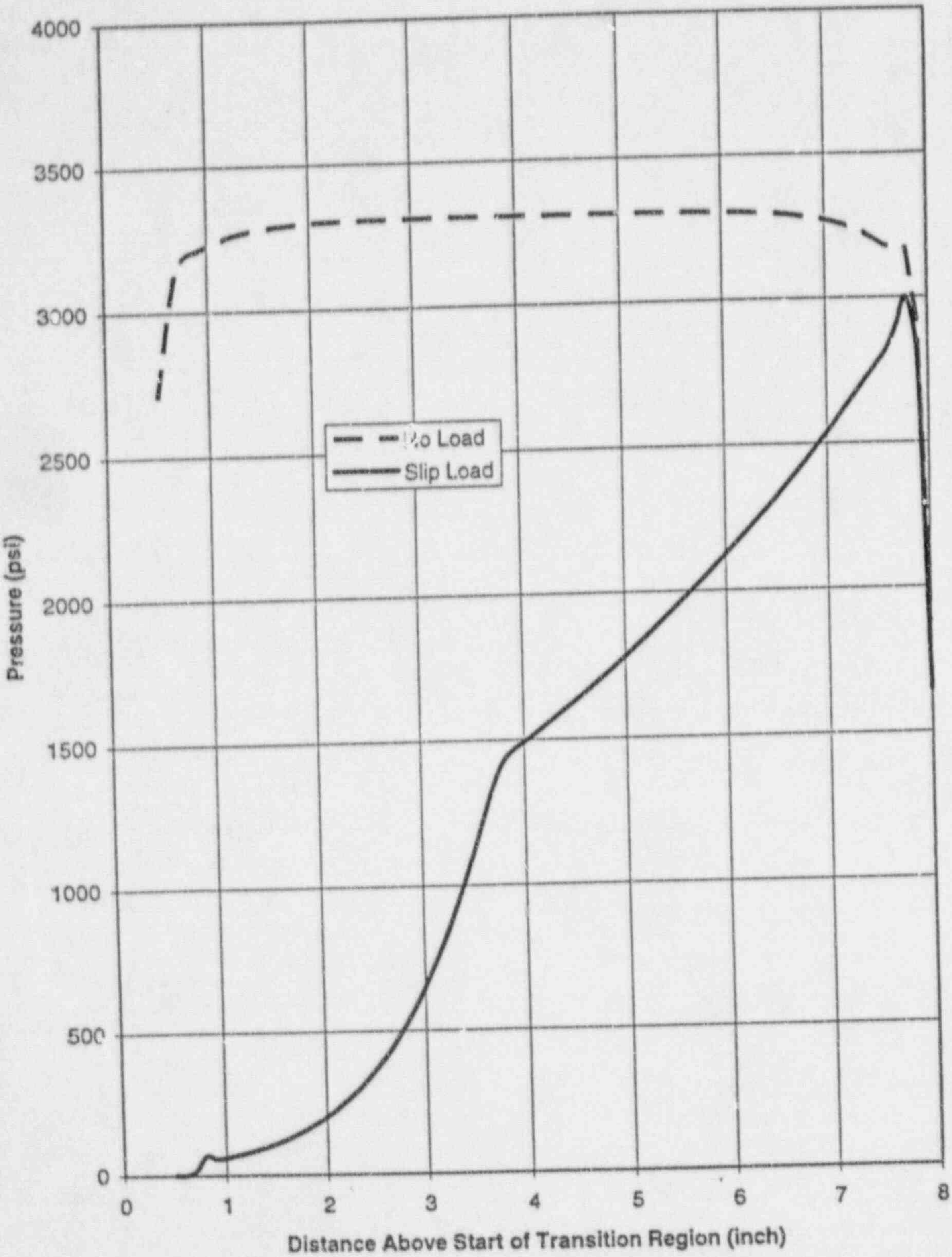



Figure 3-3. Contact Pressure Distribution for 8-inch Long Expansion (Prequalification Tests)

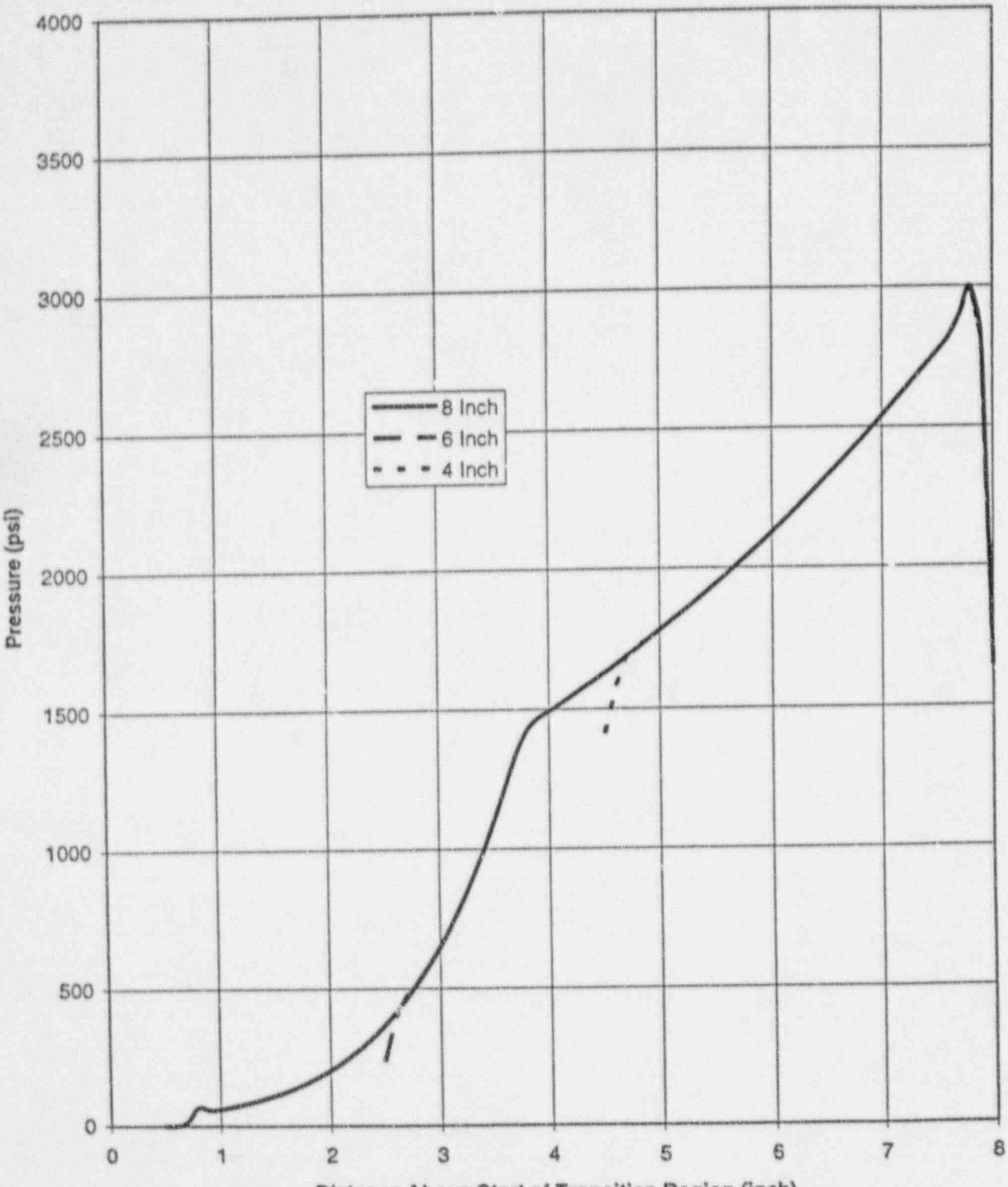



Figure 3-4. Contact Pressure Distribution for 4-, 6- and 8-inch Long Expansion (Prequalification Tests)

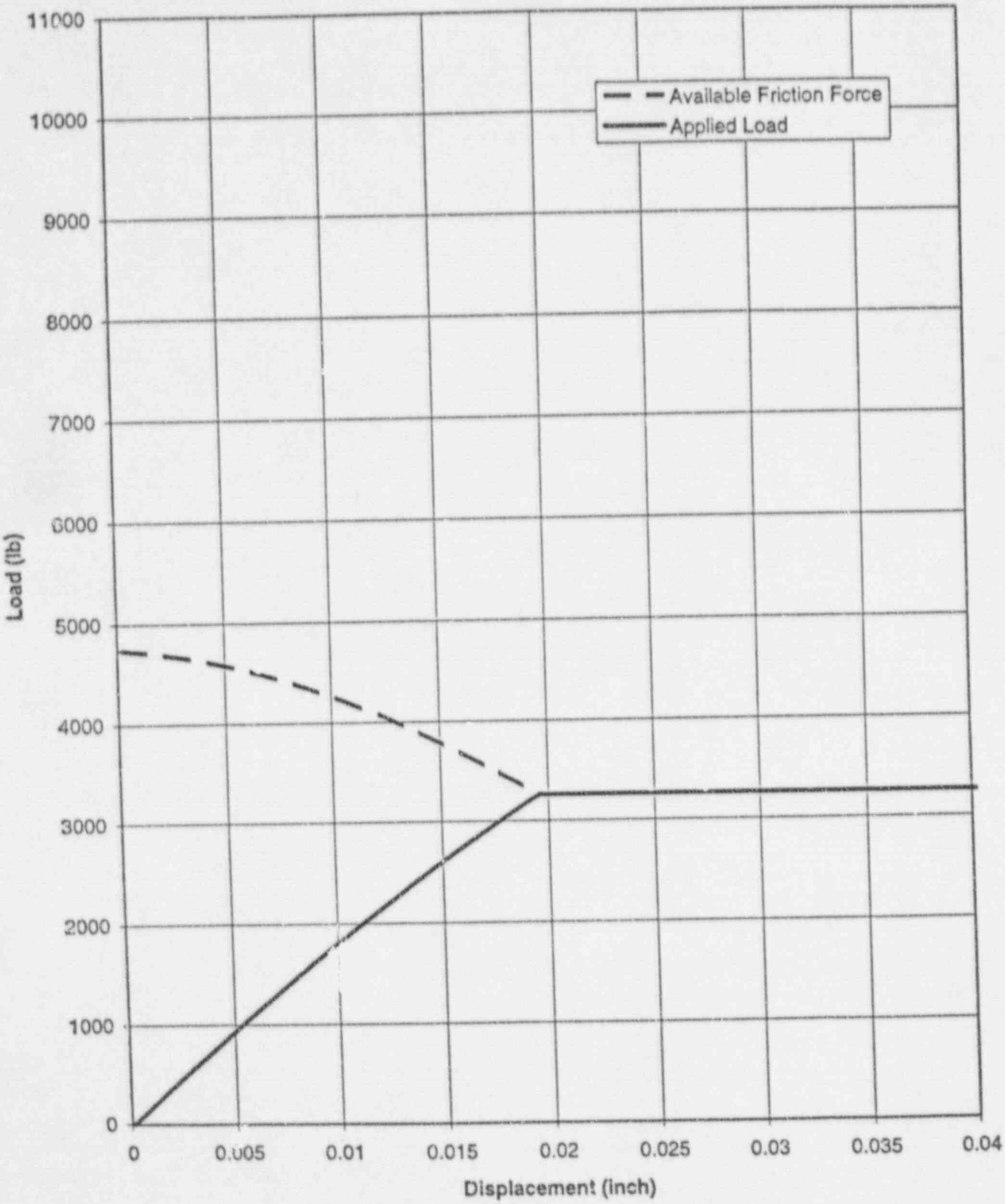



Figure 3-5. Load History for Friction Force and Applied Load for 4-inch Long Expansion (Prequalification Tests)

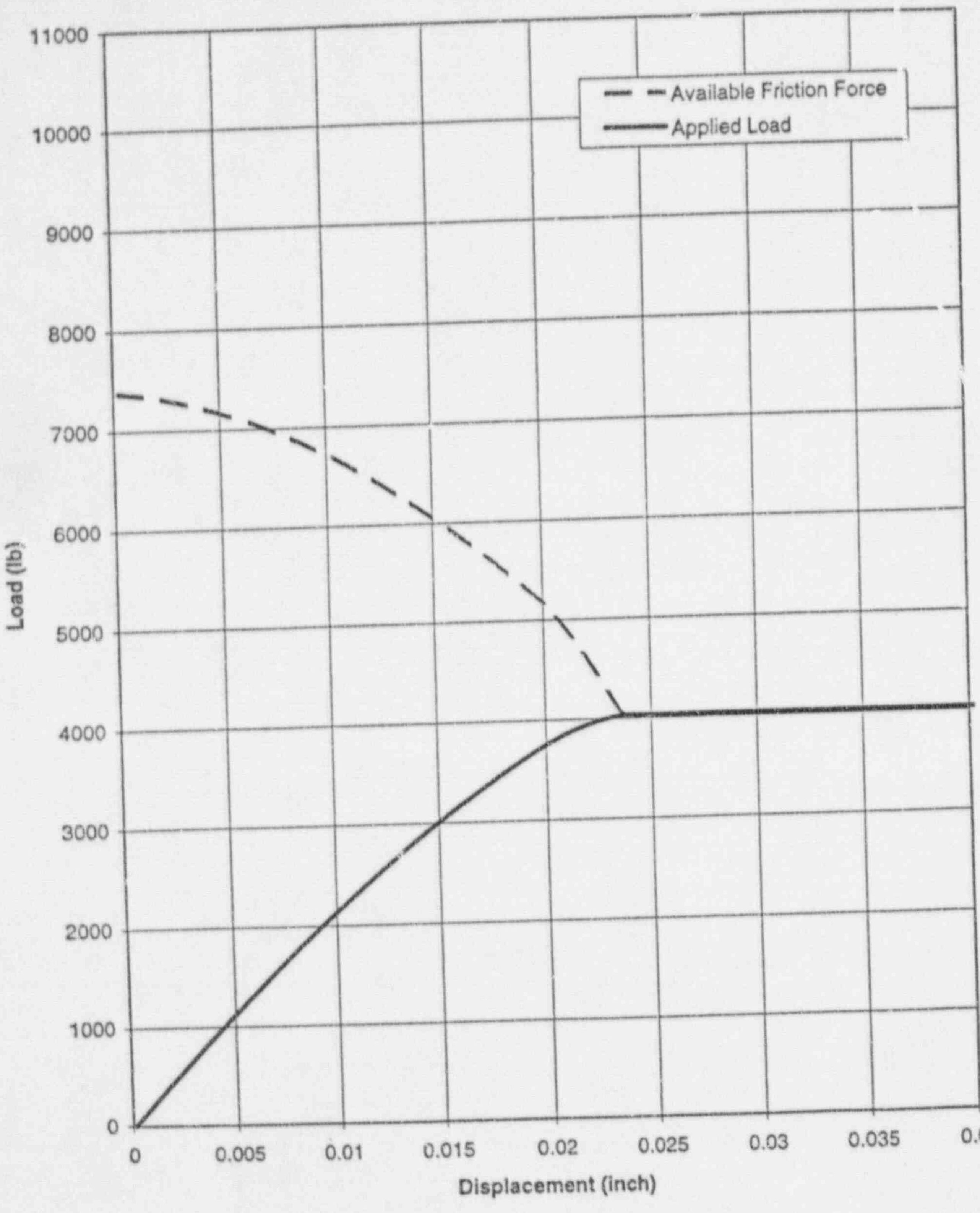



Figure 3-6. Load History for Friction Force and Applied Load for 6-inch Long Expansion (Prequalification Tests)

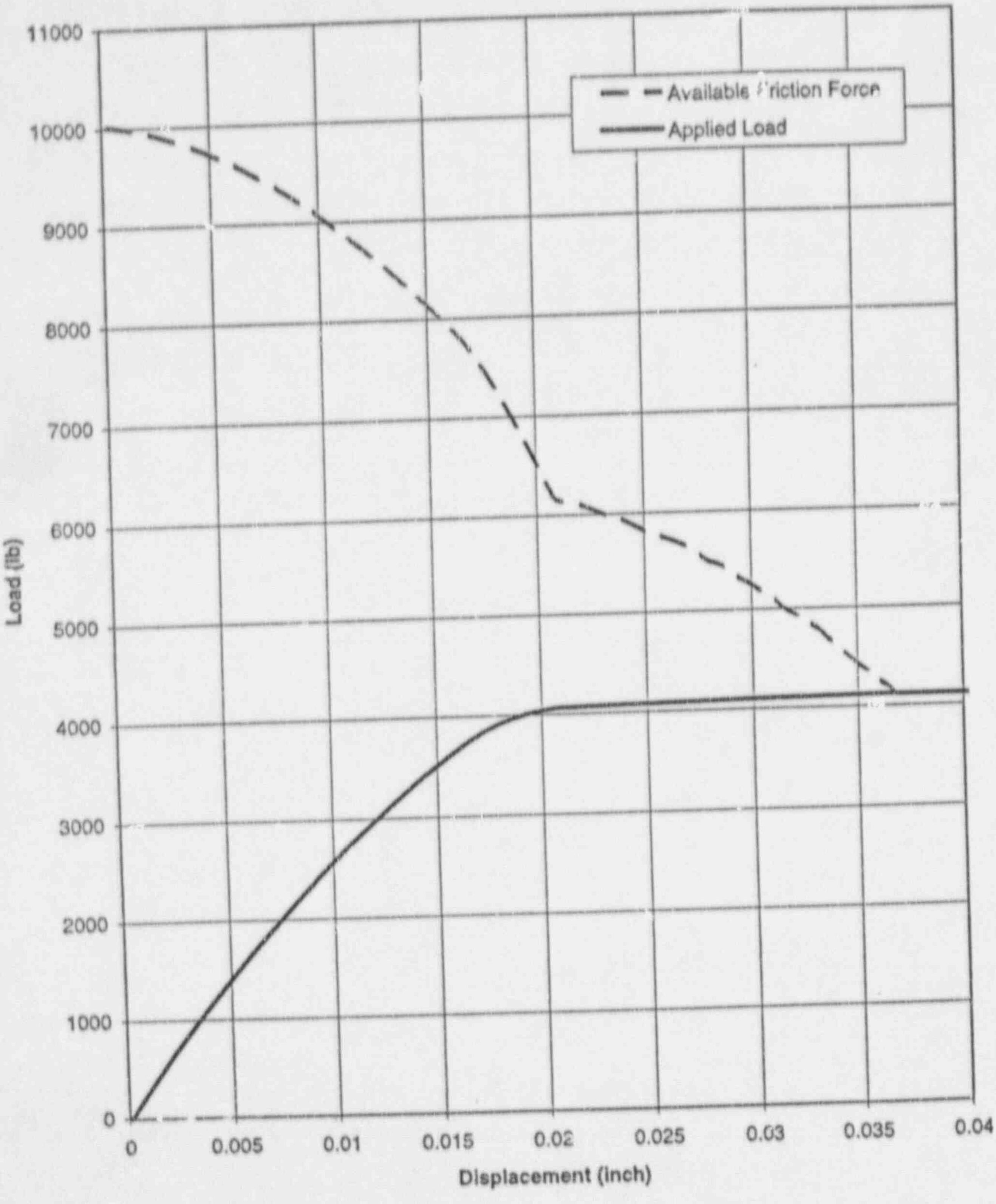



Figure 3-7. Load History for Friction Force and Applied Load for 8-inch Long Expansion (Prequalification Tests)

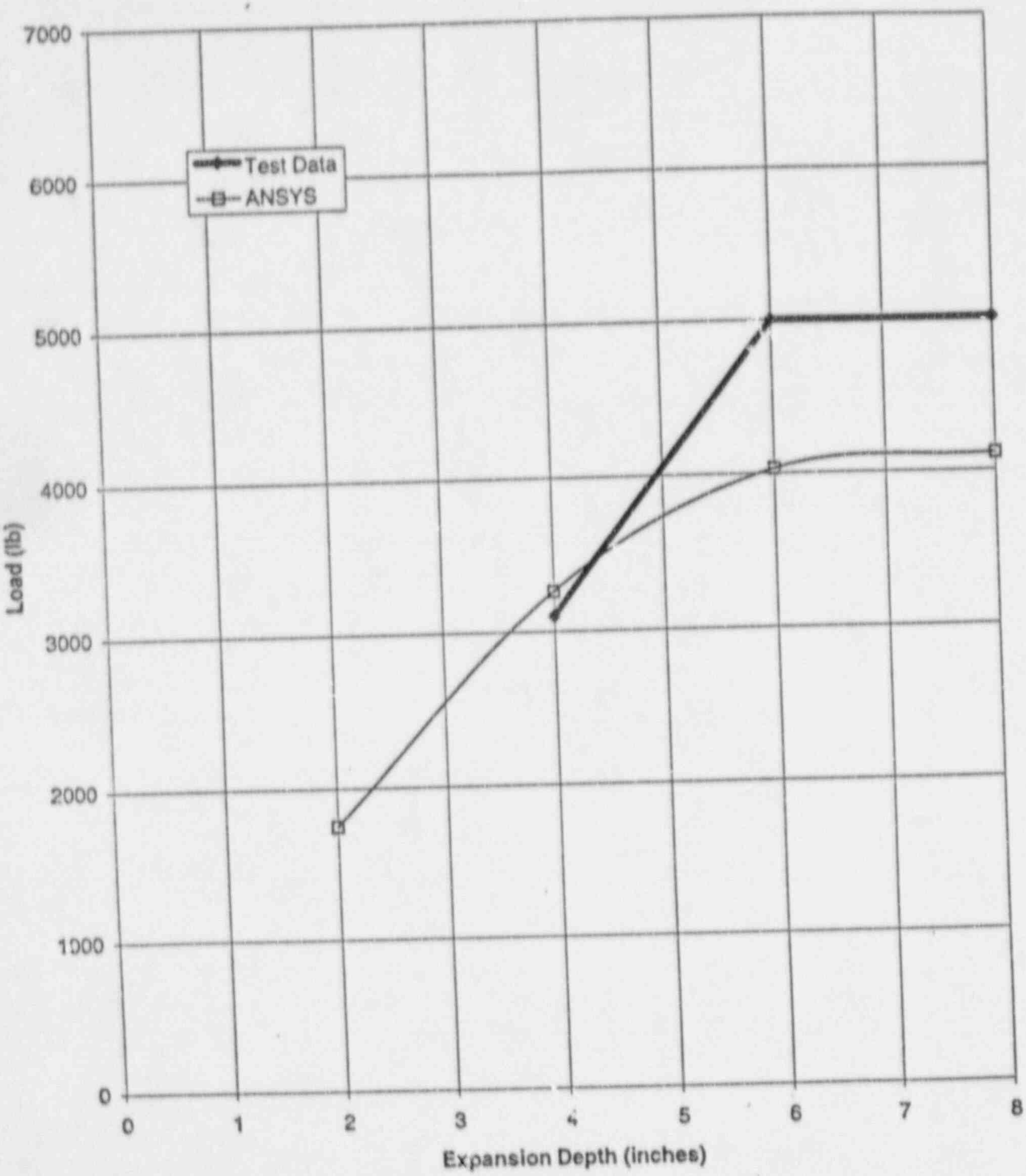



Figure 3-8. Pullout Load Versus Expansion Length for Prequalification Tests

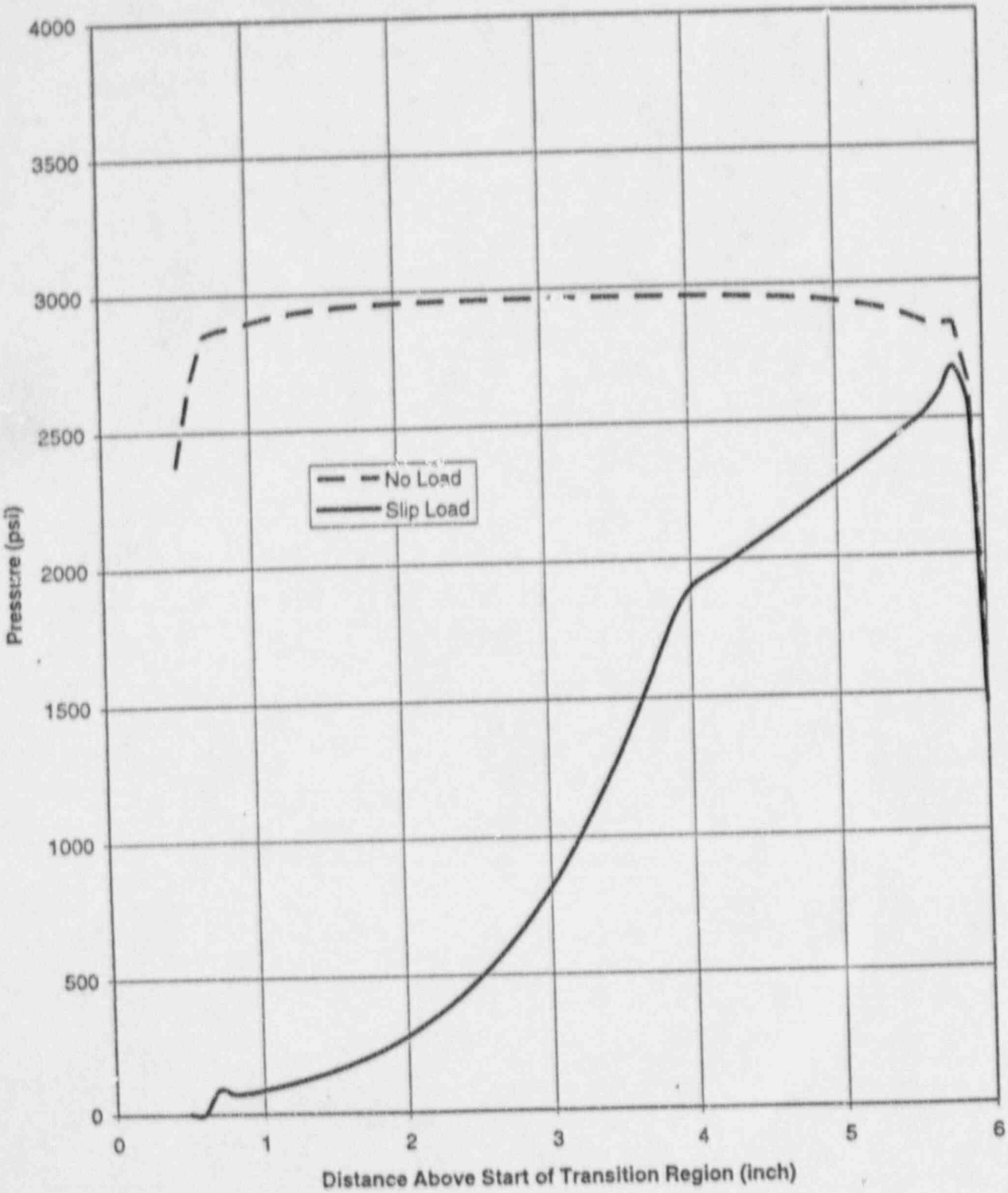



**Figure 3-9.** Contact Pressure Distribution for 6-inch Long Expansion (Peripheral OTSG Tubes)

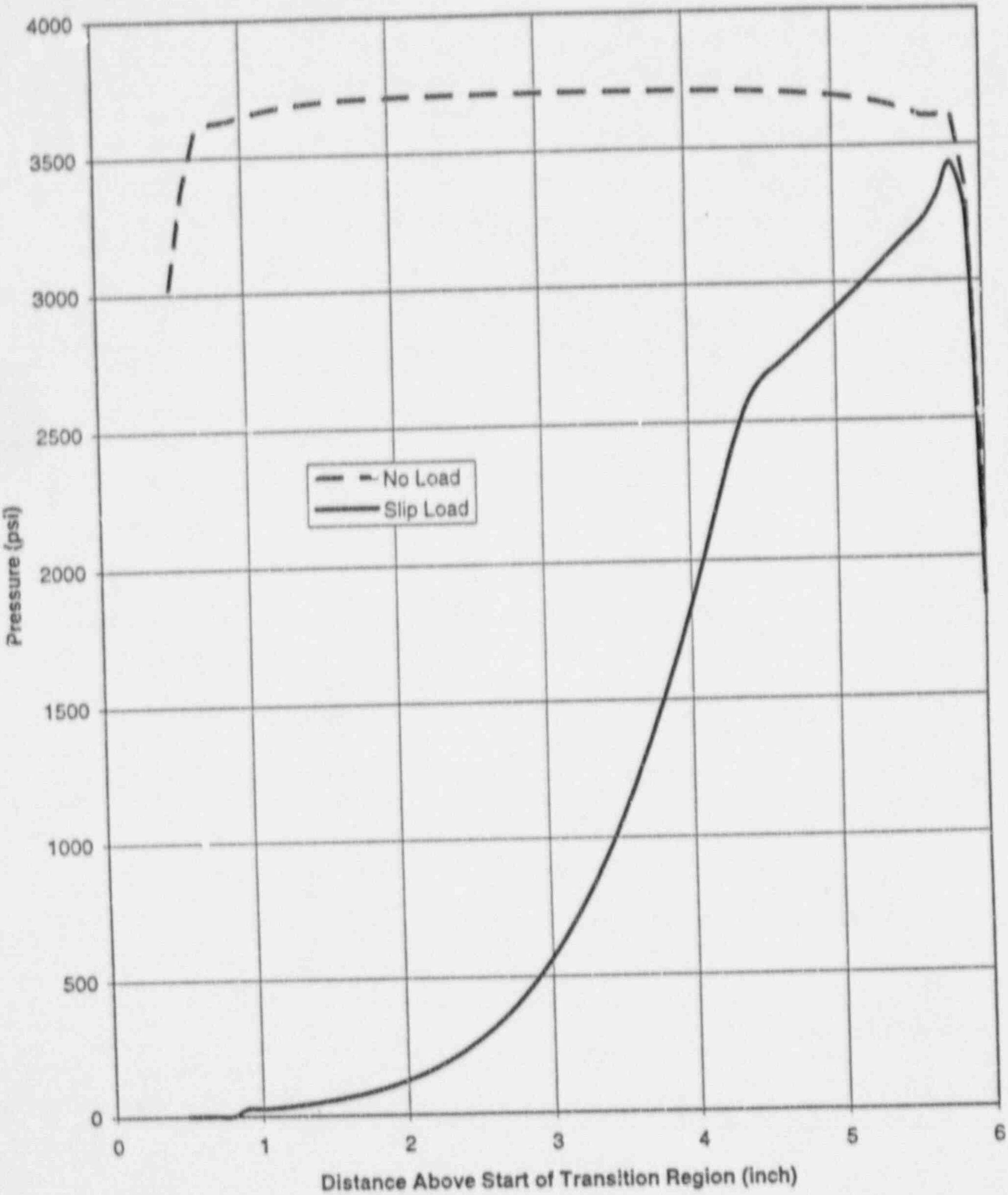



**Figure 3-10.** Contact Pressure Distribution – 1000 Psi Internal Pressure (Peripheral OTSG Tubes)

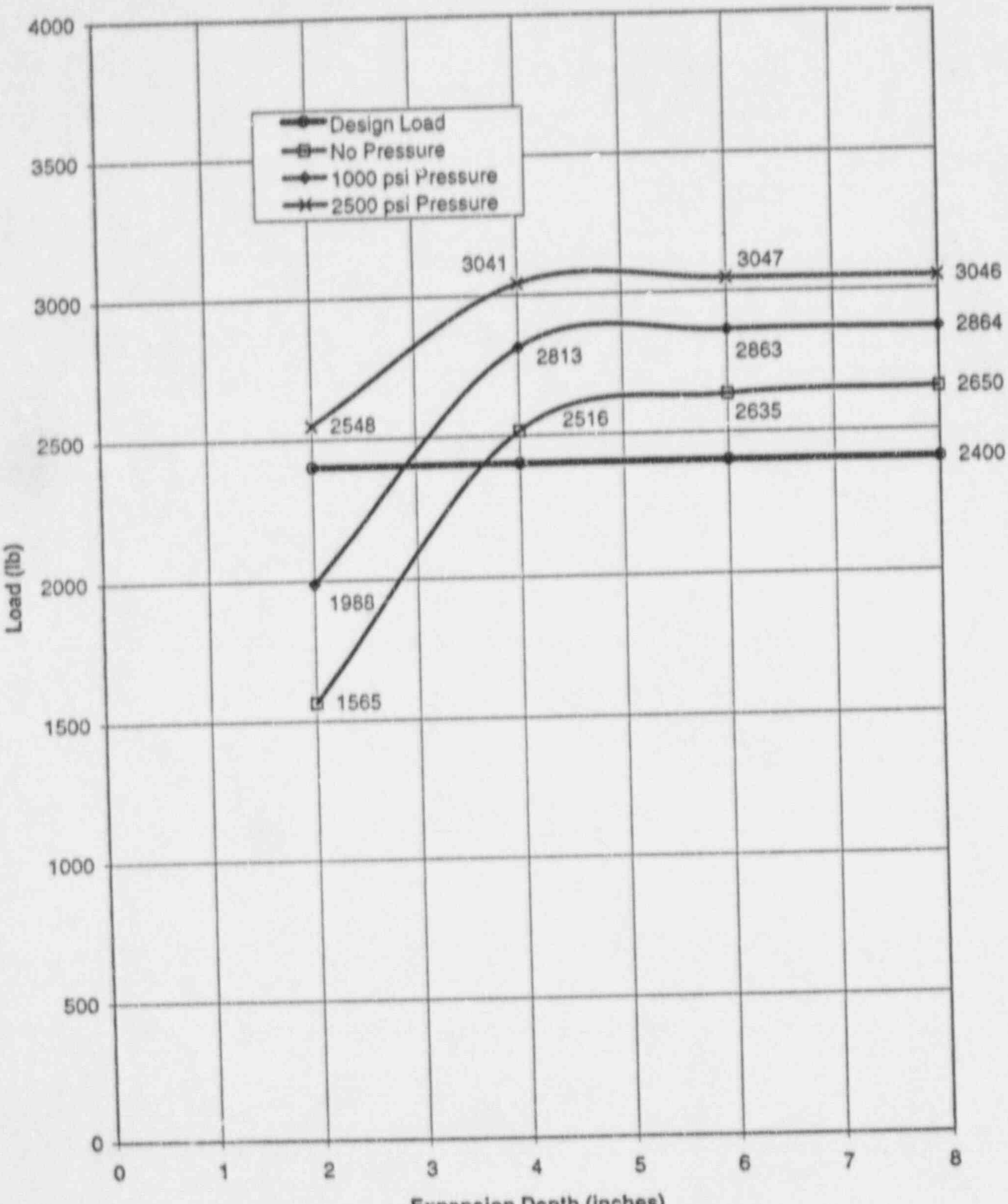



**Figure 3-11.** Pullout Load Versus Expansion Length for Peripheral OTSG Tubes

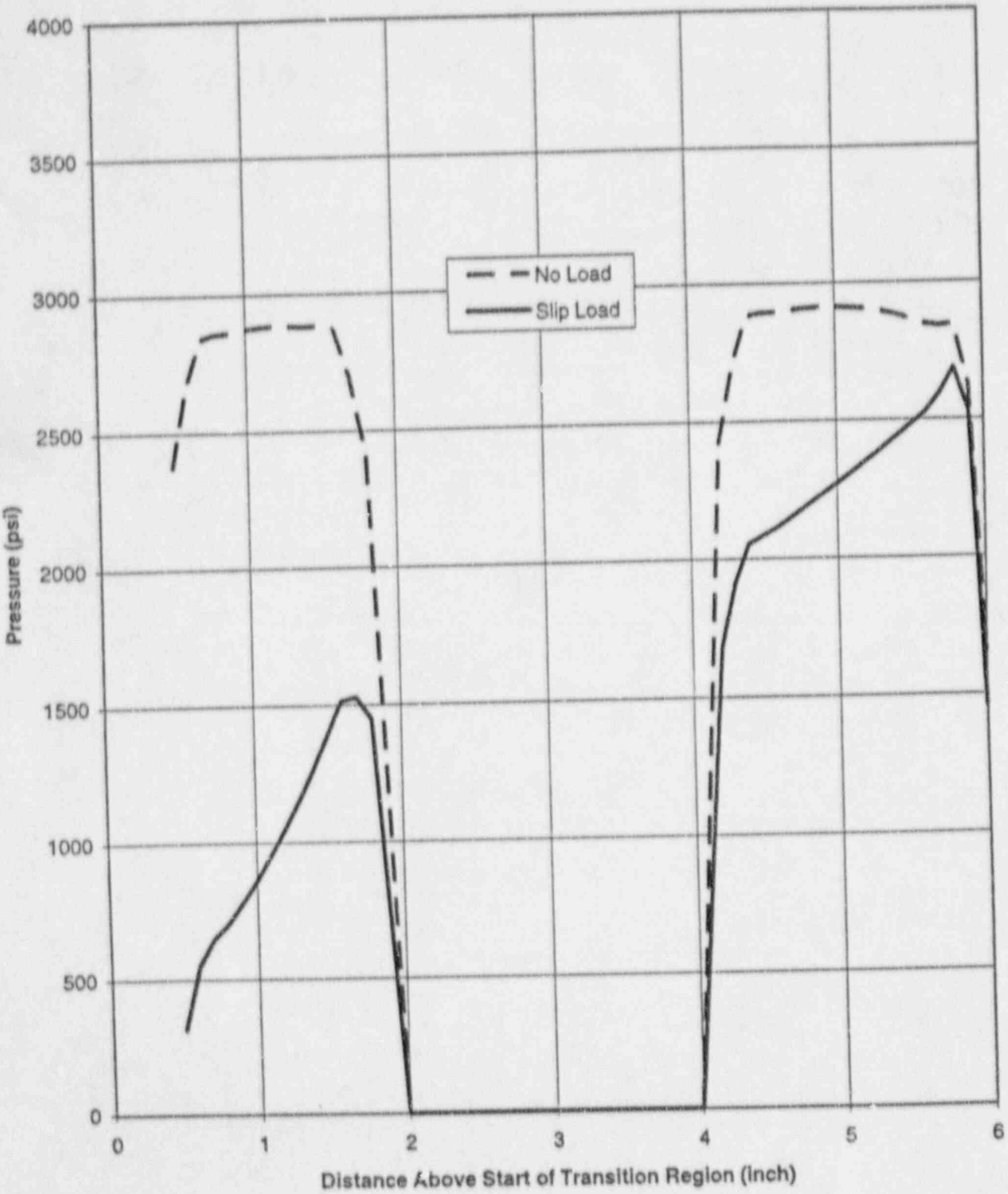



**Figure 3-12.** Contact Pressure Distribution for 6-inch Long Expansion With 2-inch Defected Length (Peripheral OTSG Tubes)

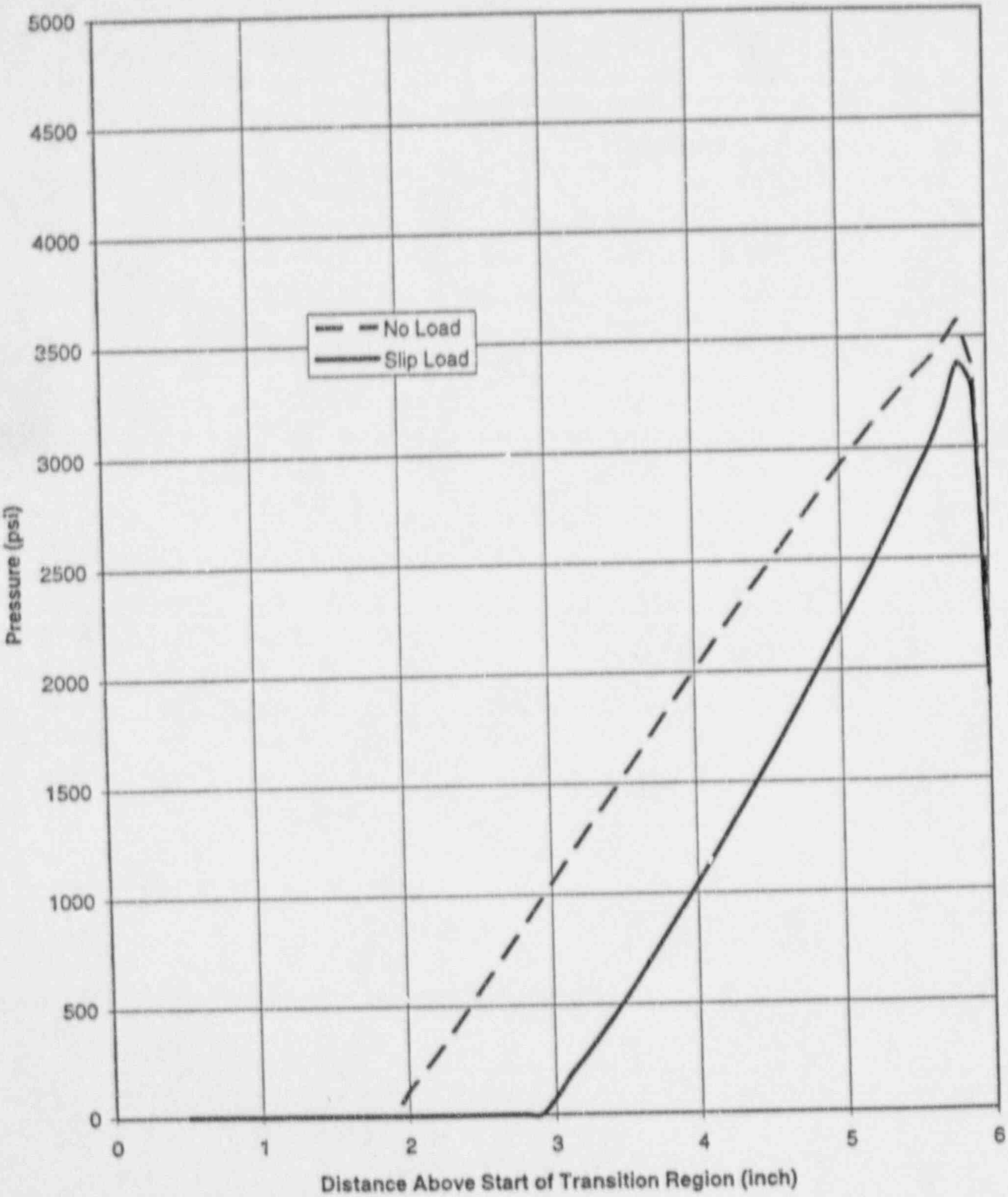



**Figure 3-13.** Contact Pressure for 6-inch Long Expansion With Tubesheet Bow (Center OTSG Tubes)

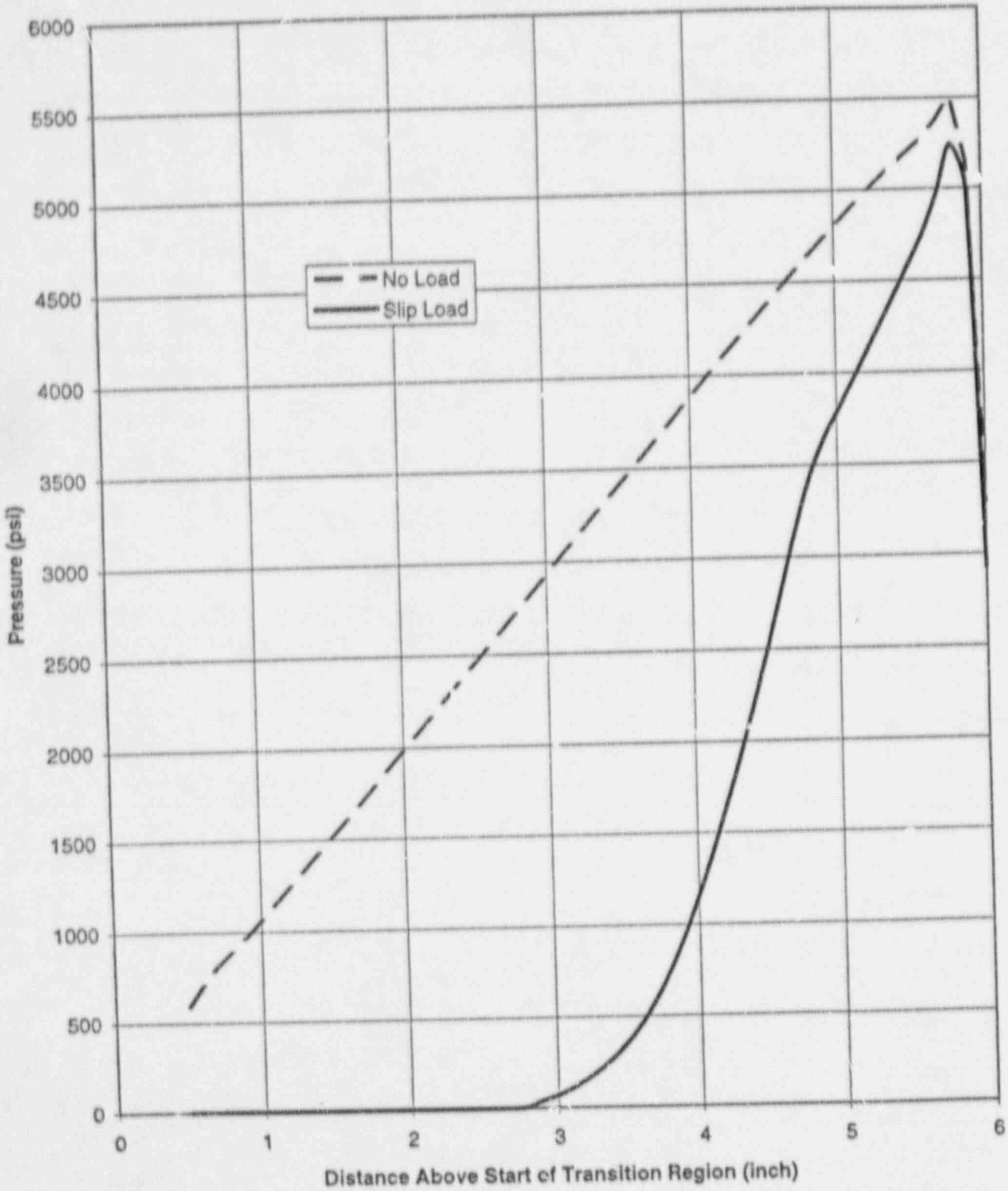



**Figure 3-14.** Contact Pressure for 6-inch Long Expansion With Tubesheet Bow and 2500 Psi Internal Pressure(Center OTSG Tubes)

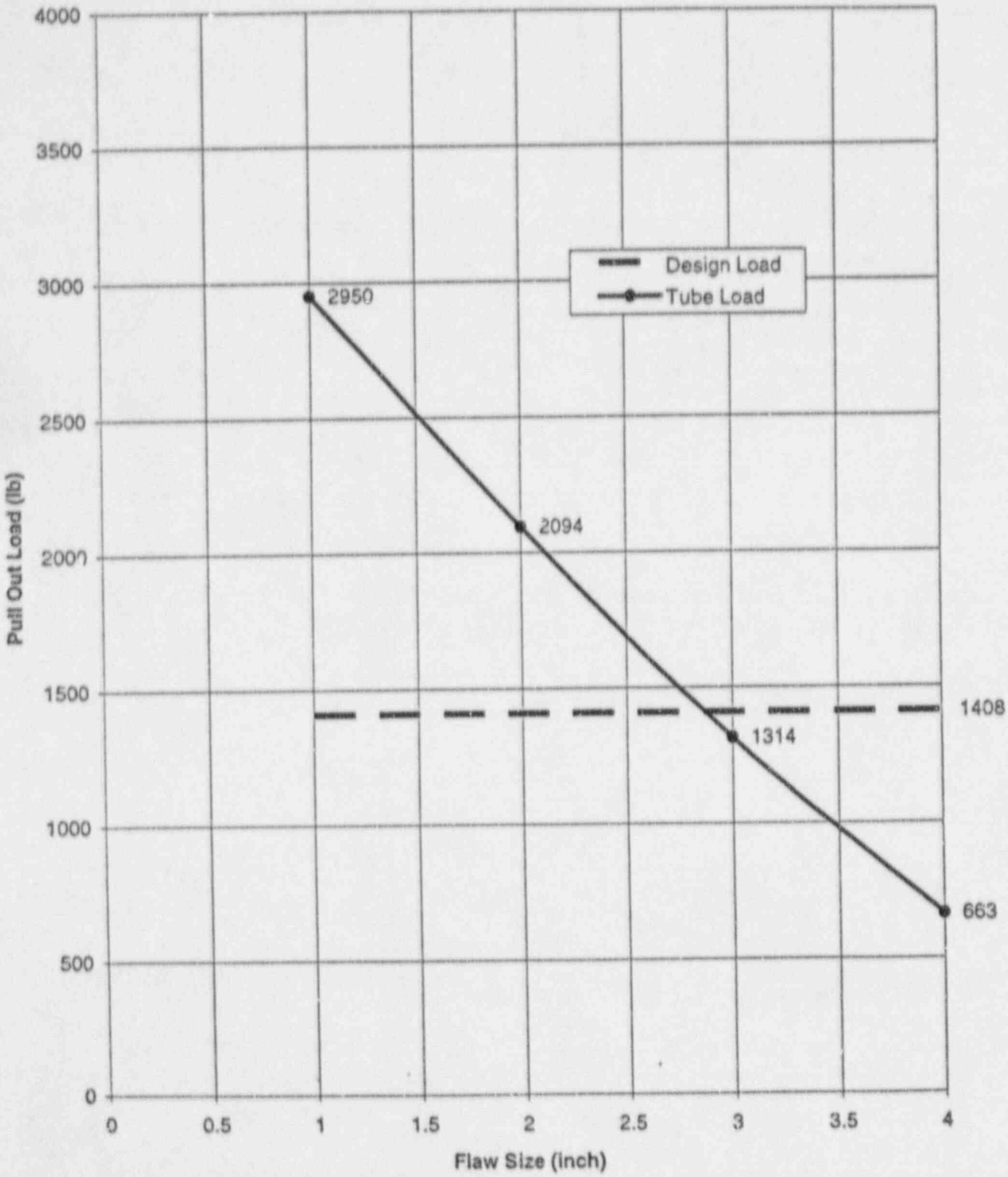



Figure 3-15. Pullout Load for Center OTSG Tubes With 17-inch Expansion Region

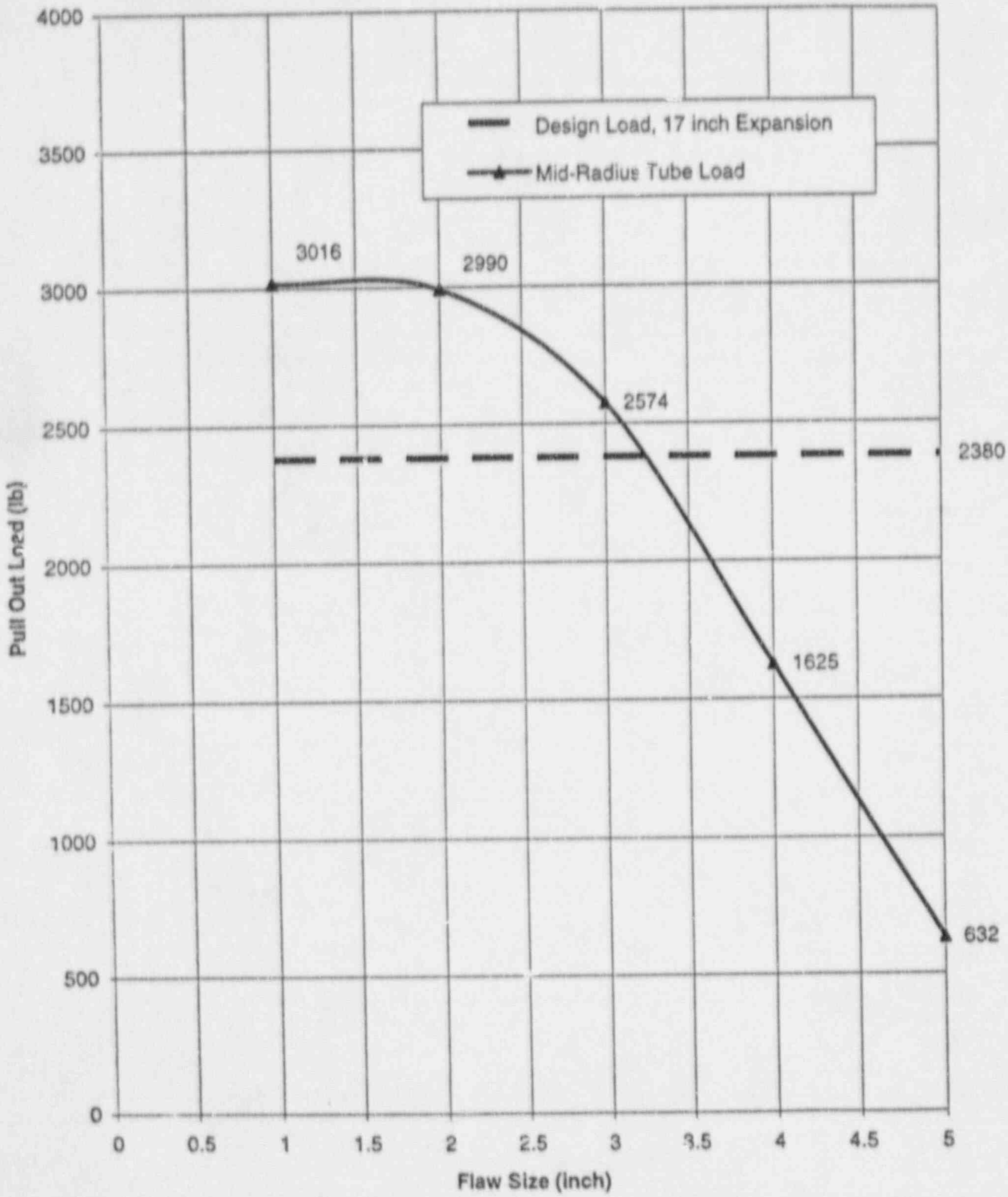



Figure 3-16. Pullout Load for Mid-Radius OTSG Tubes With 17-inch Expansion Region

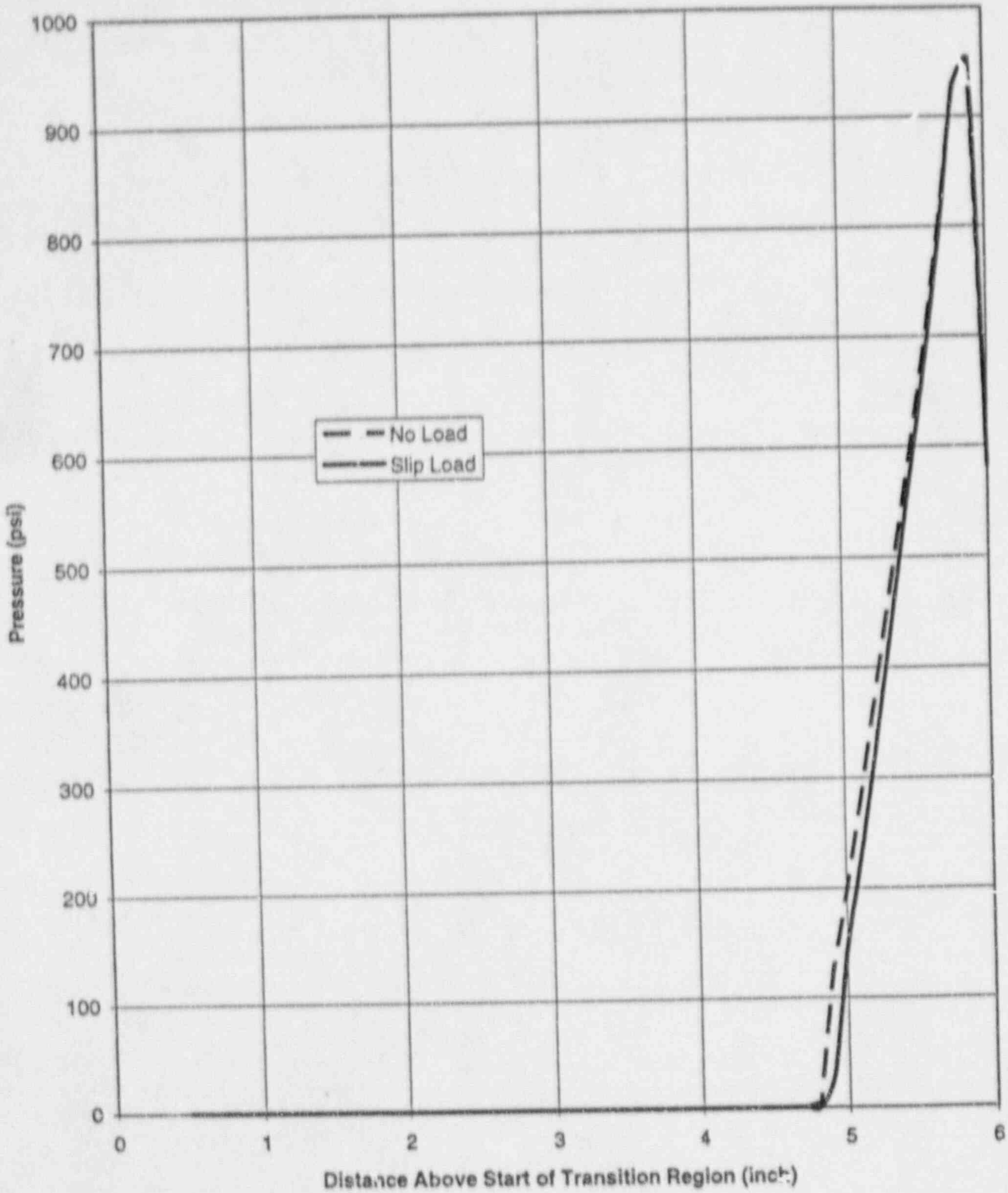



**Figure 3-17.** Contact Pressure for Center OTSG Tubes With 22-inch Expansion Region

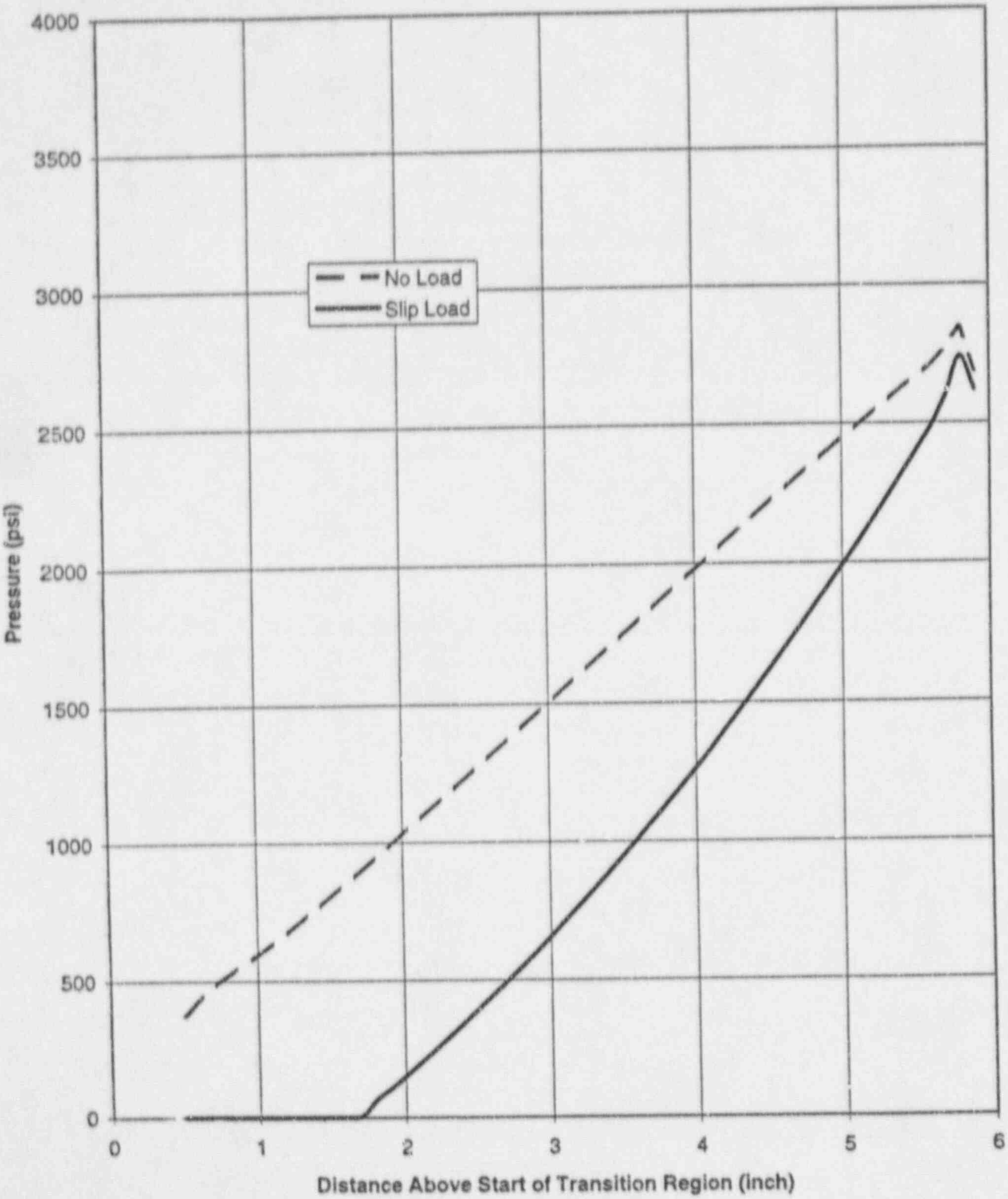



**Figure 3-18.** Contact Pressure for Mid-Radius OTSG Tubes With 22-inch Expansion Region

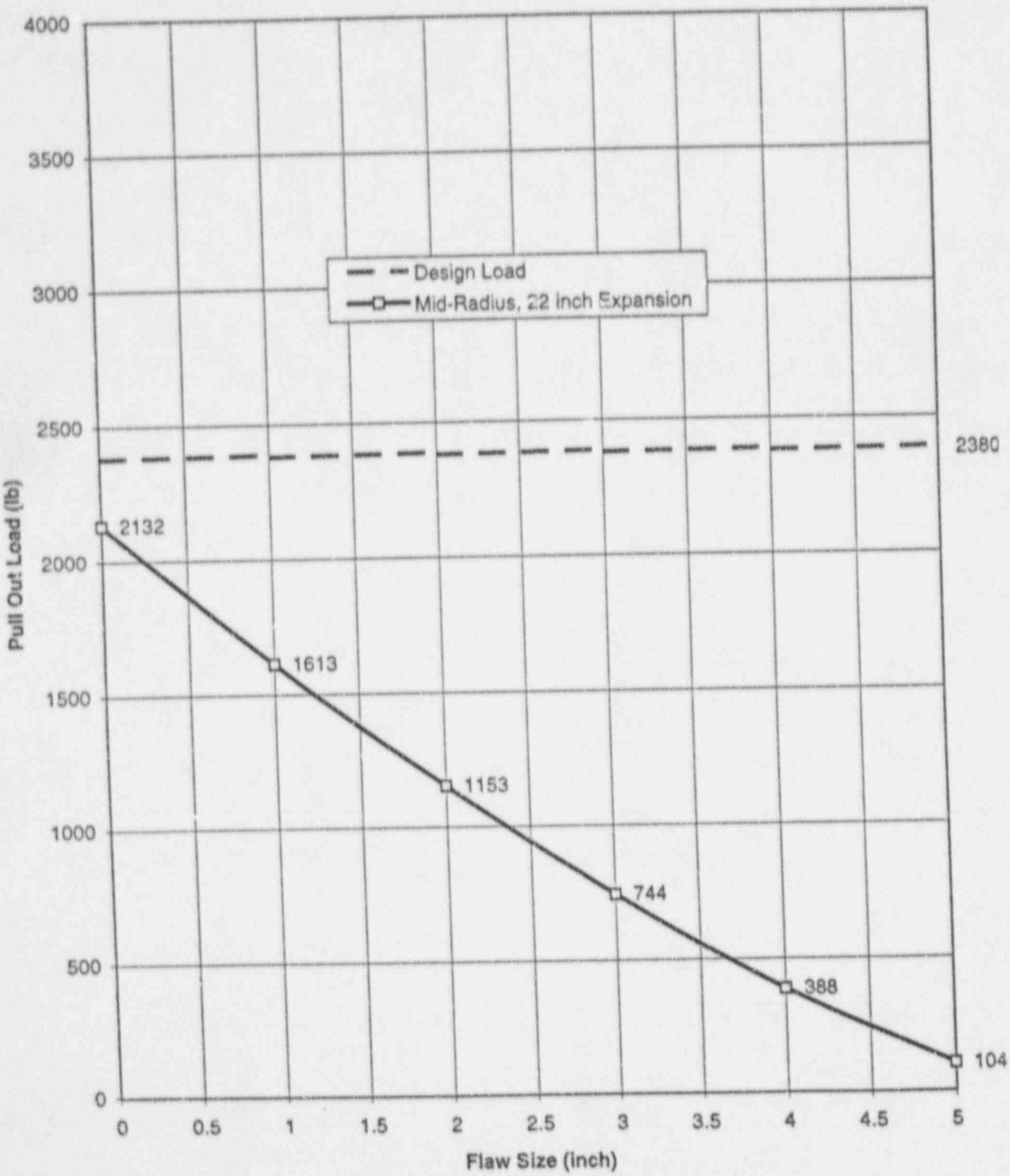



**Figure 3-19**. Pullout Load for Mid-Radius OTSG Tubes With 22-inch Expansion Region

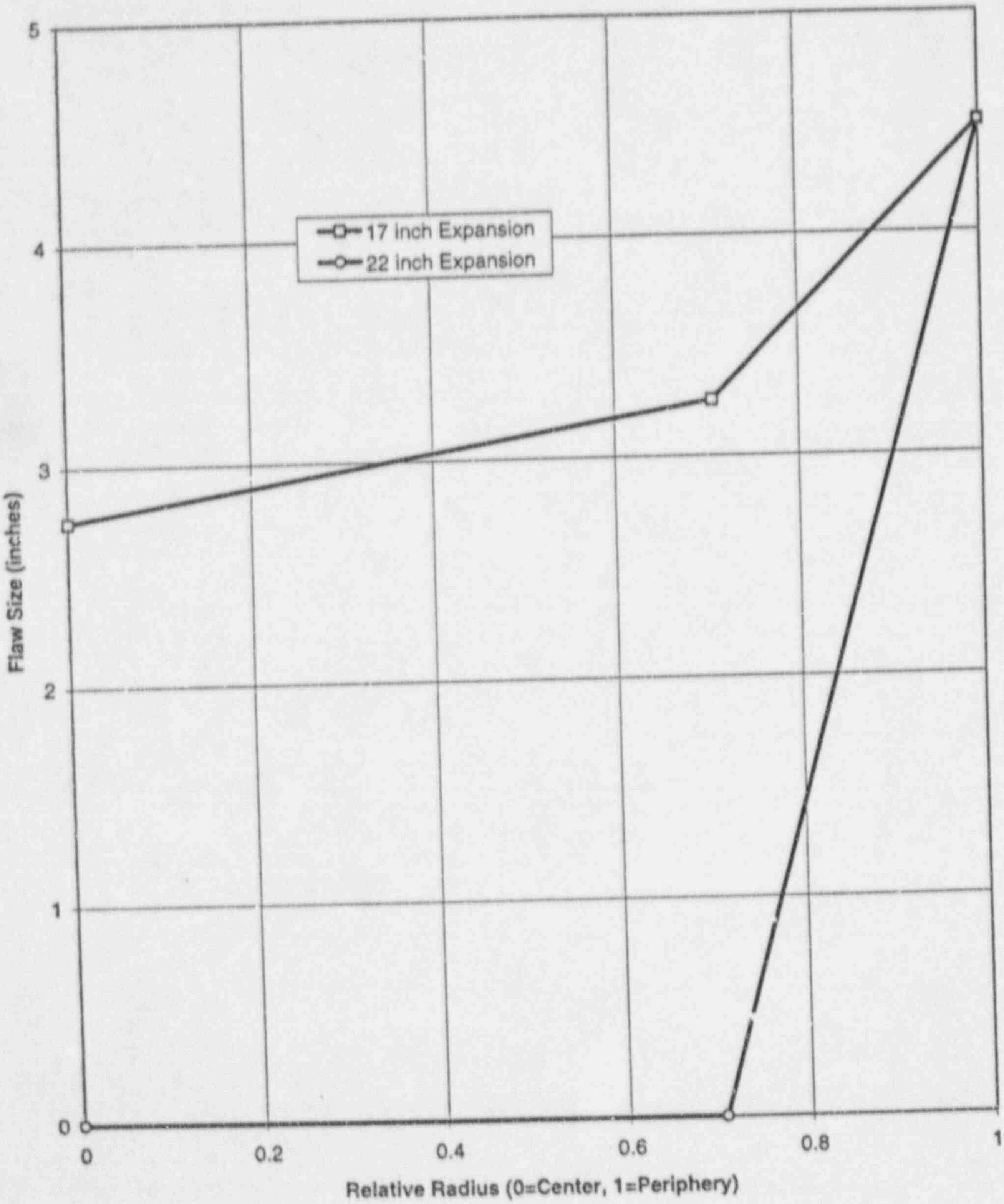
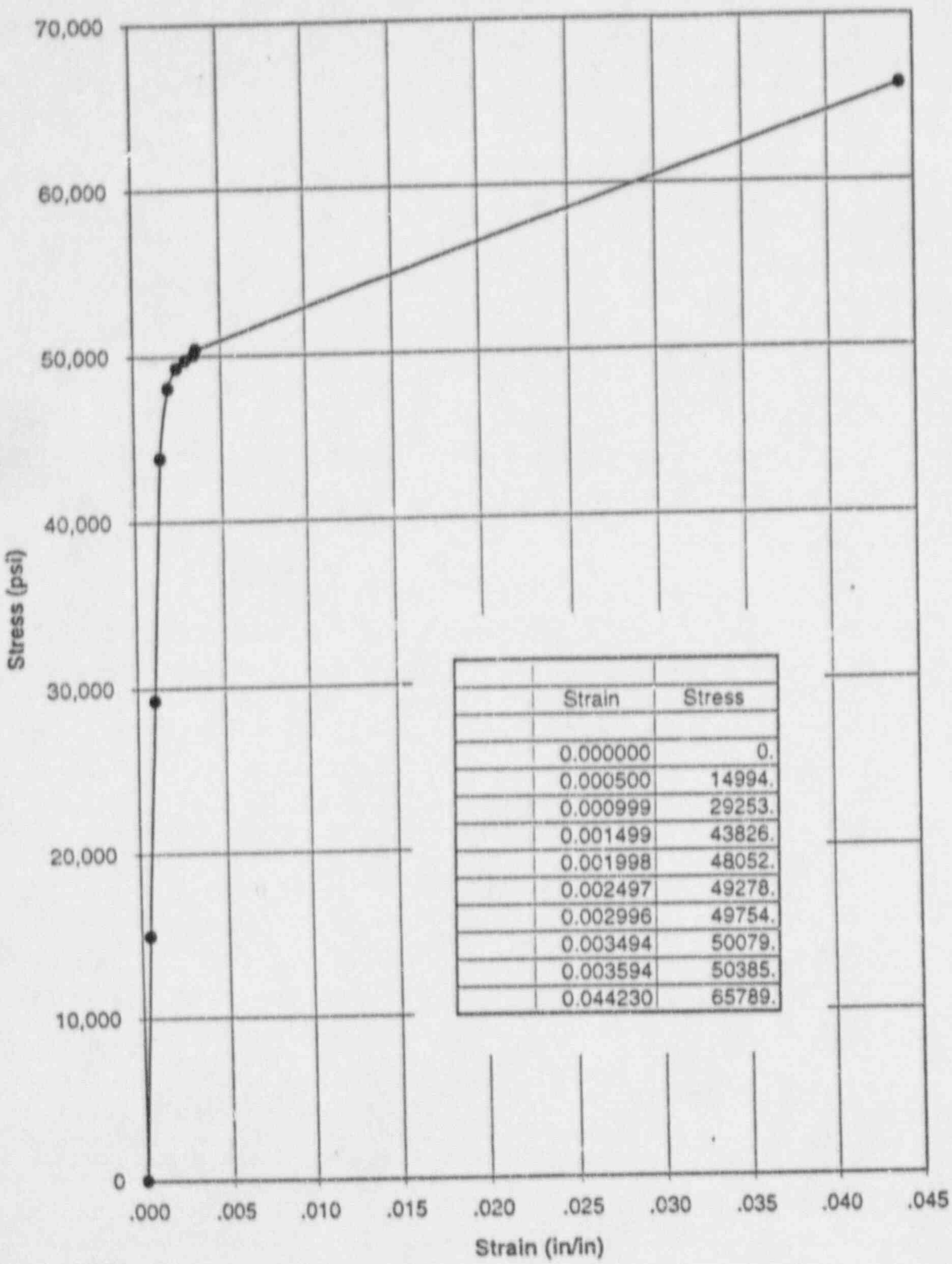



Figure 3-20. Acceptable Flaw Size Results




| Strain | Stress |
|---|---|
| 0.000000 | 0. |
| 0.000500 | 14994. |
| 0.000999 | 29253. |
| 0.001499 | 43826. |
| 0.001998 | 48052. |
| 0.002497 | 49278. |
| 0.002996 | 49754. |
| 0.003494 | 50079. |
| 0.003594 | 50385. |
| 0.044230 | 65789. |

Figure 3-21. True Stress Versus True Strain for Typical Tube Material

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Section 4

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