Argonne NATIONAL LABORATORY

ANL-17/10

Evaluation of Pressure Rating Methods Recommended by API RP 17TR8

Final Report with Peer Review Responses

Global Security Sciences Division

BSEE
Bureau of Safety and Environmental Enforcement

Report Authors

This Argonne report has multiple authors depending on section. Argonne employed a contractor, William Aiken (Aiken Engineering Company), to perform a major portion of the work described. Mr. William Aiken and his firm were charged with completing a detailed design of two typical high-pressure high-temperature subsea components and analytically verifying the designs applying principles of ASME BPVC Sections VIII Divisions 2 and 3 as set forth in the first edition of API 17TR8. Upon completion of a verified design Aiken Engineering had two components fabricated per industry practices using a common material, characterized the material, and pressure tested the components to failure. Dr. Dan Fraser and Roy A. Lindley contributed to conclusions and recommendations with Mr. Aiken's concurrence. The initial report was peer reviewed in accordance with BSEE practices. Responses to the peer review comments are provided in Appendix G of the report. The responses are a joint effort of Mr. Aiken, Roy A. Lindley, and Dr. Bruce Miglin (ADICA, LLD under subcontract to Argonne). Mr. Aiken is a professional engineer and attached his engineering stamp to the report.

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ANL-17/10

“THE RESEARCH PROJECT OUTCOME DID NOT CONCLUDE AS A HIGHLY INFLUENTIAL OR INFLUENTIAL CATEGORY. THEREFORE, BSEE WOULD NOT CONDUCT A PEER REVIEW FOR THIS RESEARCH.”

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July 18, 2017

EVALUATION OF PRESSURE RATING METHODS RECOMMENDED BY API 17TR8

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FINAL WITH PEER REVIEW RESPONSES- JULY 18, 2017

EVALUATION OF PRESSURE RATINGS METHODS RECOMMENDED BY API 17TR8

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Preface

The first edition of API Technical Report 17TR8, *High-Pressure High-Temperature (HPHT) Design Guidelines*, was released in February 2015. As stated in the introduction to the report, the report provided “design guidelines for high-pressure, high-temperature equipment specifically for subsea applications.” The technical report was written by a large task group that included many highly qualified engineers and scientists in the subsea industry. The task group is to be commended for their efforts and the well-written, comprehensive document they produced.

API Technical Report TR8 advocates for engineering mechanics methods that have not been commonly used in the subsea industry or adopted by codes pertaining to subsea applications. Although the theories advanced by the report are not altogether new, some are new to the subsea industry. Many industry engineers and scientists would like to see validation of these new theories as they apply to subsea equipment. For this purpose, BSEE, in collaboration with Argonne National Laboratory, developed and funded a study to validate the pressure rating methods in API Technical Report TR8.

This report describes the methods and results of the study conducted. However, this study is only a first step in validating the methods set forth in API Technical Report TR8. Proper validation will require many similar studies concerning other types of subsea equipment, especially more complex equipment with multibody contact.

To simplify the reading of this report, several shorthand style abbreviations were adopted throughout. These are discussed in the following paragraphs.

Section VIII, Division 2 (2013 Edition) and Division 3 (2013 Edition) of the ASME Pressure Vessel Codes are referenced throughout this report. Throughout the report, these codes are simply referred to as Division 2 and Division 3. Another code referenced throughout this report is API Specification 6A, *Specification for Wellhead and Christmas Tree Equipment,* Twentieth Edition, October 2010. In this report, API Specification 6A is referred to as API 6A. Lastly, hereafter, API Technical Report 17TR8, *High-Pressure High-Temperature (HPHT) Design Guidelines* is referenced simply as TR8.

During this study, rupture pressures for components were determined using hydrotest and finite element analysis (FEA). Thus, in this paper, the term *burst pressure* is defined as “the rupture pressure determined by hydrotest.” Similarly, the term *plastic collapse pressure*, or simply *collapse pressure*, is defined as “a rupture pressure determined by elastic-plastic FEA.”

A study as comprehensive as this one requires guidance, assistance, and work by many people and organizations. These people and companies need to be acknowledged.

First and foremost, Argonne National Laboratory must be acknowledged for its huge part in this effort. Argonne personnel, specifically Dan Fraser and Roy Lindley, conceived this study, guided its execution, provided insight and direction, and, very importantly, obtained funding for the study.

Greg Bailey of Shell Oil Company and Bruce Miglin, a consultant who recently retired from Shell Oil Company, were on the advisory team along with Dan Fraser and Roy Lindley. Throughout the study, Greg provided guidance and insight based on his many years of experience in subsea and related industries. Many times during the study, Greg guided us toward a beneficial path. Bruce was the materials and fracture expert on the team. His greatest contribution to the team was designing, supervising, and evaluating the testing of ruptured material from the study.

The contributions of Forged Products Incorporated (FPI) were important to the success of the study. FPI forged, performed all QA/QC for, and machined the test components. FPI must be commended for meeting scheduled dates and providing high-quality, machined components that met all requirements. The FPI personnel whose efforts need to be recognized are Kevin Crowley, Joe Murphy, Lee White, and Rigoberto Cendejas.

Successful performance of hydrotests was an important part of this study. Southwest Research Institute (SwRI) in San Antonio, Texas, performed all aspects of the hydrotests. SwRI must be complimented for the professional, competent, and thorough way they performed the hydrotest program. The SwRI engineers who supervised the test program were Veronica McDonald and Chris Storey.

The material specifications for the test components were written by Manuel Maligas, a consulting metallurgist in Houston, Texas. Manuel has several decades of experience writing material specifications for subsea equipment. His contribution to the study was valuable.

Last, but certainly not least, Aiken Engineering personnel must be recognized for their contributions. Maurice Peltier was the project manager for the study. He ensured tasks were completed correctly, on time, and on budget. Ryan Moore's vast experience as a lead engineer in a subsea equipment manufacturer's test lab was valuable during designing and performing the hydrotests. Ryan monitored all testing at SwRI and offered many helpful suggestions to the test engineers during the test program.

1.0 Summary

API Technical Report 17TR8, *High-Pressure High-Temperature (HPHT) Design Guidelines* was released in February 2015, and as the title suggests, its purpose was to provide technical guidance for the design of subsea equipment operating at either high pressure (>15 ksi) or high temperature (>350 F). TR8 advocated for engineering methods that had not been commonly used in the subsea industry or adopted by codes pertaining to subsea applications.

Specifically, in Section 5.0, TR8 specifies the following analysis procedures for the verification of HPHT equipment:

- API 6A/6X/17D;
- ASME Division 2: 2013 Part 5 by Linear-Elastic FEA;
- ASME Division 2: 2013 Part 5 by Elastic-Plastic FEA; and
- ASME Division 3: 2013 Part KD by Elastic-Plastic FEA.

The linear-elastic methods set forth in API 6A and ASME Division 2 have been used for many years in the design of subsea equipment. However, the use of Division 2 and Division 3 elastic-plastic methods are new to the industry.

The purpose of this study is to evaluate the elastic-plastic methods set forth in the ASME Codes to confirm that they provide adequate margins of safety for subsea equipment. This is especially important since TR8 allows equipment designed for pressures above 20 ksi to be verified only using Division 3 elastic-plastic methods.

The methodology of this study is summarized below:

- Two special test bodies for a 20 ksi operating pressure were designed and manufactured;
- The team performed both elastic-plastic and linear-elastic FEAs on both test bodies using ASME procedures;
- The team calculated pressure ratings based on the four methods allowed by TR8;
- Hydrotests were performed on the two test bodies to determine the actual rupture pressures;
- The team calculated the margin of safety for TR8 ratings based on actual burst pressures; and
- The margins of safety from all the rating methods in TR8 were compared.

The following are the important conclusions of this study. These conclusions are based on the results of the elastic-plastic FEA and the hydrotests performed as part of this study. The following conclusions apply to HPHT subsea equipment rated for a pressure of 20 ksi or lower. No consideration has been given to equipment rated for pressures greater than 20 ksi. However, there is no apparent reason that these conclusions could not apply to equipment rated for pressures higher than 20 ksi. The conclusions are as follows:

1. The Division 3 elastic-plastic method is not recommended for HPHT subsea equipment published with a 1.8 design-load factor.
2. A Division 3 analysis with a design load factor of 1.8 is acceptable only if the factor is applied to the rupture pressure determined by proof test to failure, and if provided justification demonstrates that additional requirements in Division 3 sufficiently reduce the risk of failure.
3. The Division 2 elastic-plastic method with a design load factor of 2.1 is a suitable method for calculating load ratings for HPHT subsea equipment.
4. For a Division 2 linear-elastic analysis, it is recommended that stress intensities and not von Mises stresses be compared with allowable stresses.
5. It is recommended that the subsea industry compare collapse pressures from FEA with burst pressures from hydrotests for a variety of subsea equipment.
6. The subsea industry should confirm that performing the fracture mechanics analysis required by Division 3 justifies reduction of the design load factor to 1.8.

2.0 Discussion of Verification Methods in TR8 and Other Codes

API 17TR8 is a new API technical report that provides design guidelines for subsea drilling and production equipment operating at high pressures or high temperatures (HPHT). TR8 defines *high pressure* as greater than 15 ksi and *high temperature* as greater than 350 F. When operating temperature or pressure meets the HPHT criteria, TR8 requires design verification using one of four methods, and the specific method to be used depends on the operating pressure. The four methods for design verification are listed below:

- Linear-elastic analysis based on the methods in API 6A/6X/17D;
- Linear-elastic analysis based on the methods in ASME Section VIII Division 2;
- Elastic-plastic analysis based on the methods in ASME Section VIII Division 2; and
- Elastic-plastic analysis based on the methods in ASME Section VIII Division 3.

Table 2.1 identifies the acceptable verification methods in TR8. Note that if pressure exceeds 15 ksi or temperature exceeds 350 F, then equipment is considered HPHT. The information in the table is taken from Figure 1 in TR8. For some pressure ranges, TR8 allows the use of limit-load analysis. This method is similar to standard elastic-plastic analysis, but does not consider the effects of strain hardening. The limit-load method is seldom used because it is less accurate, because it requires the same analysis as standard elastic-plastic FEA, and because it is often difficult to achieve convergence. For these reasons, limit-load analysis is not considered in this study.

Table 2.1 - TR8 Verification Methods for HPHT

Pressure	Temperature	Failure Criterion	Acceptable Validation Methods
Pi ≤ 15 ksi	T ≤ 350 °F	Yield Strength	Not HPHT - No TR8 Verification Required
Pi ≤ 15 ksi	T > 350 °F	Yield Strength	API 6A with Stress Intensity
15 ksi > Pi ≤ 20 ksi	T > 350 °F	Yield Strength	Division 2 Linear-Elastic or
		Tensile Strength	Division 2 Elastic-Plastic or
		Tensile Strength	Division 3 Elastic-Plastic
Pi > 20 ksi	T > 350 °F	Tensile Strength	Division 3 Elastic-Plastic

Prior to 2007, linear-elastic analysis was the only method accepted by API or ASME for verifying pressure ratings. Since the late 1970s, the majority of pressure-containing equipment in subsea drilling and production has been verified using the linear-elastic method in Division 2. This method was required by API 6A, which, at the time, was the most widely used code in the subsea industry.

Based on long operating histories, designs verified by this methodology have unquestionably passed the test of time. Structural failures of equipment designed by this method are rare and are usually due to overloads, design errors, QA/QC mistakes, or leakage.

In 2007, Divisions 2 and 3 of the ASME Code added procedures for verification using elastic-plastic FEA. Currently, API has not approved verification by elastic-plastic FEA. API still requires verification by the linear-elastic procedures set forth in the 2004 release of Division 2.

As Table 2.1 shows, for pressures between 15 ksi and 20 ksi, TR8 allows validation by elastic-plastic FEA or by linear-elastic FEA. Furthermore, the elastic-plastic FEA can use either Division 2 or Division 3 procedures. However, for pressures greater than 20 ksi, TR8 allows only the use of elastic-plastic FEA according to the procedures in Division 3. Neither elastic-plastic analysis using Division 2 procedures nor linear-elastic analysis is acceptable if pressures exceed 20 ksi.

The maximum pressure ratings allowed by the three validation methods are different. The ratings from ASME Divisions 2 and 3 elastic-plastic analysis both use the same elastic-plastic FEA procedure to calculate plastic collapse pressure. Both Division 2 and Division 3 define maximum pressure rating as the collapse pressure from FEA divided by a design factor. However, the values of these design factors are much different for Divisions 2 and 3. Division 2 specifies a design factor of 2.4, and Division 3 specifies a design factor of 1.8. As such, the pressure rating using Division 2 procedures will be 25 percent lower than the pressure rating allowed by Division 3. Division 3 justifies its lower design factor by adding enhanced material requirements and fatigue calculations using fracture mechanics methods.

The linear-elastic method is very different from the two elastic-plastic methods, and the fundamental difference lies in the basis of pressure ratings. In linear-elastic FEA, pressure ratings are based on yield strength, whereas in elastic-plastic procedures, tensile strength is the basis of pressure ratings. Pressure ratings from linear-elastic FEA will be different from ratings using elastic-plastic procedures.

3.0 Purpose of Study

The petroleum industry has a long and successful history of setting pressure ratings using the procedures set forth in API 6A. These procedures are based on linear-elastic FEA methods described in Division 2 and allowable stresses based on yield strength. For pressures greater than 15 ksi, TR8 allows pressure ratings to be set using elastic-plastic methods from the ASME Codes. Furthermore, for pressures above 20 ksi, TR8 requires that pressure ratings be set using only Division 3 elastic-plastic methods. This is a significant procedural change for the industry, and the consequences of using the elastic-plastic methods specified in TR8 must be carefully evaluated before they are adopted by the subsea industry. Evaluation of the elastic-plastic methods in TR8 as related to HPHT subsea equipment is the purpose of this study.

4.0 Procedure of Study

The elements of this study were wide ranging and numerous. The study included engineering, design, manufacturing, material testing, hydrotesting, and 3-D finite element analyses. Rather than include an extensive description of the tasks performed during the study, an outline of the discreet steps that comprised the study is provided on the following page.

A review of the procedure outline shows that internal pressure was the only load that was considered in this study. Although internal pressure is arguably the most critical load that is applied to subsea equipment, it is not the only load that can produce or contribute to failure. Other loads such as external tension, shear and bending moments are significant and can either cause or contribute to failure. It is imperative and required by TR8 that all loads be included in a structural analysis of HPHT equipment.

5.0 Components Evaluated in Study

A total of four components were evaluated in this study. In the context of the study, *evaluation* means determining pressure rating based on analysis by FEA, hydrotest, or both.

Pressure ratings were determined by both hydrotest and FEA for two of the four components in this study. Pressure ratings for the other two components were determined by only FEA. The two components evaluated by both hydrotest and FEA are the primary focus of this study. The other two components were a later addition and were included to provide evaluations of additional shapes commonly used in the subsea industry.

Outline of Discrete Tasks Performed in Study

I. DESIGN THE TEST BODIES
   - A. Identify the design conditions
   - B. Identify the bore size and shape for functionality
   - C. Choose material
   - D. Write material specification
   - E. Perform conceptual design based on strength of materials calculations
   - F. Perform detail design
   - G. Produce detail drawings of test bodies

II. MANUFACTURE THE TEST BODIES
   - A. Forge the test bodies
   - B. Rough machine test bodies
   - C. Removed test coupons from rough machined bodies
   - D. Perform all tests and QA/QC required by the material specification
   - E. Perform final machining of test bodies
   - F. Perform dimensional inspection to confirm conformance to drawing dimensions

III. PERFORM FEA OF THE TWO TEST BODIES
   - A. Calculate the collapse pressure using elastic-plastic FEA
     - 1. Case 1: using the minimum specified material properties
     - 2. Case 2: using the actual material properties
   - B. Perform linear-elastic FEA at the rated pressures

IV. HYDROTEST THE TEST BODIES
   - A. Choose bolt torque based on pressure end loads
   - B. Design and fabricate the containment canister
   - C. Design the test procedure
   - D. Choose strain gage locations and mount strain gages
   - E. Test the two bodies to the API required hydrotest pressure
   - F. Mount the test bodies inside the containment canisters
   - G. Incrementally apply internal pressure until the test bodies burst.
   - H. Produce a comprehensive test report

V. DETERMINE PRESSURE RATING FOR THE TWO TEST BODIES BASED ON THE FOLLOWING PROCEDURES:
   - A. API 6A with linear-elastic FEA
   - B. API 6A based on burst pressure
   - C. API TR8 Division 2 procedures with elastic-plastic FEA
   - D. API TR8 Division 3 procedures with elastic-plastic FEA
   - E. API TR8 Division 3 based on burst pressure

VI. COMPARE THE BURST PRESSURES FROM TEST AND ELASTIC-PLASTIC FEA; AND, THE PRESSURE RATINGS BY THE VARIOUS CODE PROCEDURES:
   - A. Compare the burst pressures based on tests and elastic-plastic FEA
   - B. Compare pressure ratings based on tests and FEA by the following methods:
     - 1. Linear-elastic FEA using API 6A procedures (Approved by TR8)
     - 2. Elastic-plastic FEA using Division 2 procedures (Approved by TR8)
     - 3. Elastic-plastic FEA using Division 3 procedures (Approved by TR8)

4. Burst pressure using the Division 3 factor
5. Burst pressure using the API 6A factor

VII. DISCUSS THE FINDINGS OF THE STUDY
  A. Results
  B. Conclusions
  C. Opinions

VIII. DISCUSS SUGGESTIONS FOR FUTURE STUDY
IX. PRODUCE THE FINAL REPORT

In this section, the design, geometry, loads, and materials for each of the four components are described. The two primary components that were both tested and analyzed are discussed first, followed by discussions about the two components that were only analyzed.

5.1 Components Analyzed and Tested

The two components specifically designed for this study were the large neck test body and the small neck test body. Both components were designed, manufactured, hydrotested, and analyzed using FEA. The design philosophy for the two components is summarized in the following statements:

- The design pressure rating for both components was 20,000 psi. However, calculations for this study were actually performed at the design pressure of 26,000 psi. The purpose of the high design pressure was to provide a margin of 6,000 psi and allow the components to safely accommodate loads other than internal pressure. Note that this is common design practice for subsea components. Although a subsea component is rated for a specific design pressure, a designer will normally include some margin so external loads will not overstress the component;
- The geometry of each component was similar in size and shape to typical components used in subsea applications, such as valves and connectors. The neck diameter and wall thickness of each test body were determined by pressure requirements. The balance of each test body including the cross bore areas are the same since there needs to be sufficient material for the bolt holes of the attached blind flanges;
- The geometry of each component included cross-bores that produced very high local stresses; and
- The material was typical of common low-alloy steels used in subsea applications and met all the requirements of API 17TR8, the chemical composition requirements of API 6A PSL 3, and the requirements of NACE MR0175.

Although both components were designed for the same pressure rating, different rating criteria were used for each component. The large neck test body was designed to meet the rating criterion specified in the elastic-plastic method in Division 2. The small neck test body was designed to meet the rating criterion specified by the elastic-plastic method in Division 3.

Detailed drawings of the two bodies are shown in Figure 5.1 and Figure 5. 2. The design calculations, material properties, and material specifications are included in Appendix A.

As Figures 5.1 and 5.2 show, the shapes and dimensions of the two test bodies are almost identical. There are only two differences between them. First, the large neck test body has a neck

OD of 5.680 inches, and the small neck body has a neck OD of 4.880 inches. Second, the transitions taper on the small neck body is slightly longer. All other dimensions and materials are identical for the two bodies.

The weak section in both bodies is located midway through the neck between the transition tapers. Internal pressure will rupture the neck at this location before failure occurs at any other location. The OD of the small neck body was designed based on the criterion in the 2013 Edition of Division 3, and the OD of the large neck body was designed using the more conservative criterion in the 2013 Edition of Division 2.

One end of each test body has a thick wall housing with width, length, and height dimensions of 17 3/4 inches. A long, cylindrical neck extends from one end of the housing. The end of the neck moving away from the housing is an integral API 3 1/16 x 20k flange. The 3.060-inch bore through each test body extends for the entire length. The face of the housing opposite the flange includes drilled and tapped holes to mate with a 3 1/16 x 20k API blind flange and a seal groove for a BX gasket.

A bore of 4.062 inches is machined through the two opposed faces of the housing. This bore is perpendicular to the 3.060-inch bore, and its centerline intersects the centerline of the 3.060-inch bore. Seal grooves and tapped holes are machined into the two faces with the 4.062-inch bores for the attachment of a 4 1/16 x 20k flange on each face. An enlarged cavity is machined in the center of the housing. The purpose of the enlarged cavity is to provide large, internal cross-bores that produce high-peak stresses where they intersect.

It is important to note that the length, width, and height dimensions of the large end were dictated by the ODs of the connecting flanges, not the functionality or stresses from external loads. Often in the design of subsea equipment, features other than functionality or stresses dictate the shapes and dimensions of components. Nonetheless, the majority of subsea equipment includes a cylinder or tubular section that contains high stresses, and this is often where failure will occur. Stresses in the majority of the material apart from the thin cylindrical section are often low.

During hydrotest, blind flanges were attached to the four external penetrations of the test bodies. Figure 5.3 shows the two test bodies with flanges and seals in place for hydrotest.

5.2 Components Analyzed but Not Tested

The following components were analyzed with FEA, but were not hydrotested:

- API 16 3/4 x 10k Weld Neck flange; and
- API 13 5/8 x 20k Weld Neck flange.

Both linear-elastic and elastic-plastic FEA were performed on these components. The geometry, materials, and loads for each component are discussed in the following paragraphs.

The 16 3/4 x 10K flange and the 13 5/8 x 20k flange are standard API flanges with shapes and dimensions specified in Tables B.53 and B.54 of API 6A. The two API flanges were chosen for evaluation because flanged connections are commonly used in subsea applications. One flange had thicker sections because it was rated for a 20,000 psi operating pressure, whereas the other, with thinner sections, was rated for a 10,000 psi operating pressure. This provided an evaluation of components with thick and thin sections to see if section thickness affected the effectiveness of analysis methods.

Linear-elastic FEA was performed on both flanges at their rated internal pressure. The results of this analysis were used to calculate the maximum pressure ratings allowed by API 6A and Division 2 linear-elastic methods. Elastic-plastic FEA was performed with an internal pressure that was incrementally increased until plastic collapse occurred. Results of these solutions were used to calculate the minimum pressure ratings allowed by Division 2 and Division 3 elastic-plastic methods.

5.3 Material Properties of Components

The material for all four components was ASTM A182 F22 low-alloy steel with a minimum yield strength of 75,000 psi and a minimum tensile strength of 95,000 psi. The material specification is provided in Appendix A. All the required material properties are listed in the specification.

In addition, tensile tests and impact tests were performed on specimens taken from prolongations of the forging from which the test bodies were machined. Tests were performed at 70 F and 350 F. The material properties from these tests are the actual properties of the material. The actual yield strength is 92,200 psi and the actual tensile strength is 111,100. The results of material tests are included in Appendix F.

As a part of this study, elastic-plastic FEA was performed using the actual material properties and the as-specified properties. The true stress-strain data for the actual material was determined by the tensile tests. True stress-strain values for the as-specified material were calculated using the procedures in Appendix 3.D of ASME Division 2.

6.0 Comparison of Collapse Pressures and Burst Pressures

As stated in the preface, in this report, the term *collapse pressure* refers to the theoretical plastic collapse pressure based on FEA, and *burst pressure* refers to the failure pressure based on hydrotest to failure. Since TR8 procedures rate subsea equipment using the theoretical plastic collapse pressure, it is crucial that the theoretical collapse pressure closely agrees with the actual burst pressure.

An important part of this study was to determine and compare the collapse pressures and burst pressures of the two test bodies. To achieve this goal, elastic-plastic FEAs were performed to calculate the collapse pressures. Then hydrotests of the two test bodies were performed to measure the burst pressures.

This section describes the FEA and hydrotest procedures that were used to calculate the collapse and burst pressures. Lastly, the collapse pressures are compared with the burst pressures.

6.1 Collapse Pressures by Elastic-Plastic FEA

TR8 recommends that load ratings should be based on the plastic collapse FEA methods in Divisions 2 and 3. For calculation of prudent load ratings it is imperative that the theoretical collapse pressures from FEA be accurate or at least conservative. For this reason an important part of this study was to compare collapse pressures using the Divisions 2 and 3 elastic-plastic methods with the actual burst pressures from tests.

For a valid comparison the material properties of the FEA models and the test bodies must be the same. For this reason, the actual material properties determined from tensile tests of prolongations from the actual test body forgings were used for this part of the study.

Figure 6.1 shows a volume plot of the FEA model for the large neck test body. The small neck model is identical in every respect except that the OD of the neck is slightly smaller and the transition tapers are slightly longer. As Figure 6.1 shows, the models are one-quarter symmetrical. The following is a list of the important features of the models:

- ANSYS Revision 16.2 FEA software was used for all solutions;
- All elements were type Solid 186 with full integration and pure displacement element formulation;
- A large displacement option was used to account for nonlinear geometrical changes;
- Elastic-plastic material properties were used as listed in Appendix F;
- Internal pressure was applied to the ODs of seal grooves;
- A bolt tension equal to the pressure end load was applied as negative pressure to bolt circles;
- The large neck model was comprised of 205,773 elements and 307,063 nodes;
- The small neck model was comprised of 251,526 elements and 404,186 nodes; and
- Multiple models were solved with finer meshes and more load steps, and the results were virtually identical (within 1 percent based on pressure at non-convergence of solution).

Appendix B includes numerous plots of the finite element model, mesh, and loads and boundary conditions for both test bodies. In addition, Appendix B contains important results for the elastic-plastic analysis and for the linear-elastic analysis. This section of the report is about the plastic-collapse pressures of the test bodies. Therefore, this section only discusses the elastic-plastic analysis. Linear-elastic analysis will be discussed later in this report. Also, Appendix B includes results for both test bodies, as well as for the other components that were evaluated. Appendix B1 concerns the large neck test body, and Appendix B2 concerns the small neck test body.

For elastic-plastic FEA, Divisions 2 and 3 require that a model with elastic-plastic material properties be solved with incrementally larger loads until the solution fails to converge. If the FEA is properly performed, non-convergence of the solution means that plastic collapse has occurred. The internal pressure at the last converged solution is defined as the plastic collapse pressure by ASME procedures.

Appendix B1 includes calculations for the collapse pressures of the large neck test body with the actual material properties and the as-specified material properties. Likewise, Appendix B2 includes the collapse pressures for the small neck test body. The collapse pressures are summarized below:

- 72,850 psi…Collapse pressure of large neck test body with actual material;
- 62,750 psi…Collapse pressure of large neck test body with as-specified material;
- 55,375 psi…Collapse pressure of small neck test body with actual material; and

- 47,850 psi…Collapse pressure of small neck test body with as-specified material.

6.2 Burst Pressure by Hydrotest

As stated in Section 5.1, prototypes of the large neck and small neck test bodies were manufactured in accordance with the detail drawings shown in Figures 5.1 and 5.2. The two test bodies were then prepared for hydrotesting. Figure 6.2 shows the assembled large neck test body ready to be tested. A figure of the assembled small neck is not included because it is almost identical to the assembled large neck body.

Two types of hydrotests were performed on each body. First, the test bodies were hydrotested inside a hyperbaric chamber with various combinations of internal and external pressure. For these tests, strain gages were mounted at critical locations on the test bodies, and strain readings were recorded throughout the test program. Second, the test bodies were mounted inside a blast containment structure as shown in Figure 6.3. Then, internal pressure was incrementally applied until the test bodies ruptured and relieved pressure. A comprehensive description of all test procedures, equipment, and results is included in Appendix C at the end of the report. This section of the report will only discuss the rupture hydrotest.

Figure 6.4 is a photograph of the large neck test body after rupture, and Figure 6.5 is a photograph of the small neck test body after rupture. The photographs show, as expected, that both ruptures occurred in the thin neck sections. The internal pressures when rupture occurred were:

- 67,959 psi…Burst pressure of large neck test body; and
- 51,469 psi…Burst pressure of small neck test body.

6.3 Comparison of Collapse Pressure and Burst Pressure

As discussed in Section 2.0 of this report, TR8 bases pressure ratings of equipment on the plastic collapse pressure calculated using elastic-plastic FEA. The pressure rating is the collapse pressure divided by the design factor specified in the code. For Division 2, the design factor is 2.4, and for Division 3, the design factor is 1.8. Obviously, the accuracy of the collapse pressure calculated by FEA is extremely critical. If calculated collapse pressure is greater than actual burst pressure, then pressure rating will not have the necessary margin of safety.

An important part of this study was designing, manufacturing, and hydrotesting components similar to typical subsea components used in subsea service. Collapse pressures were calculated using elastic-plastic FEA as required by TR8. The actual burst pressures of the components were determined by hydrotests to failure.

The collapse pressures calculated with elastic-plastic FEA were discussed in Section 6.1. The actual burst pressures determined by hydrotests were discussed in Section 6.2. Table 6.1 compares the burst pressures from the tests with the collapse pressures from FEA.

The most significant result of the comparison is that actual burst pressure was more than 6.7 percent lower than the FEA-determined collapse pressure based on actual material properties. This means that pressure ratings calculated by analysis were greater than pressure ratings calculated by burst tests. This is the reverse of what engineers normally try to achieve in the design process. Analysis methods are normally designed to calculate failure pressures less than actual failure pressures. This ensures conservative load ratings. It is important that failure pressures from analysis are less than actual failure pressures from a test.

Another observation from Table 6.1 is that burst pressures from tests are more than 7 percent higher than collapse pressures determined from FEA using specified material properties. Although the strengths of actual components will usually be greater than the minimum specified strengths, this is not always true. The design engineer must assume that material strengths are the minimum properties in the specification. For this reason, elastic-plastic FEA for TR8 validation should always use minimum tensile strengths. This result indicates that, if actual material properties are equal to minimum specified properties, then the margin of safety based on elastic-plastic may be less than expected.

Table 6.1 - Comparison of Burst and Plastic Collapse Pressures

Method of Determining the Failure Pressure	Failure Pressure (psi)	
	Small Neck	Large Neck
Plastic Collapse Pressure from FEA with Specified Material Properties	47,850	62,750
Plastic Collapse Pressure from FEA with Actual Material Properties	55,375	72,850
Burst Pressure from Hydrotest of Actual Components	51,469	67,959
Burst Pressure Compared to Plastic Collapse of Actual Material	-7.05%	-6.71%
Burst Pressure Compared to Plastic Collapse of Specified Material	7.56%	8.30%

6.4 Validation of FEA Model

In Section 6.3, collapse pressures from FEA were compared with burst pressures from hydrotests. For conclusions from this comparison to be correct, it is imperative that the FEA is accurate. The most reliable method of validating the accuracy of FEA is comparing FEA results with test results. For the purpose of validating FEA of test bodies, strain gages were attached to the two test bodies, and strain data was recorded throughout the hydrotest program. Then strains measured during the hydrotests were compared to strains calculated by the FEA.

The important features and results of this comparison are presented in Appendix D. The comparison confirms that critical values of calculated strains from FEA are within 4 percent of measured strains from hydrotests.

7.0 Pressure Ratings of Test Bodies

In this section, the pressure ratings using the following five code procedures are calculated and compared:

- Pressure Ratings by Division 2 Elastic-Plastic FEA;
- Pressure Ratings by Division 3 Elastic-Plastic FEA;
- Pressure Ratings by API 6A Linear-Elastic FEA;
- Pressure Ratings by Division 2 Linear-Elastic FEA; and
- Pressure Ratings by Proof Test.

The first four procedures are those that are allowed in TR8. These are the four procedures listed in Section 2.0. The fifth procedure is pressure rating by proof test. This procedure is allowed in API 6A and Division 3 but not in TR8. Since pressure ratings based on the proof test are not allowed in TR8, they are included in this study for comparison purposes only. A normal expectation would be that pressure ratings by an actual proof test would be higher than pressure ratings by theoretical methods.

Codes require that load ratings be determined using the minimum material strengths provided in the material specification. For this reason, all calculations for load ratings were done using the minimum specified material strengths.

Pressure ratings by Division 2 and Division 3 elastic-plastic FEA are based on the theoretical collapse pressures reported in Section 6.0. Pressure ratings by API and Division 2 linear-elastic FEA are based on linear-elastic FEA described in this section and in Appendix B. Pressure ratings by proof testing are described in this section and in Appendix E.

7.1 Pressure Ratings by Elastic-Plastic FEA

By the rules in Division 2 and Division 3, the allowable pressure rating based on elastic-plastic FEA is the theoretical plastic collapse pressure divided by the design load factor provided in the code. The design load factors are different for the two Codes:

- For Division 2:
  Design Load Factor = 2.4
- For Division 3:
  Design Load Factor = 1.8

Calculations for the collapse pressures of the large neck and small neck test bodies were completely described in Section 6.1. The collapse pressures from Section 6.1 are repeated below:

- 72,850 psi.... Collapse pressure of large neck test body with actual material;
- 62,750 psi.... Collapse pressure of large neck test body with as-specified material;
- 55,375 psi.... Collapse pressure of small neck test body with actual material; and
- 47,850 psi.... Collapse pressure of small neck test body with as-specified material.

For pressure rating calculations, the minimum material properties given in the material specification must be used. Dividing the collapse pressures for as-specified materials by the design load factor produced the following pressure ratings:

- Pressure Ratings of Large Neck Test Body:
  - 34,861 psi…Pressure rating by Division 3 elastic-plastic; and
  - 26,146 psi…Pressure rating by Division 2 elastic-plastic.
- Pressure Ratings of Small Neck Test Body:
  - 26,583 psi…Pressure rating by Division 3 elastic-plastic; and
  - 19,938 psi…Pressure rating by Division 2 elastic-plastic.

Comparing the pressure ratings shows that ratings by Division 3 are significantly higher than ratings by Division 2 (33 percent higher). Division 3 justifies its 33 percent higher pressure ratings by requiring enhanced material properties and fracture mechanics analyses that are not required by Division 2. However, the following important question must be answered: Does the requirement of fracture mechanics analysis and enhanced material properties justify a 33-percent increase in pressure rating for subsea equipment?

7.2 Pressure Ratings by Linear Elastic FEA

Pressure rating based on linear-elastic FEA is allowable under API 6A and under ASME Division 2, but not under ASME Division 3. API 6A adopts the analysis procedures in ASME Division 2. However, ever since the 2007 edition, API 6A and Division 2 have differed in a significant way: API 6A compares stress intensity with allowable stress, whereas Division 2 compares von Mises stress with allowable stress. In this report, pressure ratings for the large neck test body and the small neck test body were calculated based on stress intensity and von Mises stress.

Linear-elastic FEA was performed on the large neck and small neck test bodies using the same FEA models that were used for the elastic-plastic FEA. The only difference was that linear-elastic material properties were used for linear-elastic solutions. The two linear-elastic FEA models were solved for an internal pressure of 10,000 psi; however, since loads and stresses are linear in a linear-elastic FEA, the value of internal pressure is not important. The results at any pressure can easily be found using linear ratios of loads and stresses.

For both test bodies, stresses were linearized at the critical neck sections using post-processing options in the ANSYS FEA Program. Critical linearized stresses at the internal pressure of 10,000 psi are reported in Appendix B1 for the large neck test body and in Appendix B2 for the small neck test body.

As reported in Appendix B1 and Appendix B2, all critical linearized stresses at 10,000 psi are lower than the allowable stresses. Since FEA stresses are linear with pressure when linear-elastic materials are used, the internal pressure that produces the allowable stress can be easily calculated using linear analysis. These calculations are detailed in Appendix B1 and Appendix B2. Based on the calculations in these appendices, the rated pressures for the two bodies using the specified material properties were:

- Pressure Ratings for Large Neck Test Body Based on Linear-Elastic FEA:
  - 29,551 psi…Pressure rating based on API 6A (stress intensity); and
  - 34,091 psi…Pressure rating based on ASME Division 2 (von Mises stress).
- Pressure Ratings for Small Neck Test Body Based on Linear Elastic FEA:
  - 23,825 psiPressure rating based on API 6A (stress intensity); and
  - 27,483 psiPressure rating based on ASME Division 2 (von Mises stress).

API 6A and ASME Division 2 include maximum allowable stresses for the hydrotest load condition. When external forces and moments are zero or low, pressure ratings may be limited by the hydrotest case and not the normal operating case. This is especially true for ratings by API 6A. The pressure ratings listed above do not consider the hydrotest load condition. This means that for some applications, the pressure ratings may be lower than shown above.

7.3 Pressure Ratings by Proof Test

Many codes concerning pressure ratings describe methods for determining pressure ratings based on hydrostatic proof tests to failure. Generally, the procedure in one of these tests is to build a prototype of the component or assembly and then apply an incrementally increasing hydrostatic pressure until burst occurs. The allowable pressure rating, then, is the hydrostatic pressure at which burst occurs multiplied by a load reduction factor specified in the code.

Of the codes considered in this study, API 6A and ASME Division 3 provided procedures for pressure rating components based on proof test results. Division 2 and TR8 do not provide these procedures. However, TR8 does state that validation programs may include a proof test to failure. Since the burst tests performed on the two test bodies can be considered proof tests, pressure ratings can be calculated based on the proof test procedures described in these two codes.

Both codes provide an equation for calculating pressure rating based on burst pressure, a load reduction factor, and the ratio of minimum yield strength to actual yield strength of the component tested. These pressure rating calculations are included in Appendix E of the report. The pressure ratings for the two test bodies are summarized in Table 7.1.

Table 7.1 - Comparison of Pressure Ratings by Proof Test and Elastic-Plastic FEA

Test Body	Maximum Pressure Rating (psi)			
	API 6A Proof Test	Division 3 Proof Test	Division 3 Elastic-Plastic	Division 2 Elastic-Plastic
Small Neck Body	20,934	24,173	26,584	19,938
Large Neck Body	27,641	31,918	34,861	26,146

Comparing the ratings by proof test with the ratings by Division 3 FEA reveals an interesting result. Pressure ratings determined by Division 3 elastic-plastic FEA are greater than those determined by proof test. The natural expectation for this phenomenon is that a pressure rating based on proof test would be greater than one based on a theoretical analysis. Comparing pressure ratings by Division 2 to ratings by proof test shows that ratings determined by proof test are higher than theoretical ratings determined by Division 2 elastic-plastic FEA.

8.0 Pressure Ratings of Other Components by FEA

The original scope of this study was to calculate pressure ratings for the large neck and small neck test bodies. During the process of the study, the decision was made to also include two standard API flanges loaded with internal pressure.

Pressure ratings were calculated for the two flanges using both linear-elastic FEA and elastic-plastic FEA. Using the results of the linear-elastic FEA, pressure ratings were calculated using the procedures in API 6A and Division 2. Likewise, using the results of elastic-plastic FEA, pressure ratings were calculated using the design load factors in Division 2 and Division 3. Thus, four pressure ratings were calculated for each component.

In this section of the report, the FEA procedures and pressure rating calculations for the two API flanges are summarized. More extensive details of the FEA and the pressure rating calculations are included in the following Appendices:

- Appendix B3 ..... API 13 5/8 x 20k Flange; and
- Appendix B4 ..... API 16 3/4 x 10k Flange.

8.1 API 13 5/8 x 20k Flange

Geometry and FEA Model

The geometry and dimensions of the API 13 5/8 x 20k flange are given in Table B-54 in API 6A. Figure 8.1 shows the axisymmetric model and mesh for the elastic-plastic analysis. This same model was used for the linear-elastic analysis, but the elastic-plastic material properties were changed to reflect linear-elastic properties, and the internal pressure was changed to the rated pressure of 20 ksi. Internal pressure was applied to the OD of the seal groove. Pressure end load was provided by compressive pressure on the bolt area and was reacted by fixed axial displacements of all nodes on the pipe end of the model. The loads applied to the model were all pressure-induced loads.

Elastic-Plastic FEA

The elastic-plastic analysis for the flanges was performed just like the elastic-plastic analysis for the two test bodies. Since details of elastic-plastic procedures are described in Section 6.1, they are not repeated in this section. Also, the method of calculating pressure ratings from collapse pressures was described in Section 7.1 and will not be repeated in this section.

As shown in Figure 8.1, the elastic-plastic model was solved for a single load step with 300 equal iterations. The internal pressure after the 300th iteration was 75,000 psi. The 240th iteration was the last iteration that converged. Hence, the collapse pressure was:

collapse pressure = (240/300) x 75,000 psi = 60,000 psi

The pressure ratings based on elastic-plastic FEA were:

- Pressure Ratings for API 13 5/8 x 20k Flange by Elastic-Plastic FEA (Specified Material):
    - 25,000 psiPressure rating by Division 2; and
    - 33,333 psiPressure rating by Division 3.

Linear-Elastic FEA

The linear-elastic FEA for the flanges was performed exactly like the linear-elastic FEA for the two test bodies. Since the methods of linear-elastic analysis were described in Section 7.2, they will not be repeated in this section of the report.

From the linearized stress table in Appendix B3, the important linearized stresses in the critical section are:

- Linearized membrane stress intensity = 37,040 psi;

- Linearized membrane plus bending stress intensity = 58,830 psi;
- Linearized membrane von Mises stress = 32,210 psi; and
- Linearized membrane plus bending von Mises stress = 51,550 psi.

The allowable membrane stress was 50,000 psi, and the allowable membrane plus bending stress was 75,000 psi. Since stress is linear with pressure, the pressure ratings for the flange were easily calculated using linear ratios of stress and pressure. Pressure rating calculations are included in Appendix B3.

- Pressure Ratings for 13 5/8 x 20k Flange by Linear-Elastic FEA (Specified Material):
  - 25,497 psi...Pressure rating by API 6A (stress intensity); and
  - 29,098 psi…Pressure rating by ASME Division 2 (von Mises stress).

8.2 API 16 3/4 x 10k Flange

The elastic-plastic and linear-elastic FEA models, meshes, loads, boundary conditions, and important results for the 16 3/4 flange are included in Appendix B4. All aspects of the elastic-plastic and linear-elastic analyses were identical to those performed on the API 13 5/8 x 20k flange, except the flange geometry was different and the pressure for the elastic-plastic FEA was 10,000 psi. Since the procedures for these tests have been described in previous sections of the report, they will not be repeated in this section. Only the important results are listed below. The interested reader can review methods and calculations in Appendix B4.

Elastic-Plastic FEA

The collapse pressure of the API 16 3/4 x 10k flange based on elastic-plastic FEA was:

- Collapse pressure = 34,750 psi; and
- Pressure Ratings for API 16 3/4 x 10k Flange by Elastic-Plastic FEA:
  - 14,479 psi…Pressure rating by Division 2; and
  - 19,306 psi…Pressure rating by Division 3.

Linear-Elastic FEA

The pressure ratings for the API 16 3/4 x 10k flange based on linear-elastic analysis were:

- Pressure rating for membrane stress intensity = 14,310 psi;
- Pressure rating for membrane plus bending stress intensity = 16,991 psi;
- Pressure rating for membrane von Mises stress = 16,453 psi; and
- Pressure rating for membrane plus bending von Mises stress = 18,587 psi.

The allowable membrane stress was 50,000 psi, and the allowable membrane plus bending stress was 75,000 psi. Since stress is linear with pressure, pressure ratings for the flange based on linear-elastic FEA were:

- Pressure Ratings for 16 3/4 x 10k Flange by Linear-Elastic FEA:
  - 14,310 psi…Pressure rating by API 6A; and
  - 16,453 psi…Pressure rating by ASME Division 2.

9.0 Comparison of Pressure Ratings for All Components

Sections 7.0 and 8.0 presented pressure ratings for all of the components considered in this study. The presentations in the previous sections were organized by individual component. In Section 9.0, pressure ratings for all components and all codes will be summarized in a single table. This type of presentation allows for a better comparison of pressure ratings from a global viewpoint so that general trends can be evaluated.

9.1 Comparison of Pressure Ratings by Different Codes

Table 9.1 lists all collapse pressures and pressure ratings calculated in this study using the specified material properties. Each row corresponds to an individual component. The first column lists the component, the second column lists the plastic collapse pressure, and the next four columns list pressure ratings by code method. Note that Division 2 linear-elastic ratings are based on von Mises stress, which is the current method specified in the code. As discussed earlier in the report, prior to 2007, Division 2 based pressure ratings on stress intensity, which was more conservative than von Mises stress. When Division 2 linear-elastic ratings were based on stress intensity, pressure ratings were the same as ratings by API 6A.

Table 9.2 presents the same information as Table 9.1, but in a different format. Instead of pressure ratings, the table shows collapse pressure divided by pressure rating which is the design load factor. Obviously, lower design load factors indicate a lower factor-of-safety for the pressure rating.

A study of the data in Table 9.2 shows several important characteristics of pressure ratings calculated by different codes. It’s important to observe that Division 2 elastic-plastic analysis had the most conservative pressure ratings for the two test bodies. However, pressure ratings determined by API 6A were about equal to those determined by Division 2 elastic-plastic for the two flanges.

Table 9.1 - Pressure Ratings for all Components by FEA

(Based on the Specified Material Properties)

Descripton of Component	Plastic Collapse (psi)	Pressure Ratings (psi)			
		By Linear-Elastic FEA		By Elastic-Plastic FEA	
		API 6A	Division 2	Division 2	Division 3
Large Neck Test Body	62,750	29,551	34,091	26,146	34,861
Small Neck Test Body	47,850	23,825	27,483	19,938	26,583
API 13-5/8 x 20k Flange	60,000	25,497	29,098	25,000	33,333
API 16-3/4 x 10k Flange	34,750	14,310	16,453	14,479	19,306

Table 9.2 - Ratio of Pressure Rating to Collapse Pressure by FEA

(Based on the Specified Material Properties)

Desripton of Component	Plastic Collapse (psi)	Factor of Safety from Burst			
		By Linear-Elastic FEA		By Elastic-Plastic FEA	
		API 6A	Division 2	Division 2	Division 3
Large Neck Test Body	62,750	2.12	1.84	2.40	1.80
Small Neck Test Body	47,850	2.01	1.74	2.40	1.80
API 13-5/8 x 20k Flange	60,000	2.35	2.06	2.40	1.80
API 16-3/4 x 10k Flange	34,750	2.43	2.11	2.40	1.80

For all test components but the small neck test body, the least conservative pressure ratings were determined by Division 3 elastic-plastic analysis. Pressure ratings based on Division 2 linear-elastic analysis were nearly equal to the ratings based on Division 3 elastic-plastic analysis for the two test bodies, but not for the two flanges. The ratings for the two flanges were considerably less when based on Division 2 linear-elastic analysis rather than on Division 3 elastic-plastic analysis.

In all cases, the ratings determined by API 6A were lower than Division 2 linear-elastic ratings and Division 3 elastic-plastic ratings.

Now, consider the impact of these results on the pressure rating methods in API TR8 that were presented in Table 2.1:

- For pressures of 15 ksi or below, TR8 specifies the use of API 6A. API 6A is the most conservative of all the ratings methods in TR8, except for Division 2 elastic-plastic ratings with a design load factor of 2.4;
- For pressures greater than 20 ksi, TR8 requires that pressure ratings be based on Division 3 elastic-plastic analysis, which is generally the least conservative rating method; and
- For pressures above 15 ksi, but less than 20 ksi, TR8 specifies that pressure ratings be based on either Division 2 or Division 3 elastic-plastic or Division 2 linear-elastic analysis. Currently, the standard practice for most major subsea equipment manufacturers is to perform only elastic-plastic FEA. This means that, for pressures above 15 ksi and below 20 ksi, pressure ratings are probably done using Division 2 or Division 3 elastic-plastic analysis. Division 2 elastic-plastic analysis produces pressure ratings less than or equal to those based on API 6A. Division 3 produces pressure ratings higher than those based on API 6A.

A careful study of the three observations above reveals the following conclusion based on TR8 requirements:

> API TR8 criteria allow equipment rated for pressures above 15 ksi to have a lower margin of safety than equipment rated for pressures below 15 ksi.

TR8 justifies the lower margin of safety by the addition of additional material and analysis requirements, most of which seek to match the requirements in Division 3. Some of the more important requirements in TR8 are listed below:

- Product Specification Level 5 (PSL5) was added. PSL5 includes fracture toughness requirements, higher Charpy toughness values, and improved QA/QC;
- Linear-elastic FEA must be performed in accordance with Division 2, and elastic-plastic FEA must be performed in accordance with Division 2 and Division 3 codes; and
- Rigorous fatigue analysis must be performed in accordance with Division 2 or Division 3, and/or rigorous fracture mechanics analysis must be performed in accordance with Division 3.

Consider the additional material requirements in TR8. Materials that have been used in subsea equipment for many years already meet the additional requirements in TR8. Appendix F3 presents material test results for forgings manufactured by Forged Products Inc. for subsea equipment, such as BOP bodies, wellhead bodies, and connector bodies. A review of the data shows the material has exceptional properties, especially Charpy impact values. Most of the average Charpy values exceed 100 ft-lb. Based on the properties in this table, the additional material requirements in TR8 will not improve the structural reliability of subsea equipment. Hence, the improved material requirements in TR8 should not be used to justify lower margins of safety.

For pressures greater than 15 ksi, TR8 encourages the use of the Division 3 elastic-plastic FEA pressure rating method. This study demonstrates that this method is less conservative than other rating methods and is much less conservative than API 6A, which has proven to be reliable through decades of successful operating experience. TR8 has not provided any justification that the elastic-plastic FEA method in itself can justify the lower margin of safety for complex subsea equipment.

The subsea industry already performs rigorous fatigue analysis of subsea equipment. Usually, fatigue assessment is done based on DNV RP C203, which is more comprehensive and perhaps more rigorous than ASME requirements. Furthermore, DNV RP C203was developed specifically for offshore equipment, whereas ASME fatigue and fracture methods were written for pressure vessels. Therefore, the enhanced fatigue requirements in TR8 should not justify lower margins of safety.

Furthermore, fracture mechanics' crack growth calculations have limited usefulness in the analysis of how cracks propagate in subsea equipment. This is because fracture mechanics analysis requires an explicit, time-based load history. This history is not possible for subsea equipment because loads on subsea equipment are random and must be statistically defined. Loads on subsea equipment cannot be explicitly defined in the correct sequence, as required by Division 3.

Neither TR8 nor Division 3 offers any analytical calculations or experimental data proving that additional material requirements and more rigorous analysis requirements justify lower margins of safety. If the lower margins of safety in Division 3 are allowed, then engineering calculations and tests should be performed to confirm that additional requirements adequately lower risks of failure, so that lower margins of safety are safe from failure.

For example, this study revealed that failure pressures calculated from burst tests were 7 percent lower than failure pressures calculated from rigorous analysis. Although a 7 percent error is not huge, it is non-conservative. Moreover, the error may be greater for other, more complex components, like BOP connectors. Before the lower margins of safety in Division 3 are adopted, failure pressures by hydrotest and rigorous FEA should be compared for more complex subsea equipment.

9.2 Comparison of Historical Pressure Ratings with TR8 Ratings

Table 9.3 compares the pressure ratings of the two test bodies using the allowed methods in API TR8. The table compares ratings based on the linear-elastic methods in both TR8 and Division 2, and the elastic-plastic methods in both Division 2 and Division 3. The bottom row shows the historical time frame in which the method was commonly used by the subsea industry.

Table 9.3 - Comparison of Internal Pressure Ratings of Test Bodies (At 70 F and with As-Specified Material Properties)

Test Body	Linear-Elastic FEA			Elastic-Plastic FEA	
	API 6A Using Stress Intensity	ASME Division 2 Using Stress Intensity	ASME Division 2 Using von Mises Stress	ASME Division 3 Using Plastic Collapse	ASME Division 2 Using Plastic Collapse
Small Neck	23,825	23,825	27,483	26,584	19,938
Large Neck	29,551	29,551	34,091	34,861	26,146
	From 1970 to Present	From 1970 to 2007	From 2007 to Present	From 2015 to Present	From 2015 to Present

Figure 9.1 shows plots of the pressure rating data in Table 9.3. Figure 9.1A represents data for the large neck body, and Figure 9.1B represents data for the small neck body. The purpose of Figure 9.1 is to compare pressure ratings determined by TR8 methods on a historical basis since 1970. Each line in the plots shows the historical rating by one of the following methods:

- API 6A by Linear-Elastic FEA (from approximately 1970 to present);
- ASME Division 2 by Linear-Elastic FEA (from approximately 1970 to 2007);
- ASME Division 2 by Linear-Elastic FEA (from 2007 to present);
- ASME Division 2 by Elastic-Plastic FEA (from 2015 to present); and
- ASME Division 3 by Elastic-Plastic FEA (from 2015 to present).

Note that pressure ratings determined by elastic-plastic FEA were not allowed prior to 2015 before TR8 was published. Even so, elastic-plastic pressure ratings have been extended in the plots back to 1970 so the ratings can be easily compared to historical ratings.

Note that the pressure rating curves in Figure 9.1 and the data in Table 9.3 are for the two test bodies. The figure and data point out some interesting features for the test bodies:

- The most conservative pressure ratings were determined by ASME Division 2 elastic-plastic FEA. Pressure ratings determined by this method were less than those allowed by API 6A since 1970. This means equipment rated by the Division 2 elastic-plastic method has lower pressure ratings than historical pressure ratings that have proven to be reliable. This also means equipment that has been pressure rated using Division 2 elastic-plastic analysis has a higher margin of safety than historical equipment.
- Pressure ratings by ASME Division 3 are significantly greater than those allowed by API 6A since 1970. This means equipment rated by this method has higher pressure ratings than equipment proven satisfactory based on decades of operational history. In other words, equipment pressure rated by Division 3 has lower margins of safety than historical equipment.
- Equivalent design factors for historical pressure ratings can be calculated from the data in Table 9.3. For the large neck test body, dividing the plastic collapse pressure of 62,750 psi by the API 6A pressure rating of 29,551 psi produces an equivalent design factor of 2.12. Likewise, for the small neck test body, the plastic collapse pressure is 47,850 psi, and the API 6A pressure rating is 23,825 psi, which produces a design factor of 2.01.
- When ASME Division 2 linear-elastic analysis changed from being based on stress intensity to being based on von Mises stress, pressure ratings substantially increased. In fact, pressure ratings based on Division 2 linear-elastic analysis provide the greatest ratings compared to the other methods used for the large neck test body. This means that pressure ratings based on Division 2 linear-elastic analysis after 2015 are considerably higher than historical pressure ratings, and the margins of safety are much less.

10.0 Conclusions

The following are the important conclusions of this study. These conclusions are based on results of the elastic-plastic FEA and hydro-tests that were performed as part of this study. The conclusions apply to HPHT subsea equipment rated for 20 ksi or less. No consideration has been given to equipment rated for pressures greater than 20 ksi. However, there is no apparent reason that these conclusions would not apply to equipment rated for pressures higher than 20 ksi.

These conclusions were marginally revised after the consideration of peer-review comments. The majority of the revisions are in the discussion section after each conclusion. These revisions were made to clarify a few misunderstandings that were evident from the peer-review comments. The content of the conclusions themselves has not substantially changed.

The Division 3 elastic-plastic method is not recommended for HPHT subsea equipment as published with a 1.8 design load factor until supplementary validation is performed.

ASME, Division 3, allows a 1.8 load factor for calculating load ratings based on elastic-plastic FEA. This is lower than the 2.4 load factor allowed by ASME, Division 2. The Argonne study shows that the equivalent load factor for existing subsea equipment is about 2.1 for simple shapes. Decades of successful operating experience show that the equivalent load factor of 2.1 has produced safe, reliable subsea equipment.

Pressure-vessel experts working with ASME have determined that a 1.8 load factor is suitable for pressure vessels designed and manufactured in accordance with the rules in Division 3. The Argonne study did not consider pressure vessels and does not question the use of a 1.8 load factor for Division 3 pressure vessels.

Nonetheless, just because a 1.8 load factor is suitable for pressure vessels does not mean it is suitable for HPHT subsea equipment. Many important characteristics of HPHT subsea equipment are significantly different from pressure vessels, as acknowledged in the following quote from Section 4.2.1.4 in TR8:

> *"….Oilfield equipment are of complex geometry, far from a simple cylindrical pressure vessel or piping union design. They are typically subjected to a variety of extreme external loading conditions and they are not explicitly addressed in ASME BPVC……"*

Another important consideration is that TR8 does not require that all the rules and requirements in Division 3 be used. TR8 adopts only a small part of Division 3.

A 1.8 load factor may produce HPHT equipment that is reliable and safe for subsea operation. However, TR8 does not provide any references validating that a 1.8 load factor is suitable for HPHT subsea equipment. Until scientific studies or tests are offered that validate the suitability of a 1.8 load factor for HPHT subsea equipment, it is recommended that a larger load factor be used for HPHT subsea equipment.

The Division 3 elastic-plastic method with a design load factor of 2.1 is recommended to calculate load ratings for HPHT subsea equipment.

This recommendation is based on the results of the Argonne study and the validation data currently available in the public domain. If scientific studies or tests exist in the public domain that validate a 1.8 load factor, then it is recommended that the TR8 committee publish a paper presenting this work so that it can be peer-reviewed. If the TR8 committee cannot do this, then the committee should commission appropriate scientific studies or tests validating that a 1.8 load factor is adequate for HPHT subsea equipment.

A Division 3 analysis with a design load factor of 1.8 is acceptable if the factor is applied to results of a load test, and validation is provided that demonstrates the additional requirements in TR8 and Division 3 sufficiently reduce the risk of failure.

Paragraph KD-1254 in Division 3 provides a procedure for rating equipment based on a proof test. This confirms that a proof test to failure is acceptable by Division 3 as a means to pressure-rate equipment.

The design load factor in Division 2 is 2.4, which is 33% greater than the design load factor of 1.8 in Division 3. ASME and TR8 state that this reduction in the margin of safety is validated by additional requirements, such as fracture mechanics in Division 3. HPHT subsea equipment in general has more complex shapes, more multibody contacts of components, and different materials as compared to pressure vessels. Before a load rating for HPHT subsea equipment is determined by dividing the test loads by a design load factor of 1.8, the user should confirm that the reduction in margin of safety has been validated.

For a Division 2 linear-elastic analysis, it is recommended that stress intensities are compared with allowable stresses and not von Mises stresses until supplementary validation is performed.

The Division 2 linear-elastic method is an acceptable method in TR8 to rate HPHT subsea equipment for pressures of 20 ksi or less. Division 2 allows that von Mises stresses be compared with allowable stresses, whereas API historically has compared stress intensities with allowable stresses.

The Argonne study revealed that the use of von Mises stresses allows higher pressure ratings for subsea equipment. Since subsea equipment has historically been rated using linear-elastic analysis with stress intensity, the design margins based on von Mises stresses will be lower than the design margins of historically successful equipment. The safety of reduced design margins based on the use of von Mises stresses should be investigated before the subsea industry makes this change. Until this issue is investigated, it is recommended that the HPHT subsea industry continue using stress intensities.

Note that this is not a question about the accuracy of von Mises stress, but about the safety of reduced margins of safety. Scientific studies and tests have confirmed that von Mises stress is a more accurate predictor of yield than stress intensity. Stress intensity is always greater than or equal to von Mises stress.

It is recommended that the subsea industry compare collapse pressures from FEA with burst pressures from hydro-tests for a variety of subsea equipment.

For numerous subsea components, the subsea industry should compare the collapse pressures from elastic-plastic FEA with the actual burst pressures from hydro-tests. This is necessary to validate the accuracy of collapse pressures by FEA. The reason for this recommendation is that the Argonne study showed that collapse pressures from FEA were higher than burst pressures for the two test bodies that were evaluated in this study.

This is an especially concerning outcome for subsea equipment because the two test bodies in this study were simple shapes. Many subsea components have much more complex geometries, and many have geometries with multibody contacts. It is possible that more complex shapes with multibody contacts will be even less conservative than the simple shapes evaluated in this study.

The subsea industry should confirm that performing the fracture mechanics analysis required by Division 3 justifies reduction of the design load factor to 1.8.

Reduction of the design margin based on performance of fracture mechanics may not be suitable for HPHT subsea equipment. The following are two important reasons this is true:

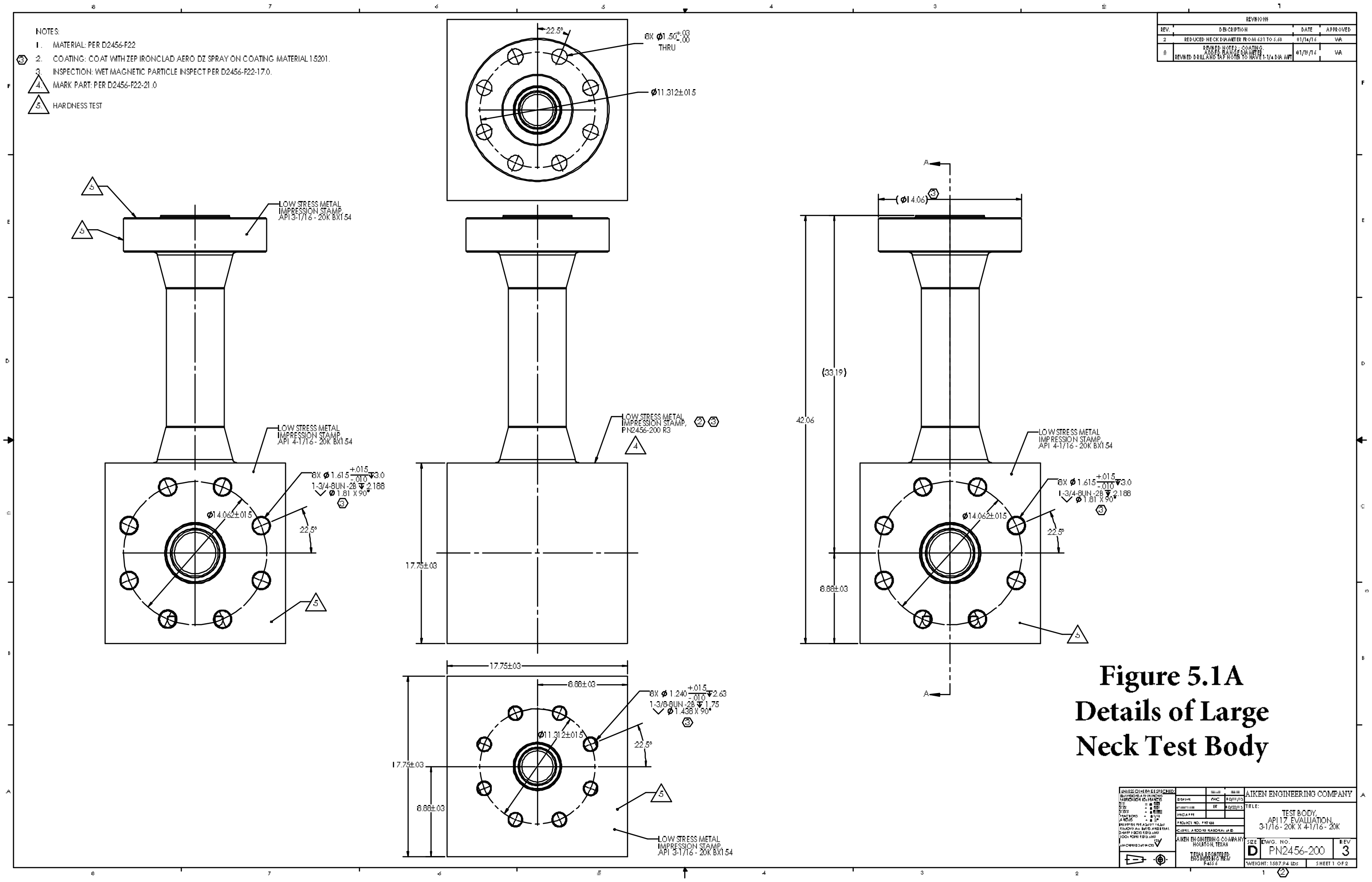
1. Division 3 justifies the reduction of the design load factor based on the requirement of fracture mechanics analysis. The purpose of a fracture mechanics analysis is to ensure that defects do not propagate to the critical crack size and cause a rapid, brittle failure. This may not be a critical failure mode for subsea equipment. TR8 requires that all pressure-containing components meet the material requirements in API 6A and NACE MR0175. Material that meets the requirements of these two codes will be ductile, have high impact strengths, and have high fracture toughness. Materials with these properties are not susceptible to brittle failures. Operating history confirms that subsea equipment

made of materials that meet these requirements are not susceptible to brittle fractures. A reduced design margin should not be justified by requiring an analysis to prevent brittle failure if brittle fracture has historically not been a problem and is not expected to be a problem in the future.

2. To perform a fracture mechanics analysis, Division 3 requires a load histogram with loads in the same sequence that they will be applied in service. This is usually easy for the pressure vessels for which Division 3 was written. However, developing a load histogram with loads in the proper sequence may not be practical or perhaps even possible for HPHT subsea equipment. The reason is that the highly cyclic loads on subsea equipment capable of causing fatigue cracks are randomly applied by the environment. This means that load histograms for subsea equipment must be statistically defined in load bins with a percent occurrence time for each load bin. The sequence of application is random and unpredictable. It may be possible to convert a statistically based load histogram into a conservative sequence. However, this has not been demonstrated in a published and peer-reviewed format. This should be done before subsea equipment design margins are reduced based on fracture mechanics analysis.

11.0 Figures

Below is a list of the figures that are referenced in the text of this report. They are provided in the following pages.



NOTES:

1. MATERIAL: PER D2456-F22
2. ③ COATING: COAT WITH ZEP IRONCLAD AERO DZ SPRAY ON COATING MATERIAL 15201.
3. INSPECTION: WET MAGNETIC PARTICLE INSPECT PER D2456-F22-17.0.
4. MARK PART: PER D2456-F22-21.0
5. HARDNESS TEST

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
2	REDUCED NECK DIAMETER FROM 6.21 TO 5.68	01/14/16	WA
3	REVISED NOTE 2 - COATING. ADDED FLANGE DIAMETER REVISED DRILL AND TAP NOTES TO HAVE 1-1/4 DIA MFT	01/19/16	WA

UNLESS OTHERWISE SPECIFIED:				AIKEN ENGINEERING COMPANY		
DIMENSIONS ARE IN INCHES	DRAWN	PWC	10/11/15	TITLE: TEST BODY, API 17 EVALUATION, 3-1/16 - 20K X 4-1/16 - 20K		
		ER	10/22/15			
	ENG APPR					
	PROJECT NO. PN2456					
MACHINED SURFACES 125	AIKEN ENGINEERING COMPANY HOUSTON, TEXAS TEXAS REGISTERED ENGINEERING FIRM F4556			SIZE D	DWG. NO. PN2456-200	REV 3
				WEIGHT: 1587.94 lbs		SHEET 1 OF 2

Figure 5.1A
Details of Large Neck Test Body

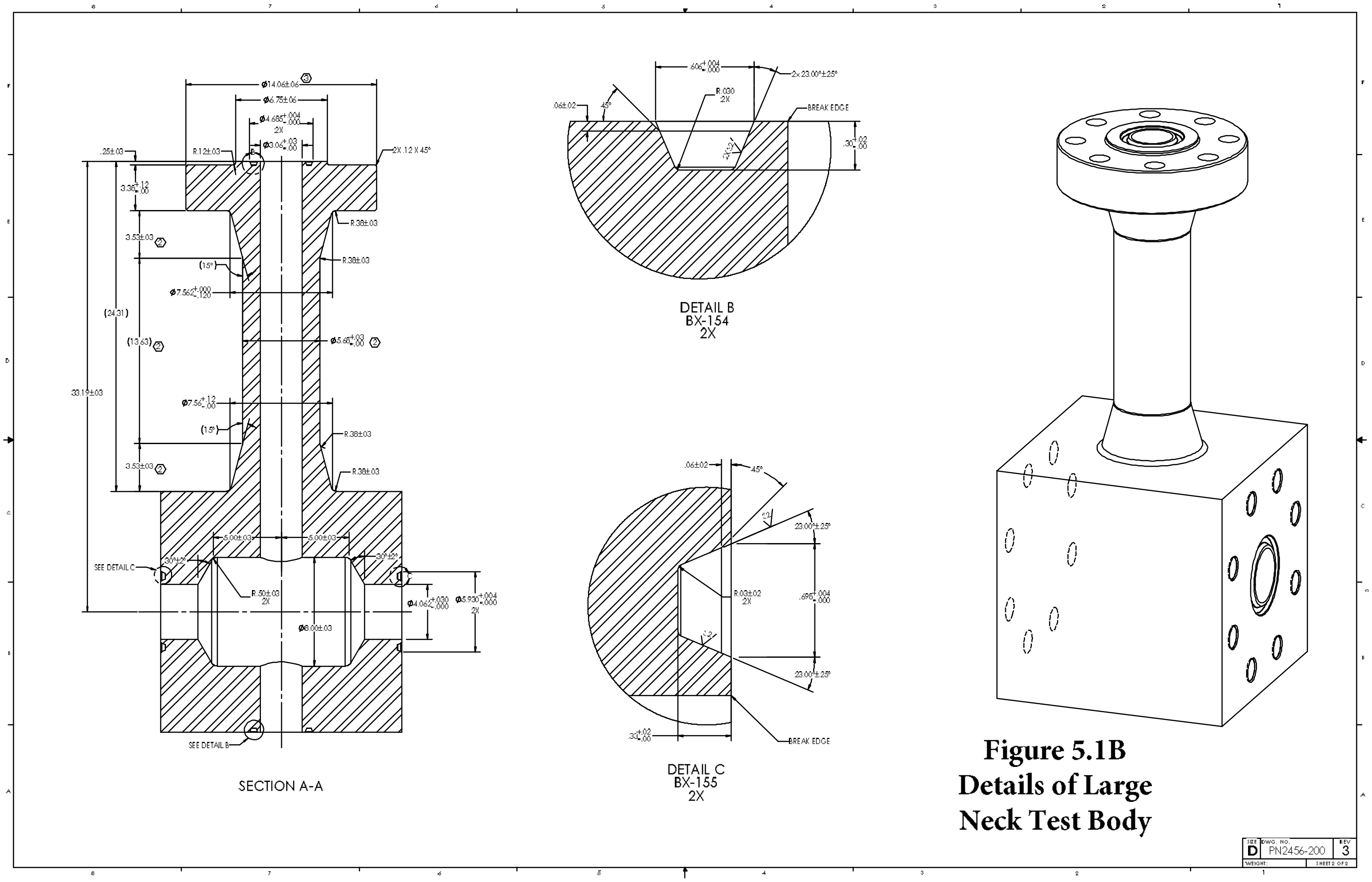


Figure 5.1B
Details of Large Neck Test Body

SIZE	DWG. NO.	REV
D	PN2456-200	3
WEIGHT:		SHEET 2 OF 2

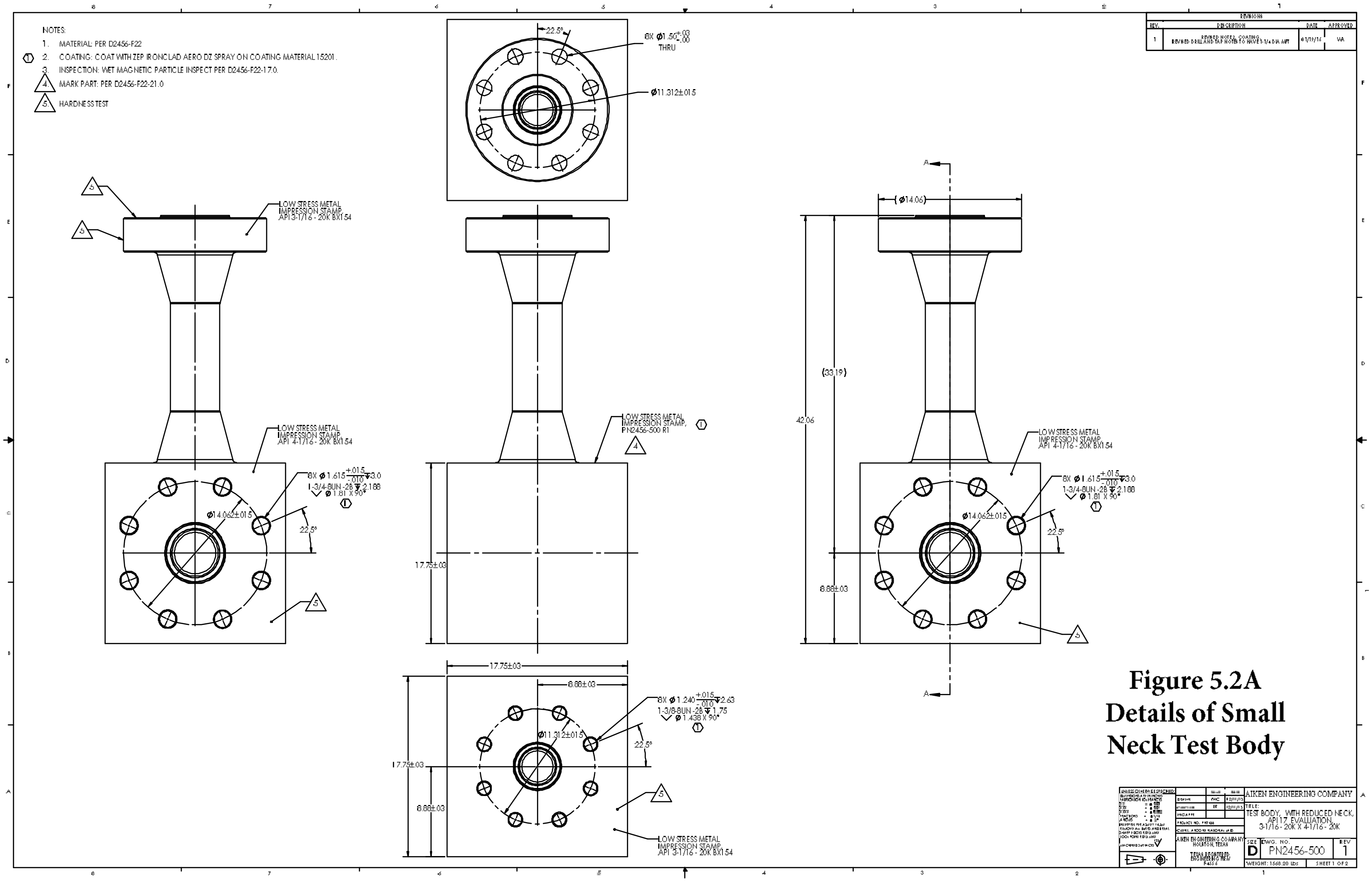


Figure 5.2A
Details of Small
Neck Test Body

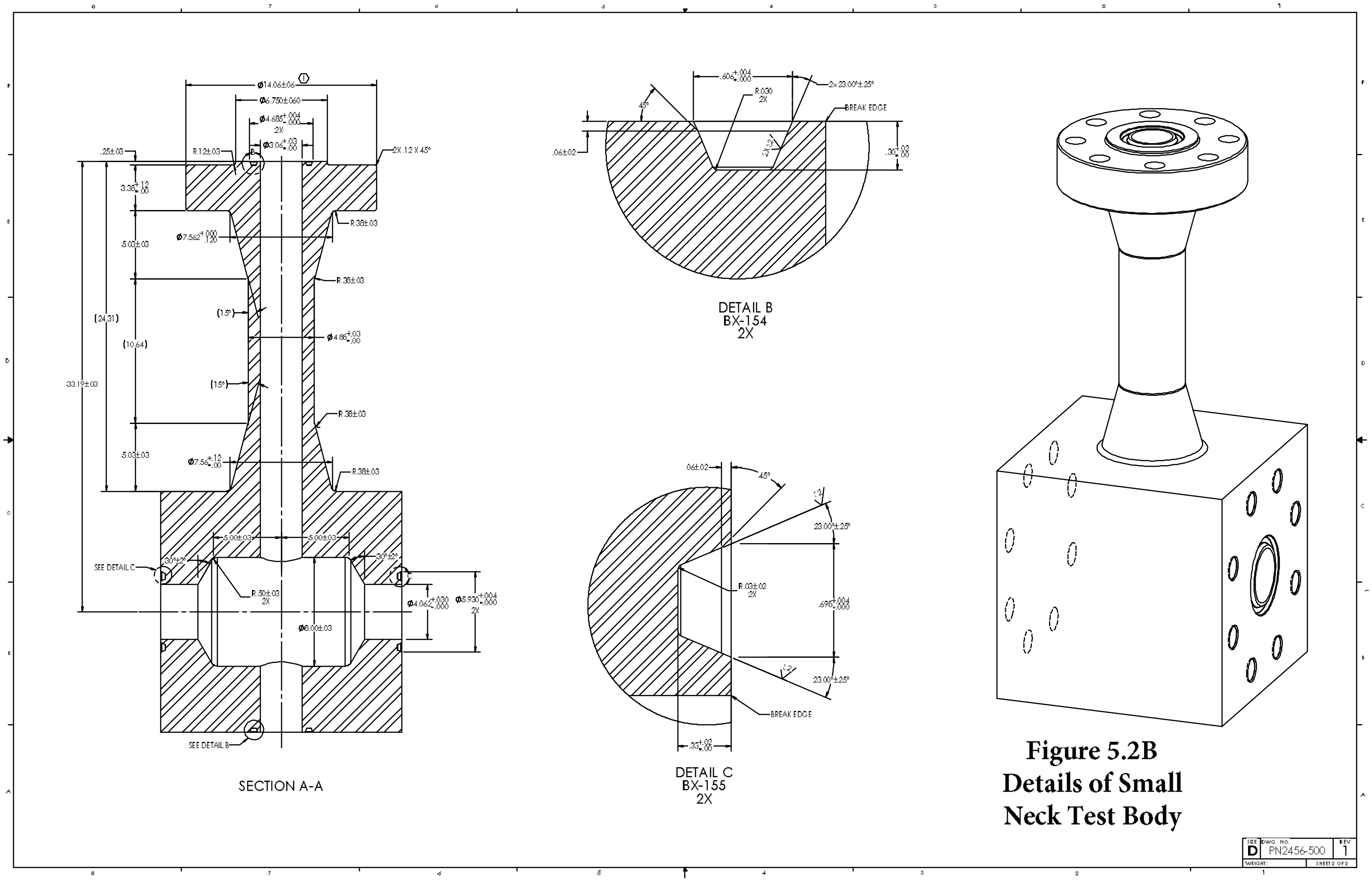
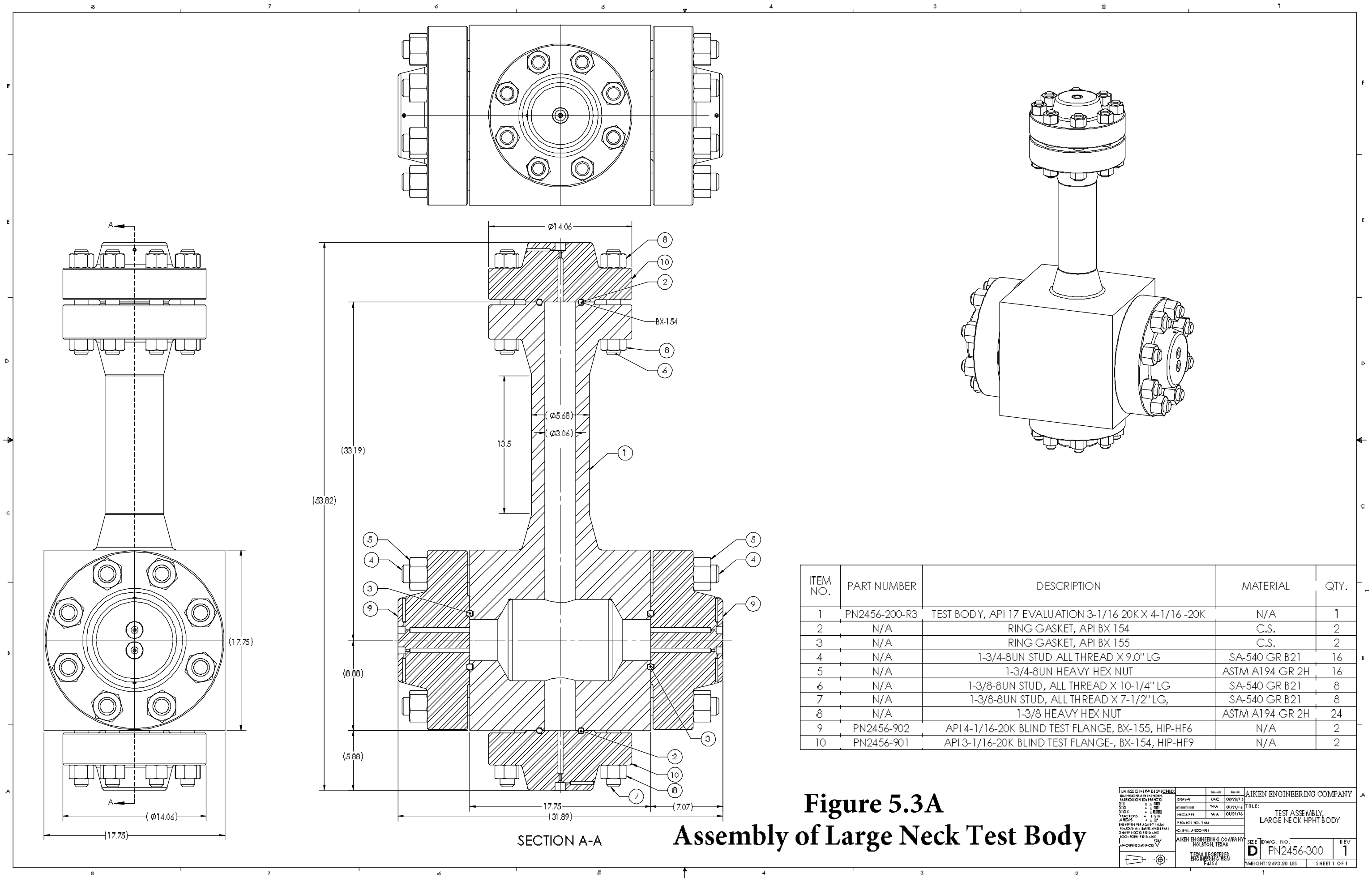


Figure 5.2B
Details of Small
Neck Test Body



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	PN2456-200-R3	TEST BODY, API 17 EVALUATION 3-1/16 20K X 4-1/16 -20K	N/A	1
2	N/A	RING GASKET, API BX 154	C.S.	2
3	N/A	RING GASKET, API BX 155	C.S.	2
4	N/A	1-3/4-8UN STUD ALL THREAD X 9.0" LG	SA-540 GR B21	16
5	N/A	1-3/4-8UN HEAVY HEX NUT	ASTM A194 GR 2H	16
6	N/A	1-3/8-8UN STUD, ALL THREAD X 10-1/4" LG	SA-540 GR B21	8
7	N/A	1-3/8-8UN STUD, ALL THREAD X 7-1/2" LG,	SA-540 GR B21	8
8	N/A	1-3/8 HEAVY HEX NUT	ASTM A194 GR 2H	24
9	PN2456-902	API 4-1/16-20K BLIND TEST FLANGE, BX-155, HIP-HF6	N/A	2
10	PN2456-901	API 3-1/16-20K BLIND TEST FLANGE-, BX-154, HIP-HF9	N/A	2

UNLESS OTHERWISE SPECIFIED:

DRAWN	CWC	09/28/15
	WA	01/21/16
ENG APPR	WA	01/21/16

PROJECT NO. 7456

AIKEN ENGINEERING COMPANY
HOUSTON, TEXAS

TEXAS REGISTERED
ENGINEERING FIRM
F-4556

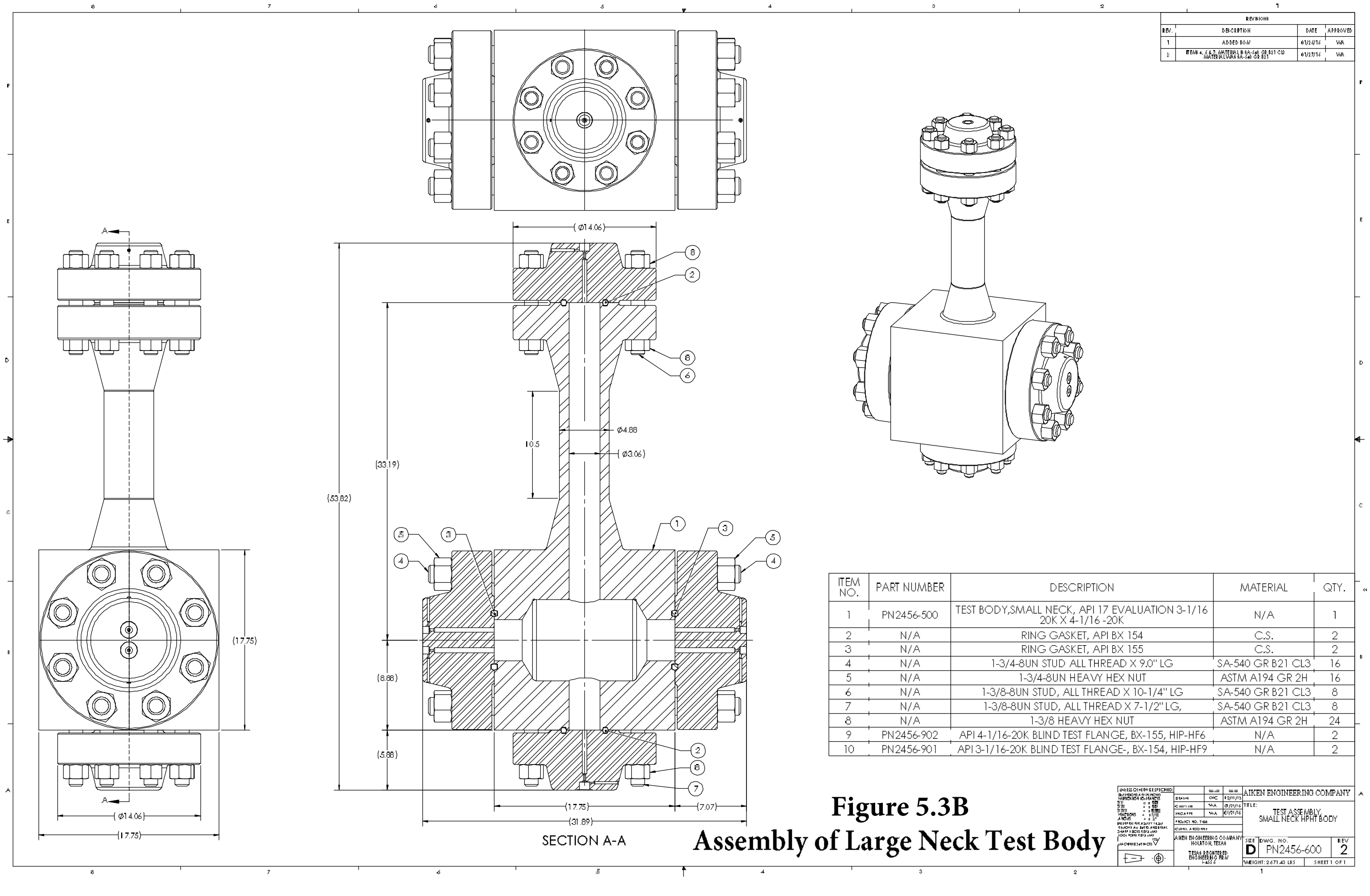
AIKEN ENGINEERING COMPANY

TITLE:
TEST ASSEMBLY,
LARGE NECK HPHT BODY

SIZE D DWG. NO. PN2456-300 REV 1

WEIGHT: 2693.20 LBS SHEET 1 OF 1

Figure 5.3A
Assembly of Large Neck Test Body



REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
1	ADDED BOM	01/26/16	WA
2	ITEMS 4, 6 & 7: MATERIAL IS SA-540 GR B21 CL3 MATERIAL WAS SA-540 GR B21	01/27/16	WA

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	PN2456-500	TEST BODY,SMALL NECK, API 17 EVALUATION 3-1/16 20K X 4-1/16 -20K	N/A	1
2	N/A	RING GASKET, API BX 154	C.S.	2
3	N/A	RING GASKET, API BX 155	C.S.	2
4	N/A	1-3/4-8UN STUD ALL THREAD X 9.0" LG	SA-540 GR B21 CL3	16
5	N/A	1-3/4-8UN HEAVY HEX NUT	ASTM A194 GR 2H	16
6	N/A	1-3/8-8UN STUD, ALL THREAD X 10-1/4" LG	SA-540 GR B21 CL3	8
7	N/A	1-3/8-8UN STUD, ALL THREAD X 7-1/2" LG,	SA-540 GR B21 CL3	8
8	N/A	1-3/8 HEAVY HEX NUT	ASTM A194 GR 2H	24
9	PN2456-902	API 4-1/16-20K BLIND TEST FLANGE, BX-155, HIP-HF6	N/A	2
10	PN2456-901	API 3-1/16-20K BLIND TEST FLANGE-, BX-154, HIP-HF9	N/A	2

UNLESS OTHERWISE SPECIFIED:

DRAWN	CWC	12/11/15
	WA	01/21/16
ENG APPR	WA	01/21/16

PROJECT NO. 7456

AIKEN ENGINEERING COMPANY
HOUSTON, TEXAS

TEXAS REGISTERED
ENGINEERING FIRM
F-4556

AIKEN ENGINEERING COMPANY

TITLE:
TEST ASSEMBLY,
SMALL NECK HPHT BODY

SIZE D DWG. NO. PN2456-600 REV 2

WEIGHT: 2671.43 LBS SHEET 1 OF 1

Figure 5.3B
Assembly of Large Neck Test Body

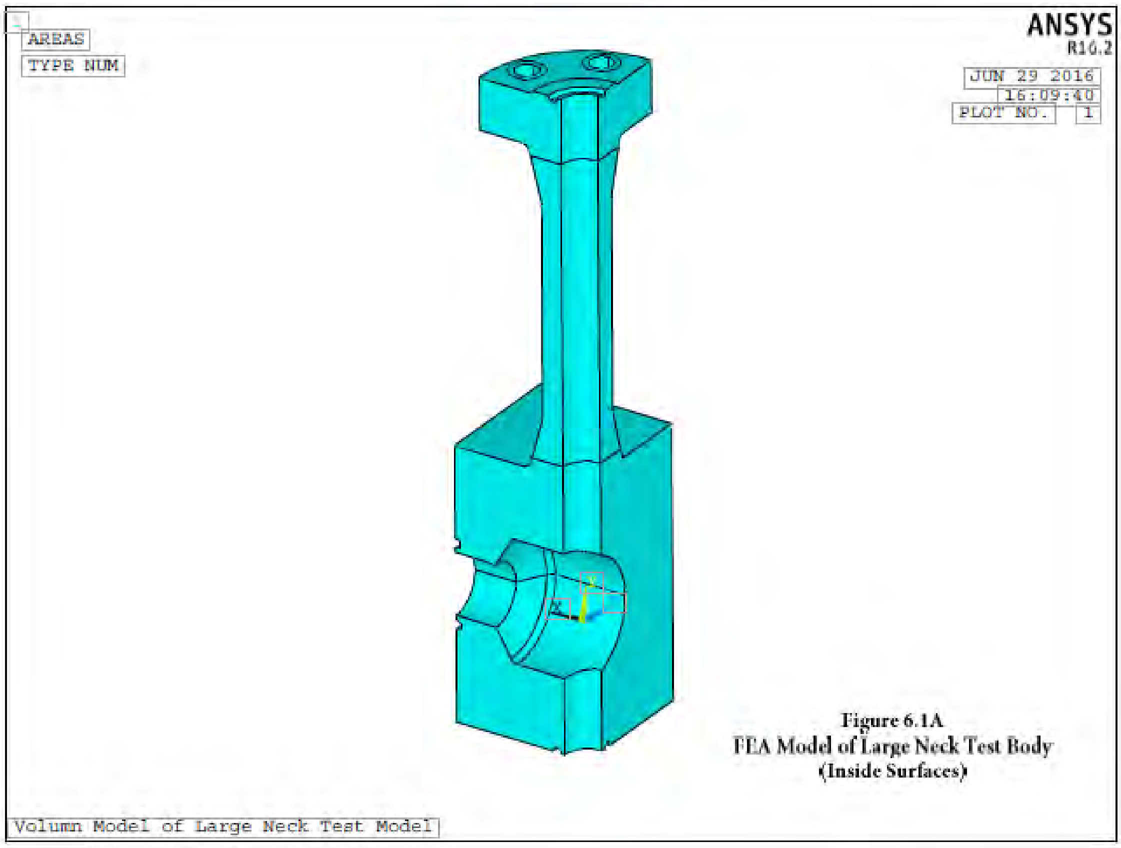


Figure 6.1A
FEA Model of Large Neck Test Body
(Inside Surfaces)

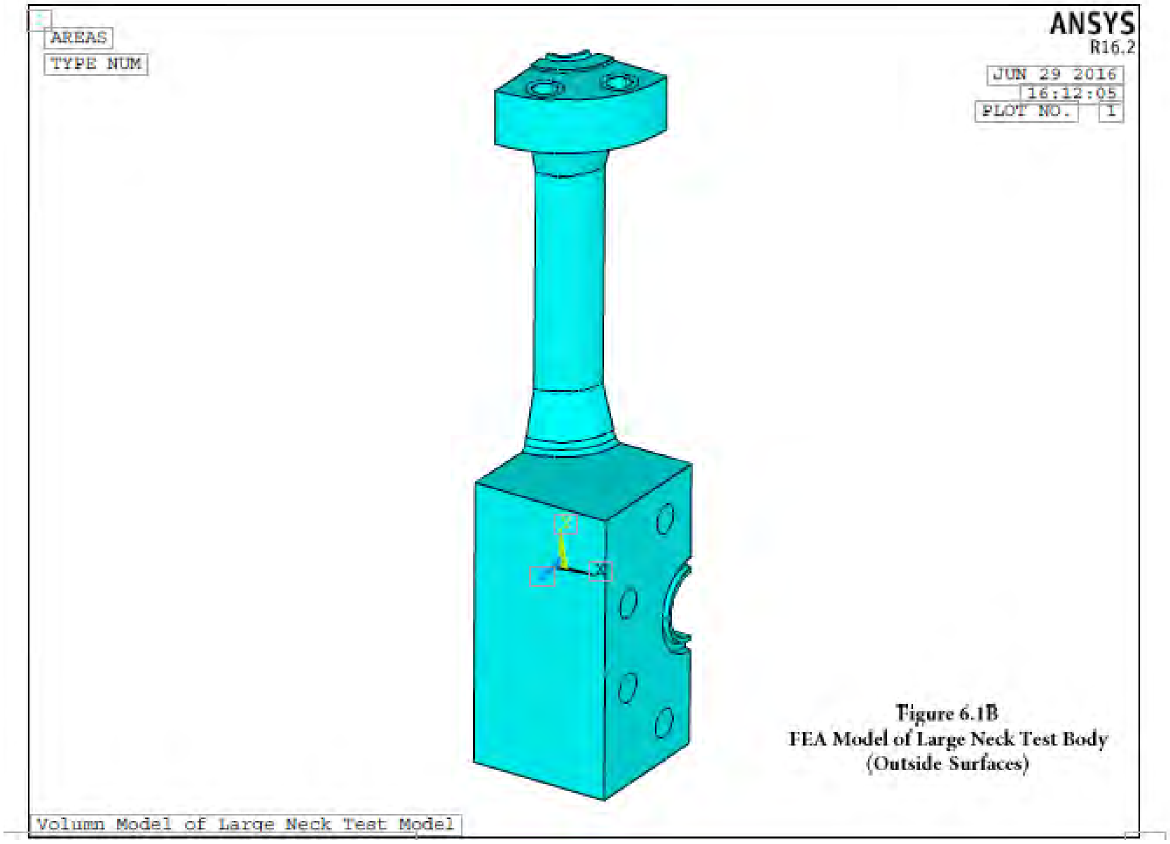


Figure 6.1B
FEA Model of Large Neck Test Body
(Outside Surfaces)

Figure 6.2
Assembled Test Body
Ready for Testing

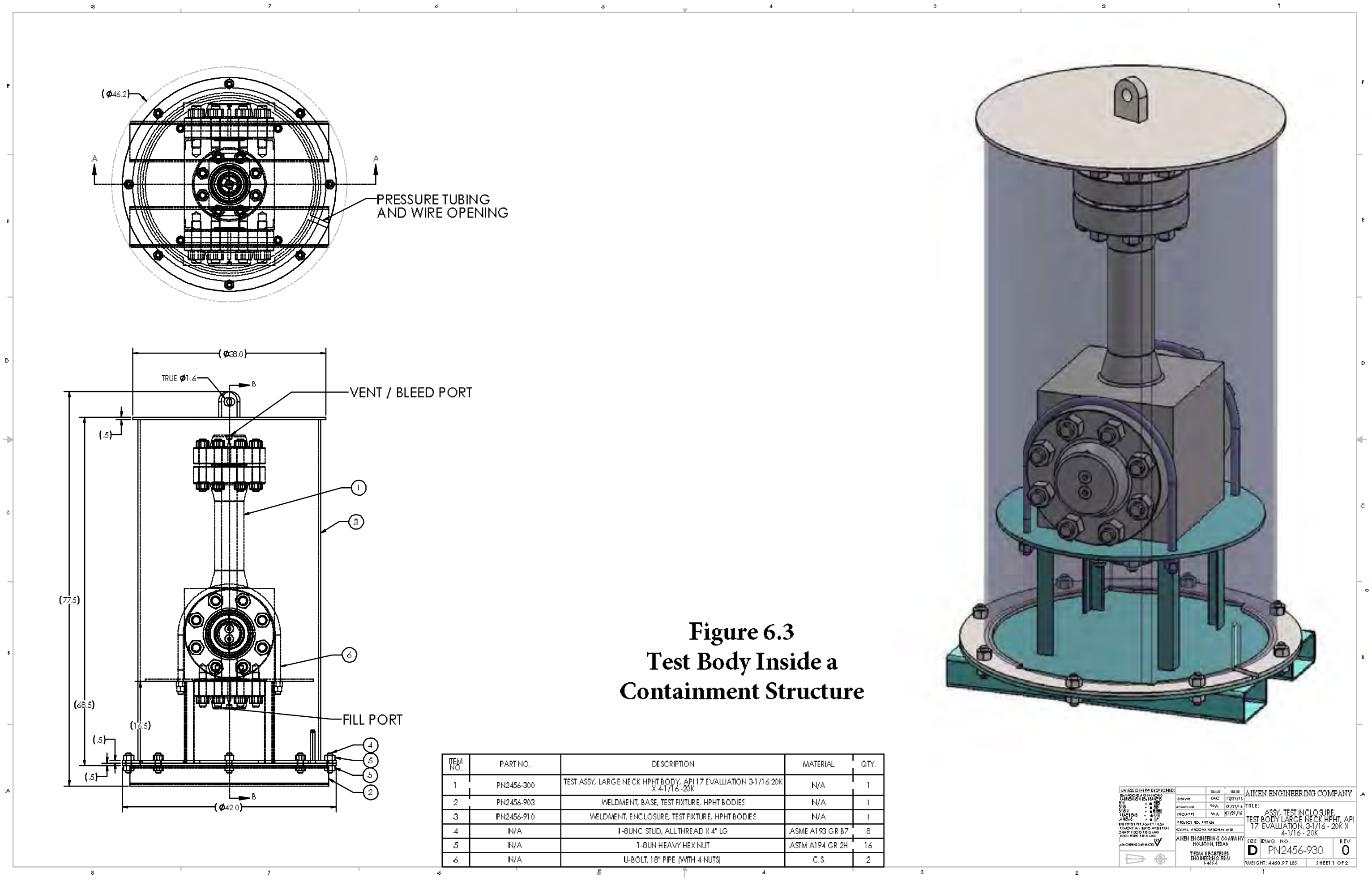
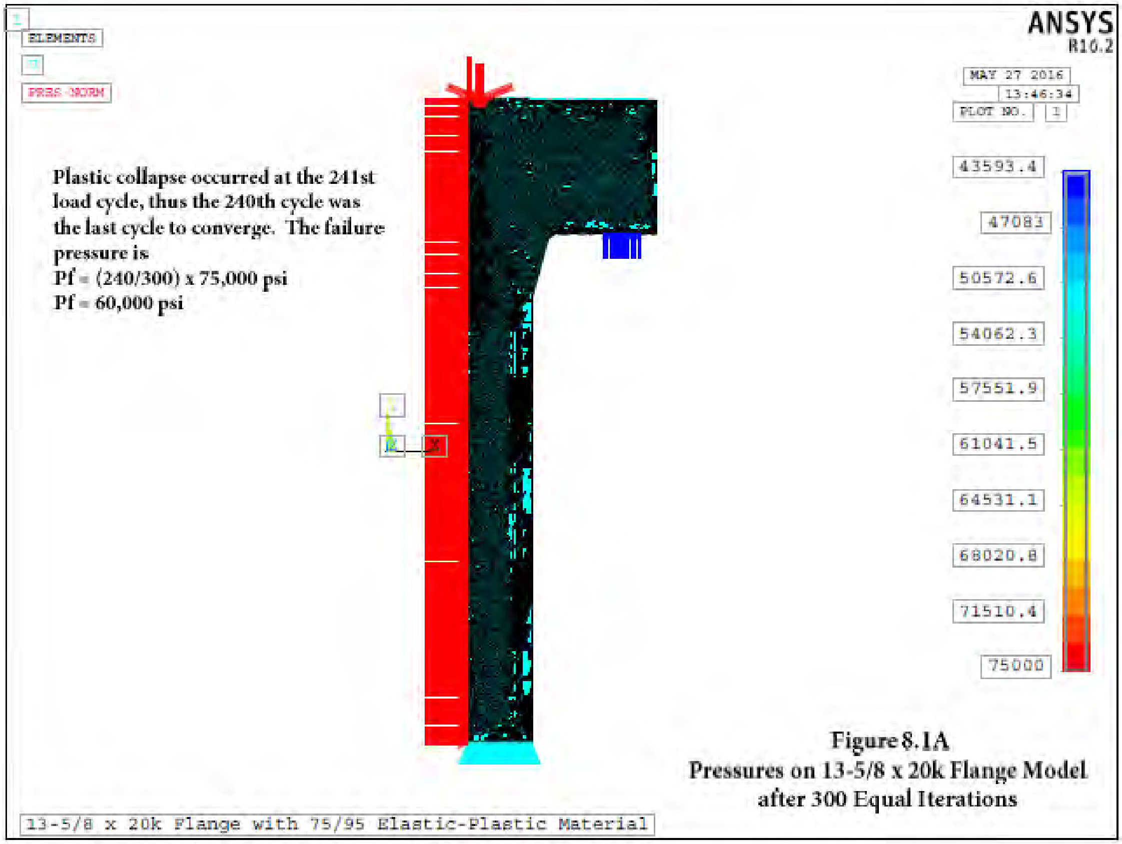


Figure 6.3
Test Body Inside a
Containment Structure

ITEM NO.	PART NO.	DESCRIPTION	MATERIAL	QTY.
1	PN2456-300	TEST ASSY, LARGE NECK HPHT BODY, API 17 EVALUATION 3-1/16 20K X 4-1/16 -20K	N/A	1
2	PN2456-903	WELDMENT, BASE, TEST FIXTURE, HPHT BODIES	N/A	1
3	PN2456-910	WELDMENT, ENCLOSURE, TEST FIXTURE, HPHT BODIES	N/A	1
4	N/A	1-8UNC STUD, ALL THREAD X 4" LG	ASME A193 GR B7	8
5	N/A	1-8UN HEAVY HEX NUT	ASTM A194 GR 2H	16
6	N/A	U-BOLT, 18" PIPE (WITH 4 NUTS)	C.S	2

Figure 6.4
Rupture Failure in
Large Test Body

Figure 6.5
Rupture Failure in
Small Test Body



Plastic collapse occurred at the 241st load cycle, thus the 240th cycle was the last cycle to converge. The failure pressure is

Pf = (240/300) x 75,000 psi

Pf = 60,000 psi

Figure 8.1A
Pressures on 13-5/8 x 20k Flange Model after 300 Equal Iterations

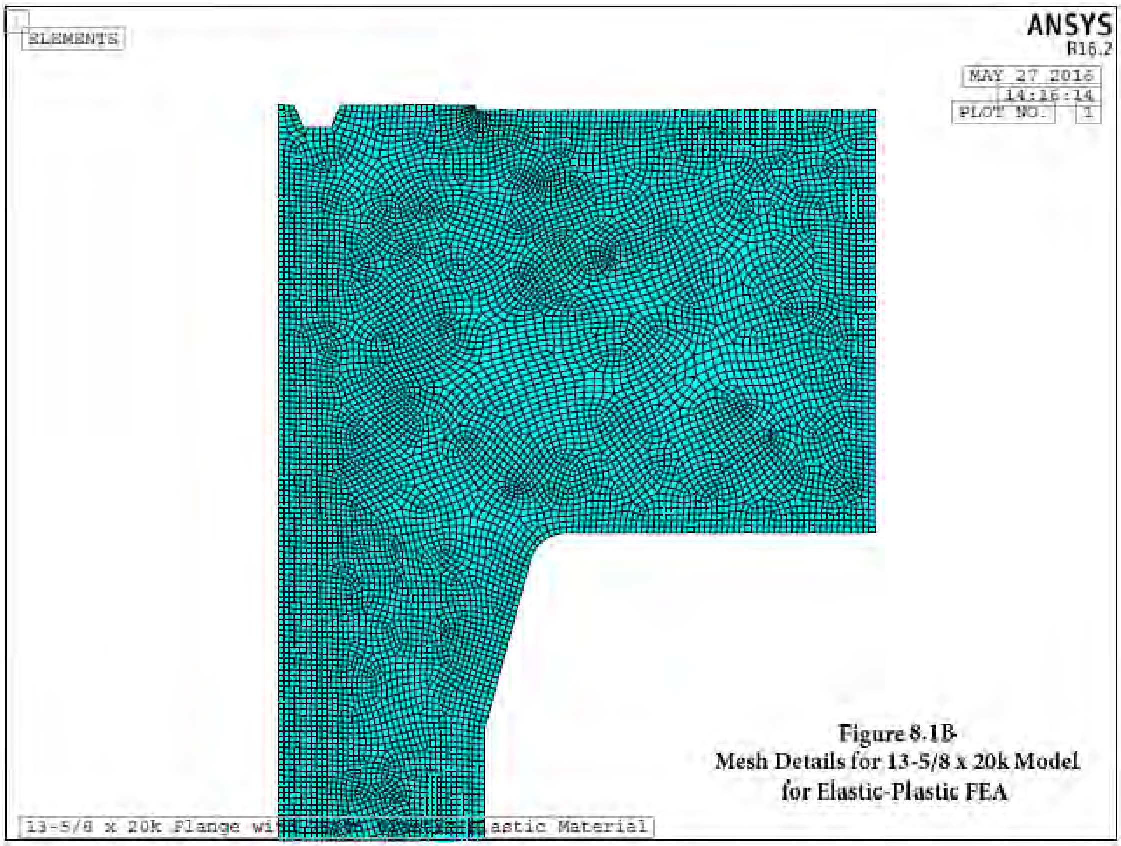


Figure 8.1B
Mesh Details for 13-5/8 x 20k Model for Elastic-Plastic FEA

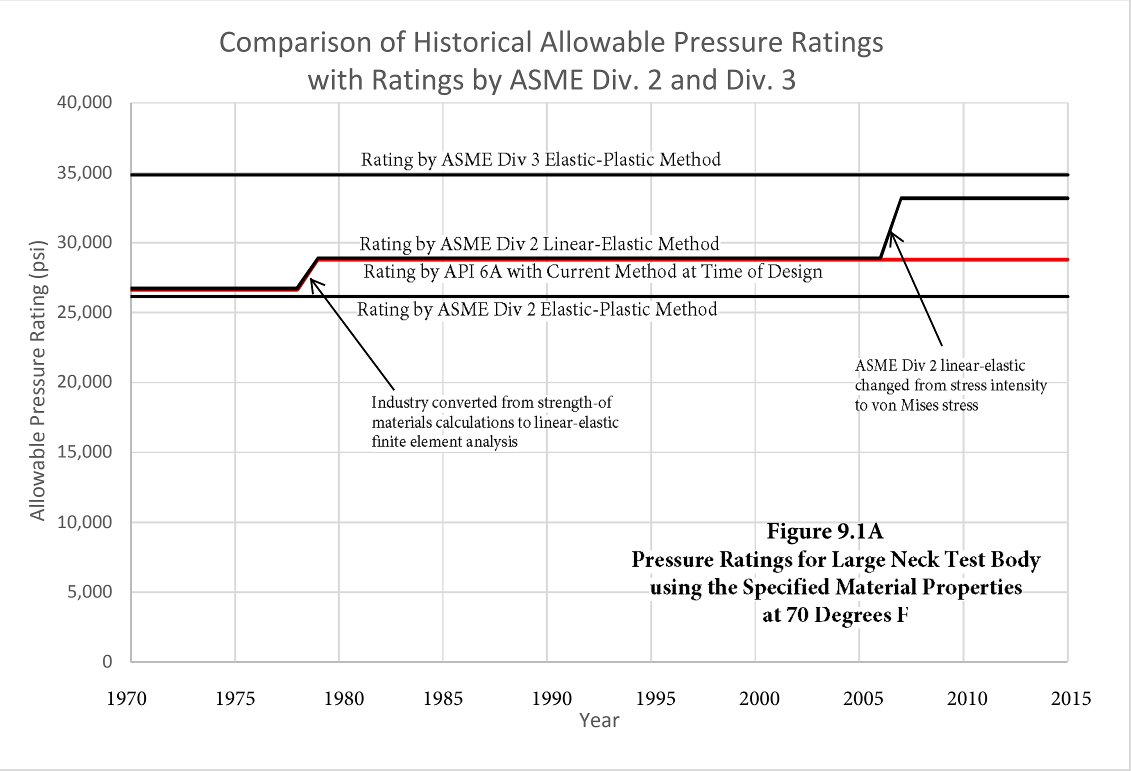


Figure 9.1A
Pressure Ratings for Large Neck Test Body using the Specified Material Properties at 70 Degrees F

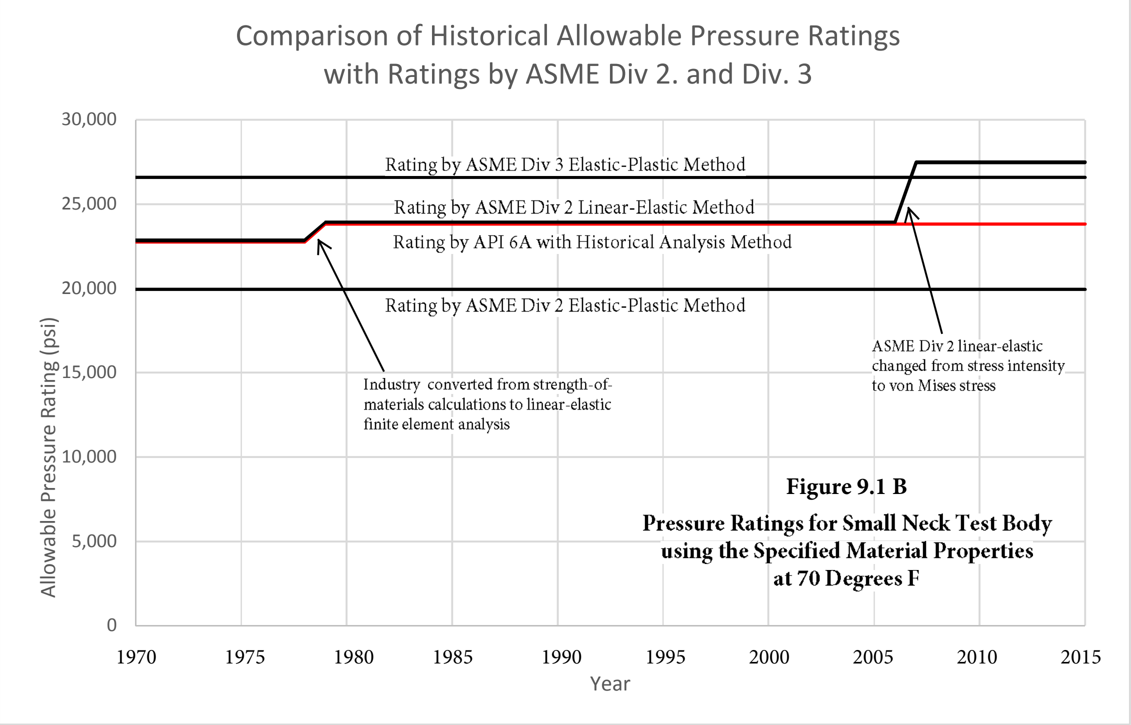


Figure 9.1 B
Pressure Ratings for Small Neck Test Body using the Specified Material Properties at 70 Degrees F

APPENDIX A

DESIGN CALCULATIONS AND MATERIAL SPECIFICATION

This appendix includes the strength-of-materials calculations that were the basis for design of the two test bodies. The design calculations used the material strengths and other material properties for the F22 material that are specified in Material Specification D2456-1 Revision 1 which is included in Appendix A.

Appendix A1
Design Calculations for HPHT Test Bodies

Design Overview

The primary subject of this study was to design, manufacture, analyze with FEA and hydrotest two test bodies that were specifically created for this study. The first test body was designed to meet API 6A design criteria based on strength-of-materials calculations. The second test body was designed with smaller sections so that critical stresses were 25% higher. This reason for the 25% higher stresses in the second test body is that the design factor in Division 3 elastic-plastic critieria is 25% lower than the design factor in Division 2. The following are additional design requirements for the two bodies:

1. The configurations were to be typical of subsea components such as gate valves.
2. The material was to be typical material that is commonly used in subsea applications.
3. The maximum operting pressure was 20,000 psi at 70 F.
4. The design pressure of bodies should be 26,000 psi to provide margin for the application of external loads.
5. The designs were to be based on strength-of-material calcuations and verified if necessary by simple FEA.
6. One test body should be designed to meet the design criteria in API 6A which requires that the primary membrane stress intensity do not exceed 2/3 of the yield strength.

Figures 5.1 and 5.2 in the main body of this report are drawings of the two HPHT test bodies. The two bodies are identical in every respect except for the outside diameter (OD) of the neck. The small neck body has been designed to have a 25% greater stress in the critical section.

The flanges in the test bodies are standard API flanges rated at 20,000 psi. The dimensions of the enlarged body are dictated by the flange and bolting dimensions. Section stresses and displacements in the enlarged portions of the bodies will not be high. However, peak stresses at the intersecting bores will be high.

The critical locations in the two bodies will be in the thin necks of the cylindrical sections. Failure will obviously be by burst in the thin necks.

The following are design calculations for the critical section in the neck. Note that during the design process, numerous neck ODs were considered. The calculations presented are only the calculations for the final designs for the test bodies.

Design Conditions

$P_i := 20000 \cdot \frac{\text{lbf}}{\text{in}^2}$ ....Pressure inside test body

— ....Pressure outside the test body

Deg F ....Design temperature

Material Data

The material specification for the test bodies is Aiken Specification D2456-1 Revision 1. The specification is included at the end of this appendix.

From the material specification, the material strengths are as follows:

$S_u := 95000 \cdot \frac{lbf}{in^2}$ ....Ultimate tensile strength at 70 Deg F

$S_y := 75000 \cdot \frac{lbf}{in^2}$ ....Yield strength at 70 Deg F

$S_{ut} := 107800 \cdot \frac{lbf}{in^2}$ ....True ultimate tensile strength at 70 Deg F

$E := 30600000 \cdot \frac{lbf}{in^2}$ ....Modulus of Elasticity at 70 Deg F

$Nu := 0.3$ ....Poissons Ratio at all temperatures

Design of Large Neck OD Based on Strength of Materials Calculations

The tubular section that extends from the 17-3/4 inch cubic body is referred to as the neck portion of the test body. The nominal inside diameter is 3 1/16 inches. The OD will be designed based on the allowable stress criteria. Note that critical stresses were calculated for several neck ODs; however, in this report calculations only for the actual OD that was built and tested will be included.

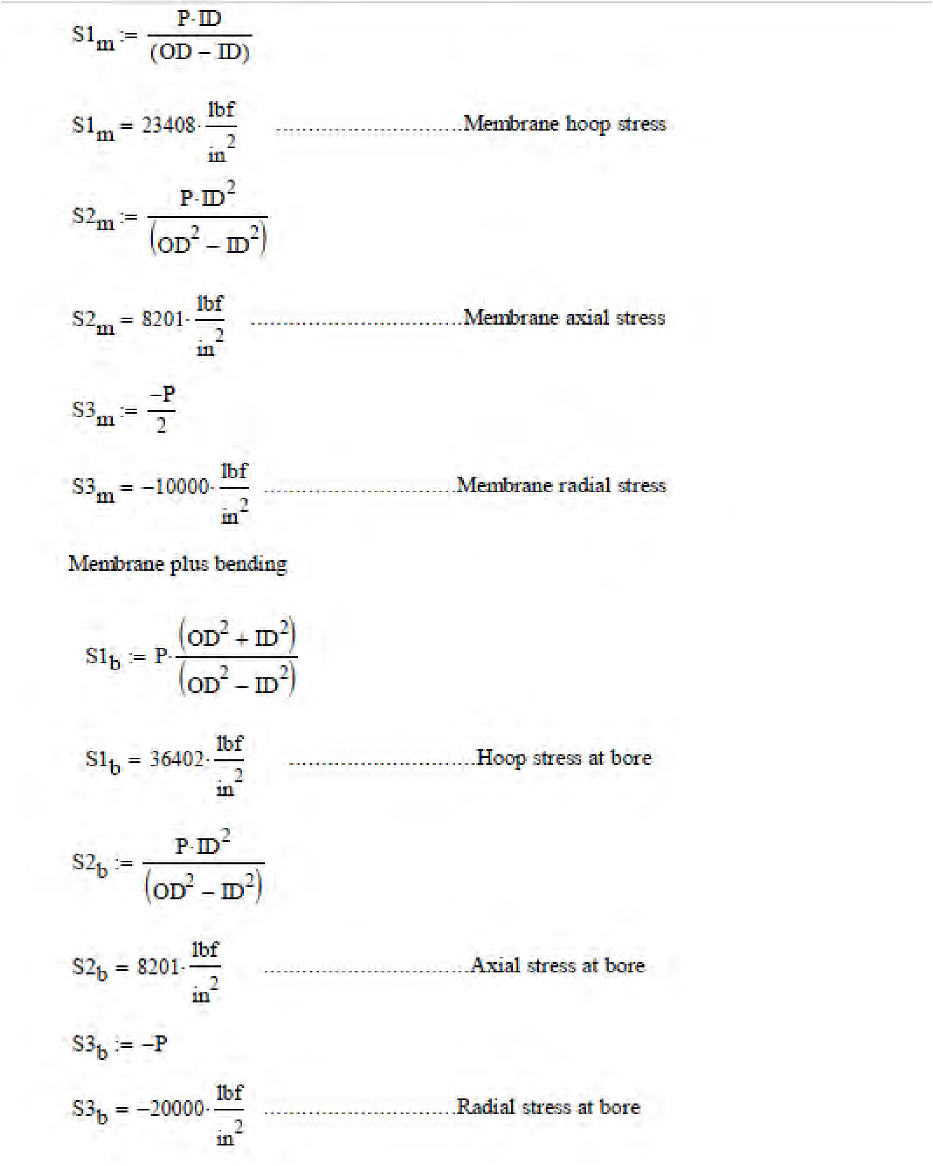
Geometry of Neck

$OD := 5.680 \cdot in \quad -0.00 + 0.030$ ....Outside diameter of throat

$ID := 3.063 \cdot in \quad -0.00 + 0.030$................Inside diameter of throat

$P := P_i = 20000 \cdot \frac{lbf}{in^2}$ ....Design internal pressure

Primary Stresses



$$S1_m := \frac{P \cdot ID}{(OD - ID)}$$

$S1_m = 23408 \cdot \frac{lbf}{in^2}$ ....Membrane hoop stress

$$S2_m := \frac{P \cdot ID^2}{\left(OD^2 - ID^2\right)}$$

$S2_m = 8201 \cdot \frac{lbf}{in^2}$ ....Membrane axial stress

$$S3_m := \frac{-P}{2}$$

$S3_m = -10000 \cdot \frac{lbf}{in^2}$ ....Membrane radial stress

Membrane plus bending

$$S1_b := P \cdot \frac{\left(OD^2 + ID^2\right)}{\left(OD^2 - ID^2\right)}$$

$S1_b = 36402 \cdot \frac{lbf}{in^2}$ ....Hoop stress at bore

$$S2_b := \frac{P \cdot ID^2}{\left(OD^2 - ID^2\right)}$$

$S2_b = 8201 \cdot \frac{lbf}{in^2}$ ....Axial stress at bore

$$S3_b := -P$$

$S3_b = -20000 \cdot \frac{lbf}{in^2}$ ....Radial stress at bore

Stress Intensity

$SI_m := S1_m - S3_m$

$SI_m = 33408 \cdot \frac{lbf}{in^2}$ ....Membrane Stress Intensity

Bending

$SI_b := S1_b - S3_b$

$SI_b = 56402 \cdot \frac{lbf}{in^2}$ ....Membrane + Bending Stress Intensity

Von Mises Stress

Membrane

$$Seq_m := \frac{1}{\sqrt{2}} \cdot \left[\left(S1_m - S2_m\right)^2 + \left(S2_m - S3_m\right)^2 + \left(S3_m - S1_m\right)^2 \right]^{\frac{}{2}}$$

$Seq_m = 28971 \cdot \frac{lbf}{in^2}$ ....Membrane Von Mises Stress

Membrane plus bending

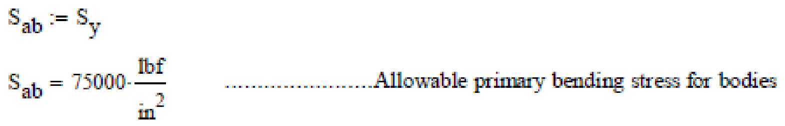
$$Seq_b := \frac{1}{\sqrt{2}} \cdot \left[\left(S1_b - S2_b\right)^2 + \left(S2_b - S3_b\right)^2 + \left(S3_b - S1_b\right)^2 \right]^{\frac{1}{2}}$$

$Seq_b = 48845 \cdot \frac{lbf}{in^2}$ ....Membrane + Bending Von Mises Stress

Allowable Stresses

$S_{am} := \frac{2}{3} \cdot S_y$

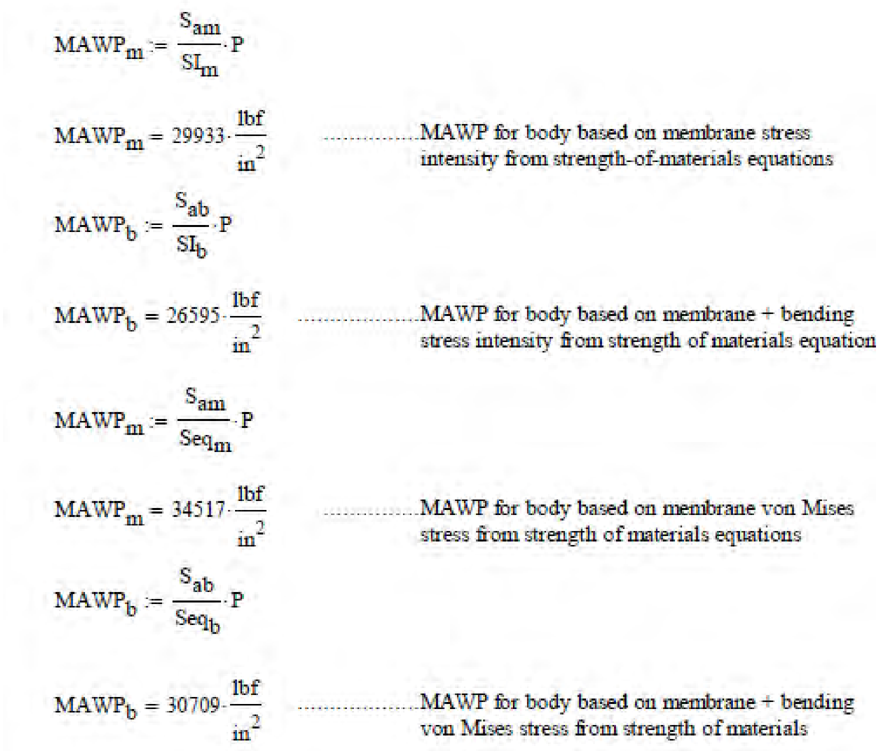
$S_{am} = 50000 \cdot \frac{lbf}{in^2}$ ....Allowable primary membrane stress for bodies



$S_{ab} := S_y$

$S_{ab} = 75000 \cdot \frac{lbf}{in^2}$ ....Allowable primary bending stress for bodies

Maximum Allowable Working Pressures (MAWP)



$MAWP_m := \frac{S_{am}}{SI_m} \cdot P$

$MAWP_m = 29933 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane stress intensity from strength-of-materials equations

$MAWP_b := \frac{S_{ab}}{SI_b} \cdot P$

$MAWP_b = 26595 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane + bending stress intensity from strength of materials equation

$MAWP_m := \frac{S_{am}}{Seq_m} \cdot P$

$MAWP_m = 34517 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane von Mises stress from strength of materials equations

$MAWP_b := \frac{S_{ab}}{Seq_b} \cdot P$

$MAWP_b = 30709 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane + bending von Mises stress from strength of materials

Note that API 6A requires that MAWPs are based on stress intensity. The MAWPs based on von Mises stresses are included for reference only. They are included because ASME Codes changed from stress intensity to von Mises stress in 2010.

Design of Neck OD Based on Finite Element Analysis

Simple FEA of the large neck design was performed prior to manufacturing the parts. This FEA is not presented in the report because much more rigorous FEA that was performed as a part of the TR8 evaluation process is included in the report.

Design of Small Neck OD Test Body Based on Strength-of-Materials Calculations

The calculations are repeated for the small neck OD test body

Geometry of Neck

$OD := 4.880 \cdot in$ ....Outside diameter of throat

$ID := 3.063 \cdot in$ ....Inside diameter of throat

$P := P_i = 20000 \cdot \frac{lbf}{in^2}$ ....Design internal pressure

Primary Stresses

$$S1_m := \frac{P \cdot ID}{(OD - ID)}$$

$S1_m = 33715 \cdot \frac{lbf}{in^2}$ ....Membrane hoop stress

$$S2_m := \frac{P \cdot ID^2}{\left(OD^2 - ID^2\right)}$$

$S2_m = 13001 \cdot \frac{lbf}{in^2}$ ....Membrane axial stress

$$S3_m := \frac{-P}{2}$$

$S3_m = -10000 \cdot \frac{lbf}{in^2}$ ....Membrane radial stress

Membrane plus bending

$$S1_b := P \cdot \frac{\left(OD^2 + ID^2\right)}{\left(OD^2 - ID^2\right)}$$

$S1_b = 46002 \cdot \frac{lbf}{in^2}$ ....Hoop stress at bore

$$S2_b := \frac{P \cdot ID^2}{\left(OD^2 - ID^2\right)}$$

$S2_b = 13001 \cdot \frac{lbf}{in^2}$ ....Axial stress at bore

$S3_b := -P$

$S3_b = -20000 \cdot \frac{lbf}{in^2}$ ....Radial stress at bore

Stress Intensity

$SI_m := S1_m - S3_m$

$SI_m = 43715 \cdot \frac{lbf}{in^2}$ ....Membrane Stress Intensity

Bending

$SI_b := S1_b - S3_b$

$SI_b = 66002 \cdot \frac{lbf}{in^2}$ ....Membrane + Bending Stress Intensity

Von Mises Stress

Membrane

$$Seq_m := \frac{1}{\sqrt{2}} \cdot \left[\left(S1_m - S2_m\right)^2 + \left(S2_m - S3_m\right)^2 + \left(S3_m - S1_m\right)^2\right]^{\frac{1}{2}}$$

$Seq_m = 37876 \cdot \frac{lbf}{in^2}$ ....Membrane Von Mises Stress

Membrane plus bending

$$Seq_b := \frac{1}{\sqrt{2}} \cdot \left[\left(S1_b - S2_b\right)^2 + \left(S2_b - S3_b\right)^2 + \left(S3_b - S1_b\right)^2\right]^{\frac{1}{2}}$$

$Seq_b = 57160 \cdot \frac{lbf}{in^2}$ ....Membrane + Bending Von Mises Stress

Allowable Stresses

$— \quad {}_{3} \cdot S_y$

$S_{am} = 50000 \cdot \frac{lbf}{in^2}$ ....Allowable primary membrane stress for bodies

$S_{ab} := S_y$

$S_{ab} = 75000 \cdot \frac{lbf}{in^2}$ ....Allowable primary bending stress for bodies

Maximum Allowable Working Pressures (MAWP)

$MAWP_m := \frac{S_{am}}{SI_m} \cdot P$

$MAWP_m = 22875 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane stress intensity from strength of materials equations

$MAWP_b := \frac{S_{ab}}{SI_b} \cdot P$

$MAWP_b = 22726 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane + bending stress intensity from strength of materials equations

$MAWP_m := \frac{S_{am}}{Seq_m} \cdot P$

$MAWP_m = 26402 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane von Mises stress from strength of materials equations

$MAWP_b := \frac{S_{ab}}{Seq_b} \cdot P$

$MAWP_b = 26242 \cdot \frac{lbf}{in^2}$ ....MAWP for body based on membrane + bending von Mises stress from strength of materials

The critical membrane stress intensity in the large neck body is 29,933 psi; and, the critical membrane stress intensity in the small neck body is 22,875 psi. The difference between the two stress intensities is 24% which is near the desired difference of 25%.

Appendix A2
Material Specification for Test Body Used in Evaluation of API 17TR8 Methods

Document D2456-1
Revision 1 Released November 2, 2015

By Aiken Engineering Company

1.0 SCOPE

This specification establishes the material requirements for parts forged from an ASTM A182 F22 low alloy steel with chemical composition to meet the requirements of API 6A, PSL 3. The material is intended for finished parts with a 20 ksi working pressure, 75 ksi strength class, temperature classification X (0-350F), and material class DD for sour service as described in NACE MR0175/ISO 15156. For all standards referenced in this specification, the revision in effect on the date of this specification shall be used.

2.0 CHEMICAL COMPOSITION

The chemical composition of the material shall conform as follows

Element	Weight Percent	Element	Weight Percent
Carbon (C)	0.10 – 0.15	Copper (Cu)	0.30 max
Manganese (Mn)	0.40 – 0.60	Nickel (Ni)	0.50 max
Phosphorus (P)	0.025 max	Aluminum (Al)	0.015 – 0.055
Sulfur (S)	0.025 max		
Chromium (Cr)	2.00 – 2.50		
Molybdenum (Mo)	0.87 – 1.13		
Silicon (Si)	0.50 max		

Calcium treatment is permitted for sulphide shape control

Chemical composition of the material shall be determined in accordance with ASTM A751.

Elements other than those used for grain refinement/de-oxidation not specified shall not be intentionally added. The total amount of residual elements shall not exceed 1.00%. All elements shall be reported.

3.0 STEEL MAKING REQUIREMENTS

The steel shall be fully killed (de-oxidized) and produced by fine grain practice with one of the following methods:

- Electric Arc Furnace (EAF), followed by Vacuum Degassing, Ladle Refining, or Argon Oxygen Decarburization

4.0 HOT WORKING REQUIREMENTS

The forging hot working shall be performed to meet the following requirements:

- The minimum forging reduction ratio shall be a minimum of 4.0 to 1
- Forging shall be rough-machined prior to heat treatment as needed to ensure mechanical properties.
- The overall reduction ratio shall be sufficient to ensure a fully wrought structure throughout the entire part.

5.0 HEAT TREATMENT

- All the items shall be heat treated. Forgings shall be heat treated by normalizing (optional), austenitizing, liquid quenching, and tempering.
- Forgings with bores or blind holes shall be oriented to allow for an optimal quench and to minimize the entrapment of steam.
- One full quench and temper is permitted by the supplier. Any additional reheat treatments shall be reviewed and approved by Aiken Engineering.
- All heat treatment equipment and procedure used shall be done in accordance with API 6A and API RP 6HT.
- Only automatic controlling and recording instruments shall be used
- Heat treatment controlling and recording instrumentation shall be calibrate according to API 6A for the full scale range.
- Instrumentation used to calibrate the production shall possess accuracy in accordance with API 6A
- Material shall be loaded into the heat treatment furnace such that the presence of one part does not adversely affect the heat treatment response of any other part in the same heat treatment load.
- Parts shall be loaded for quenching in a single layer only. Parts shall be separated for quenching so that there is sufficient space between each part to provide adequate quench media coverage during the quenching operation.
- Temperature for austenitizing and tempering shall be monitored using load thermocouples attached to one or more production parts in each load based upon the heaviest cross-section for any part in the load.

6.0 NORMALIZING

Normalizing is optional. If performed it shall be in range of 1725 – 1775F. The hold time shall be a minimum of 30 minutes per inch of heaviest cross section thickness with one hour minimum time at temperature followed by air cooling.

7.0 AUSTENITIZING

Austenitizing shall be performed at 1675 – 1725F. The hold time at austenitizing temperature shall be a minimum of 30 minutes per inch of heaviest cross section thickness with one hour minimum. The hold time shall start when the contact thermocouple reaches within 15F of the set point temperature range. The maximum hold time at the austenitizing temperature shall be 40 minutes per inch of maximum cross section thickness.

8.0 QUENCHING

Water quench shall be performed. Quenching equipment shall be located in such a manner, and handling facilities shall function with sufficient speed, to prevent the temperature of the forging from dropping below the upper critical temperature (Ar3) for the alloy prior to immersion in the quench bath. Quenching facilities shall have sufficient agitation and be of sufficient volume such that the temperature of the water quench media used shall not exceed 100F maximum at the beginning of the quench nor exceed 120F any time during and at the completion of the quench. Forgings shall be cooled to below 400F prior to removal from the quench medium. The equipment shall be capable of transporting forgings from the heat treatment furnace to the quench bath within a maximum of 90 seconds.

9.0 TEMPERING

Tempering is required and shall be performed at minimum 1225F. The hold time shall be a minimum of 60 minutes per inch of maximum cross section thickness with one hour minimum. The hold time shall start when the contact thermocouple reaches within 15F of the set point. Contact thermocouple will be placed on location of maximum section thickness.

10.0 MATERIAL QUALIFICATION

Mechanical properties (tensile, impact and hardness properties) shall be determined by testing material taken from a Qualification Test Coupons (QTC). As a minimum, there shall be one QTC per heat and per heat treat lot. The QTC shall accompany the forged product through all heat treat cycle

The QTC shall be obtained from the following:

- A prolongation shall be taken from the flanged end of the forging. The prolongation shall be removed from the forging after final base metal heat treatment.

11.0 MECHANICAL PROPERTIES

Mechanical testing shall be carried out in accordance with ASTM A370.

Testing shall be performed on prolongation taken from the flanged end. Longitudinal test specimens (parallel to the primary grain flow direction) shall be taken so that the tensile specimen gauge length as taken from the prolongation is at least 1/4T and no less than 25 mm from any heat treated surface where T is the thickness. A drawing illustrating where the material is taken from the forging will be supplied.

Two additional tensile re-tests from the same forging, without any additional heat treatment are allowed in the event that the first tensile test fails to meet minimum requirements. The results of each test shall meet the specified requirements for material acceptance.

Results for mechanical testing shall be as follows:

• Ultimate tensile strength, min	95,000 psi (6565 MPa)
• Yield strength (0.2% offset) min	75,000 psi (515 MPa)
• Reduction area, min	35%
• Elongation in 2", min	18%
• Brinell Hardness	197 – 237 HB after finish machining

12.0 Charpy V-Notch Impact Testing

The material shall undergo Charpy V-Notch impact testing at 0F (-18C). Testing shall be performed in the longitudinal direction (parallel to the primary grain flow direction).

Full sized test specimens (10 x 10 mm) shall be used. Impact values shall be as follows:

- Minimum average for three specimens: 40 ft-lbs
- Minimum for single value: 30 ft-lbs

13.0 HARDNESS TESTING

Brinell hardness shall be performed on the prolongation after the final heat treatment cycle.

Brinell hardness shall be performed in accordance with ASTM E10.

Measured hardness shall be in the range of 197 – 237 Brinell.

14.0 NONDESTRUCTIVE EXAMINATON

NDE shall be carried out after final heat treatment and in accordance with established procedures. NDT operators shall be certified in accordance with ASNT SNT-TC-1A or equivalent.

All NDE procedures shall be approved by qualified ASNT SNT-TC-1A Level III or equivalent.

15.0 VISUAL EXAMINATION

Forgings surfaces shall be 100% visually examined and shall be free from visible laps, cold shuts, cracks, porosity, slag, scale, and other surface imperfections. Any defects shall be removed by grinding or machining. Acceptance criterial for visual examination of forgings shall be in accordance with ASTM A961

16.0 VOLUMETRIC ULTRASONIC TESTING (UT)

Following quality heat treatment and prior to machining operations, the entire forging shall be volumetrically inspected according to ASTM A388. Acceptance criterial shall be as per API 6A, PSL 3.

17.0 MAGNETIC TESTING (MT)

Following finish machining all accessible wetted surfaces shall be magnetic particle inspected. A drawing will be created denoting the areas subjected to surface inspection.

Magnetic particle inspection shall be performed in accordance with procedures specified in ASTM E709. Magnetic particle inspection shall use the wet fluorescent method. The acceptance criterial shall be per API 6A PSL 3.

18.0 WELDING

Repair by welding of forgings at any point in the manufacturing process is not permissible. Surface defect may be removed by machining or grinding, provided that the amount of material remove does not encroach on the minimum required section thickness of the forging.

19.0 CUSTOMER WITNESS INSPECTION

Aiken Engineering or a representative of Aiken Engineering shall be permitted to witness any phase of the manufacturing process that is performed in accordance with this specification. A prior request shall be submitted to the supplier to witness specific operations.

A plan will be provided in advance of manufacture to allow Aiken Engineering to denote hold, witness, monitor, and review points for the process.

20.0 CERTIFICATION REQUIREMENTS.

A test report shall be created by the supplier listing the following requirements:

- Aiken Engineering Purchase Order Number
- Aiken Engineering material specification number (including revision number)
- Aiken Engineering drawing/part number (including revision number)
- Original MTR from forging supplier
- Heat number from steel mill
- Chemical analysis (ladle and check analysis)
- Melting practice
- Hot work reduction ratio
- Heat treatment information (set points, cycle times, quench media, quench media temperature before and after quench as applicable)
- Heat treatment lot number
- Tensile test results, Charpy V-Notch impact test results
- Hardness test results from test coupons
- NDE results (visual, magnetic and ultrasonic)
- Statement of compliance to this specification.

21.0 MARKING & TRACEABILITY

Finished product shall be marked to ensure full traceability to melt and heat treatment lot. The remnants of the material qualification prolongation will be marked and stored as well as a precaution against the need for further testing. Aiken will inform the supplier when the remnants may be scrapped. Identification shall consist of the following.

- Manufacturer’s symbol or name
- Heat number or manufacturer’s heat identification and heat treatment lot
- Drawing or part number as indicated in the order
- Serial number traceable to the inspections.

APPENDIX B

FINITE ELEMENT ANALYSIS OF COMPONENTS

As a part of this study, six pressure containing components were analyzed using FEA. The purpose of the FEA was to calculate pressure ratings based on the methods and requirements of the following Codes:

API 6A
ASME Division 2 Linear-elastic
ASME Division 2 Elastic-plastic
ASME Division 3 Elastic-plastic.

Performance of this task required that linear-elastic FEA solutions and elastic-plastic solutions be done for all six components. The important features of the finite element models, element meshes, boundary conditions, loads, material properties, solution cases and important results are described in Appendix B. The majority of the information and data about the FEAs are described in computer plots with annotations added to provide explanations and additional information.

Appendix B is divided into 4 sub-appendices, one for each component that was analyzed. The first page of each sub-appendices provides a brief description of the important features of the FEA for the component. The first page also lists the main contents of the appendix and the starting page number.

Appendix B1
FEA of Large Neck Test Body

Some important features of the FEA model of the large neck test body were described in Section 6.0 of the main body of this report; they will not be further discussed in this Appendix. Plots of the large neck test body model, features, mesh, loads and boundary conditions are presented in the following figures:

<u>FEA Plots of the Large Neck Test Body</u>
Figure B1.1: Outside Surfaces of Large Neck Model
Figure B1.2: Inside Surfaces of Large Neck Model
Figure B1.3: FEA Mesh of Outside Surfaces
Figure B1.4: FEA Mesh of Inside Surfaces
Figure B1.5: FEA Mesh of Main Body
Figure B1.6: FEA Mesh of Internal Cavity
Figure B1.7: FEA Mesh of 3-1/16 x 20k Flange
Figure B1.8: FEA Mesh of 3-1/16 x 20k Flange Bore

The large neck FEA model was solved with the following three material properties:

Linear-elastic properties for the as-specified material
Elastic-plastic properties for the actual material
Elastic-plastic properties for the as-specified material

The results of the solution with linear elastic properties were used to calculate pressure ratings based on the linear-elastic procedures in API 6A and ASME Division 2. The results of the solutions with elastic-plastic properties were used to calculate pressure ratings based on the elastic-plastic rules in ASME Division 2 and Division 3.

The following are discussions of the FEA solutions of the large neck model that were performed, the important results and the pressure ratings based on Code rules.

Linear-Elastic FEA

The large neck FEA model was solved with linear-elastic material properties at the design internal pressure of 10,000 psi. The pressure ratings using stresses from linear-elastic FEA were based on the minimum material strengths of the as-specified material. The linear-elastic analysis methods in API 6A and Division 2 are the same. However, API 6A and Division 2 differ in that API 6A compares stress intensity with the allowable stresses whereas Division 2 compares von Mises stress with the allowable stresses. In this report, pressure ratings are calculated based on both stress intensity and on von Mises stress.

The following figures of the linear-elastic FEA model and results are included in Appendix B1:

<u>Model and Results of Linear-elastic FEA of Large Neck Test Body</u>
Figure B1.9: Features of Large Neck Model for Linear Elastic FEA
Figure B1.10: von Mises Stresses in Large Neck Body with 10 ksi Internal Pressure
Figure B1.11: Total Displacements in Large Neck Body with 10 ksi Internal Pressure

Figure B1.12: Linearized Stresses in Large Neck Body with 10 ksi Internal Pressure
Figure B1.13: Pressure Rating Calculations.

The most important figures are the linearized stress table in Figure B1.12 and the pressure rating calculations in Figure B1.13. The stress table shows the linearized stresses through the critical section. The critical section was found by linearizing section stresses through several paths in the model and choosing the most highly stressed section to perform pressure rating calculations. The location of the critical path is shown in Figure B1.10.

From the linearized stress table in Figure B1.12, the important linearized stresses in the critical section at an internal pressure of 10 ksi are

Linearize membrane stress intensity = 14,740 psi
Linearized membrane plus bending stress intensity = 25,380 psi
Linearized membrane von Mises stress = 12,780 psi
Linearized membrane plus bending von Mises stress = 22,000 psi

The allowable membrane stress is 2/3 of yield strength and the allowable membrane plus bending stress is the yield strength. Since the minimum yield strength is 75,000 psi, the allowable stresses are

Allowable membrane stress = (2/3) x 75,000 psi = 50,000 psi
Allowable membrane + bending stress = 75,000 psi

For an elastic analysis, stress is linear with pressure. Hence, the pressure ratings for the large neck body based on linear-elastic analysis are calculated using linear interpolation as shown below (see Figure 1.13):

Rating for membrane stress intensity = (50,000/14,740) x 10,000 = 33,921 psi
Rating for membrane + bending stress intensity = (75,000/25,380) x 10,000 = 29,551 psi
Rating for membrane von Mises stress = (50,000/12,780) x 10,000 = 39,124 psi
Rating for membrane + bending von Mises stress = (75,000/22,000) x 10,000 = 34,091 psi

The pressure ratings based on membrane stress are different than those based on membrane plus bending stress. The actual pressure rating is the lessor of the two ratings. Hence, the allowable pressure ratings are

Pressure rating based on stress intensity (API 6A) = 29,551 psi
Pressure rating based on von Mises stress (ASME Division 2) = 34,091 psi

Elastic-Plastic FEA

The FEA model was also solved with elastic-plastic material properties. One elastic-plastic solution used the actual material properties which were determined by tensile tests of a prolongation from the forging. A second elastic-plastic solution used the minimum material properties listed in the material specification. The true-stress strain curve for the as-specified material was calculated based on the methods in Part 5 of ASME Division 2.

Each elastic-plastic solution was solved by incrementally increasing the internal pressures until the solution failed to converge. As required by ASME procedures the internal pressure of the last converged solution was designated as the plastic collapse pressure of the large neck test body.

The following result plots from the elastic-plastic solutions are included at the end of Appendix B1:

Results with Actual Material Properties
Figure B1.14: Pressures on Large Neck FEA Model after Completion of 2 Load Steps
Figure B1.15: Boundary Conditions on Large Neck FEA Model
Figure B1.16: Von Mises Stresses in Large Neck Body Just Before Burst
Figure B1.17: Von Mises Stresses in Large Neck Body Just Before Burst (Modified Scale)
Figure B1.18: Total Strain in Large Neck Body Just Before Burst
Figure B1.19: Displacements in Large Neck Body Just Before Burst

Results with As-Specified Material Properties
Figure B1.20: Pressures on Large Neck FEA Model after Completion of 3 Load Steps
Figure B1.21: Boundary Conditions on Large Neck FEA Model
Figure B1.22: Von Mises Stresses in Large Neck Body just Before Burst
Figure B1.23: Total Strain in Large Neck Body just Before Burst
Figure B1.24: Displacements in Large Neck Body just Before Burst.

Plastic Collapse Pressures and ASME Pressure Ratings

As previously stated by ASME rules the plastic collapse pressure is the pressure at the last converged solution of the FEA model. The following paragraphs describe the procedure for calculation of the plastic collapse pressure using the elastic-plastic FEA model. Collapse pressure calculations are performed for the large neck test body with actual material properties and with specified material properties.

A solution consists of starting with a zero internal pressure and slowly ramping the pressure up in small increments until the solution does not converge. The pressure at the end of the solution and the pressure increment are specified at the onset of the solution. If the solution converges when the maximum pressure is reached a second load step must be performed. The second load step is a continuation of the first load step but with an increased value for the final pressure and possibly a different pressure increment. If the solution still converges at the end of second load step then a third load step must be performed. This process must be continued until non-convergence is achieved.

The ANSYS program lists the time and/or the iteration number at the last converged solution. The internal pressure at the last converged is easily calculated using simple linear interpolation based on either time or iteration number. The following are calculations for the collapse pressures and pressure ratings.

Large Neck Test Body with Actual Material Properties

Plastic Collapse Iteration History
Load Step 1: 70,000 psi internal pressure after 70 equal iterations (time = 1.0)
Load Step 2: 75,000 psi internal pressure after 20 additional iterations (time = 2.0)

Time = 1.57 at last converged solution

Plastic Collapse Pressure

Plastic collapse pressure = (1.57 - 1.0) x (75,000 – 70,000) + 70,000 psi
Plastic collapse pressure = 72,850 psi for large neck body

ASME Pressure Ratings

Division 2 Pressure Rating = 72,850 psi / 2. 4 = 30,354 psi
Division 3 Pressure Rating = 72,850 psi / 1.8 = 40,472 psi

Large Neck Body with Specified Material Properties

Plastic Collapse Iteration

Load Step 1: 55,000 psi internal pressure after 50 equal iteration (t = 1.0)
Load Step 2: 60,000 psi internal pressure after 10 additional iterations (t = 2.0)
Load Step 3: 65,000 psi internal pressure after 20 additional iterations (t = 3.0)
Time =2.55 at last converged solution

Plastic Collapse Pressure

Plastic collapse pressure = (2.55 - 2.0) x (65,000 – 60,000) + 60,000 psi
Plastic collapse pressure = 62,750 psi for large neck body

ASME Pressure Ratings

Division 2 Pressure Rating = 62,750 psi / 2. 4 = 26,146 psi
Division 3 Pressure Rating = 62,750 psi / 1.8 = 34,861 psi

A third elastic-plastic solution was performed by restarting the original solution with the actual properties at the last pressure that converged. The internal pressure just before plastic-collapse was incrementally reduced to a very low pressure (less than 1 psi). This solution simulated the effect of removing internal pressure. The results after pressure has been removed are the residual stresses and strains produced by material yielding just before plastic collapse has occurred. These plots will provide important data for future testing of the material.

The following result plots from the solution after pressure is removed are included at the end of Appendix B1:

Results with Actual Material Properties after Pressure is Removed
Figure B1.25: Residual Displacements on Bore Surfaces
Figure B1.26: Residual Displacements on External Surfaces
Figure B1.27: Residual von Mises Stresses on Bore Surfaces
Figure B1.28: Residual von Mises Stresses on External Surfaces
Figure B1.29: Residual Displacements on Bore Surfaces of Main Body
Figure B1.30: Residual Displacements on External Surfaces of Main Body
Figure B1.31: Residual von Mises Stresses on Bore Surfaces of Main Body
Figure B1.32: Residual von Mises Stresses on External Surfaces of Main Body
Figure B1.33: Residual Maximum Principal Stresses on Bore Surfaces of Main Body
Figure B1.34: Residual Minimum Principal Stresses on Bore Surfaces of Main Body
Figure B1.35: Residual Total Principal Strain (1st) on Bore Surfaces of Main Body

Figure B1.36: Residual Total Principal Strain (2^{nd}) on Bore Surfaces of Main Body
Figure B1.37: Residual Total Principal Strain (3^{rd}) on Bore Surfaces of Main Body
Figure B1.38: Residual Total Principal Strain (EQV) on Bore Surfaces of Main Body

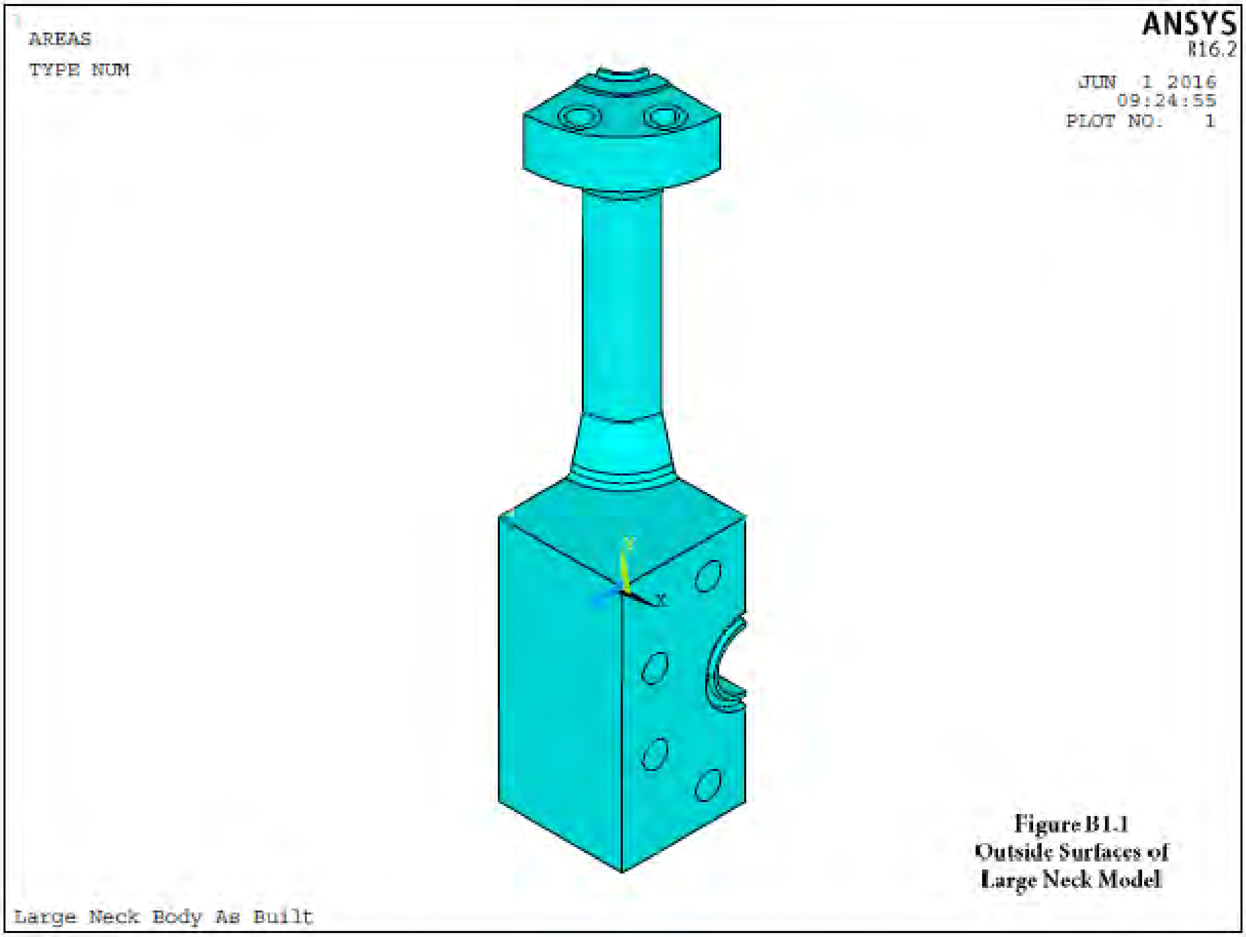


Figure B1.1
Outside Surfaces of
Large Neck Model

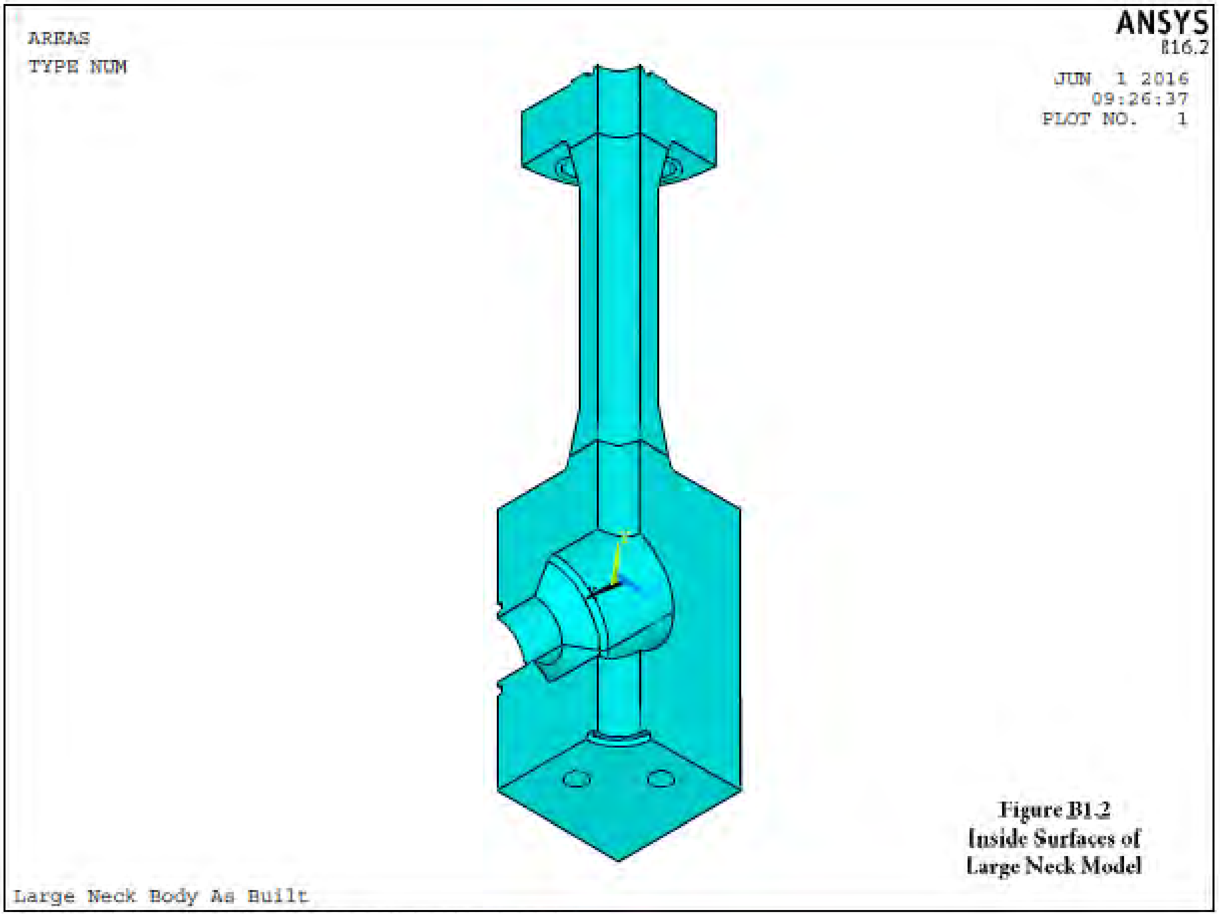


Figure B1.2
Inside Surfaces of
Large Neck Model

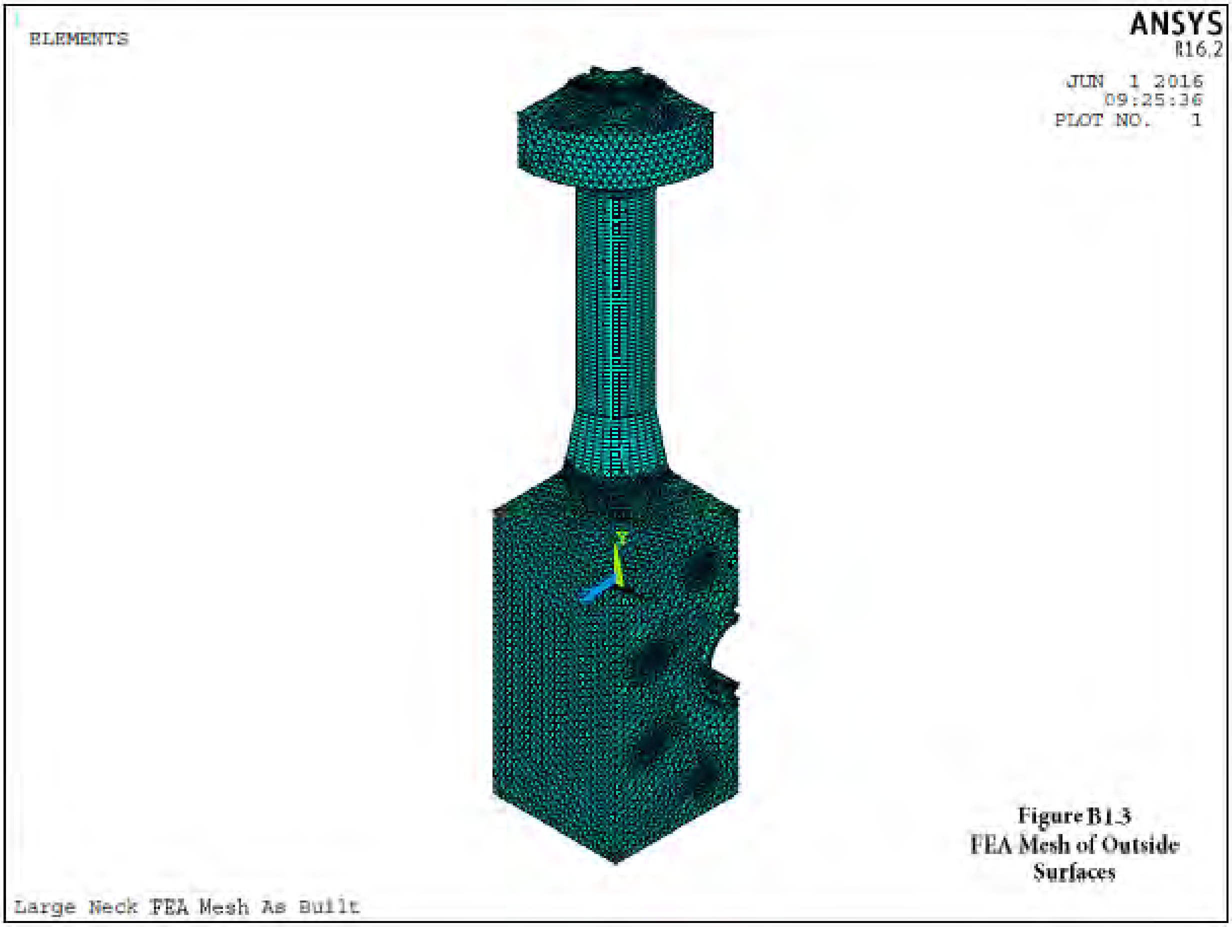


Figure B1.3
FEA Mesh of Outside
Surfaces

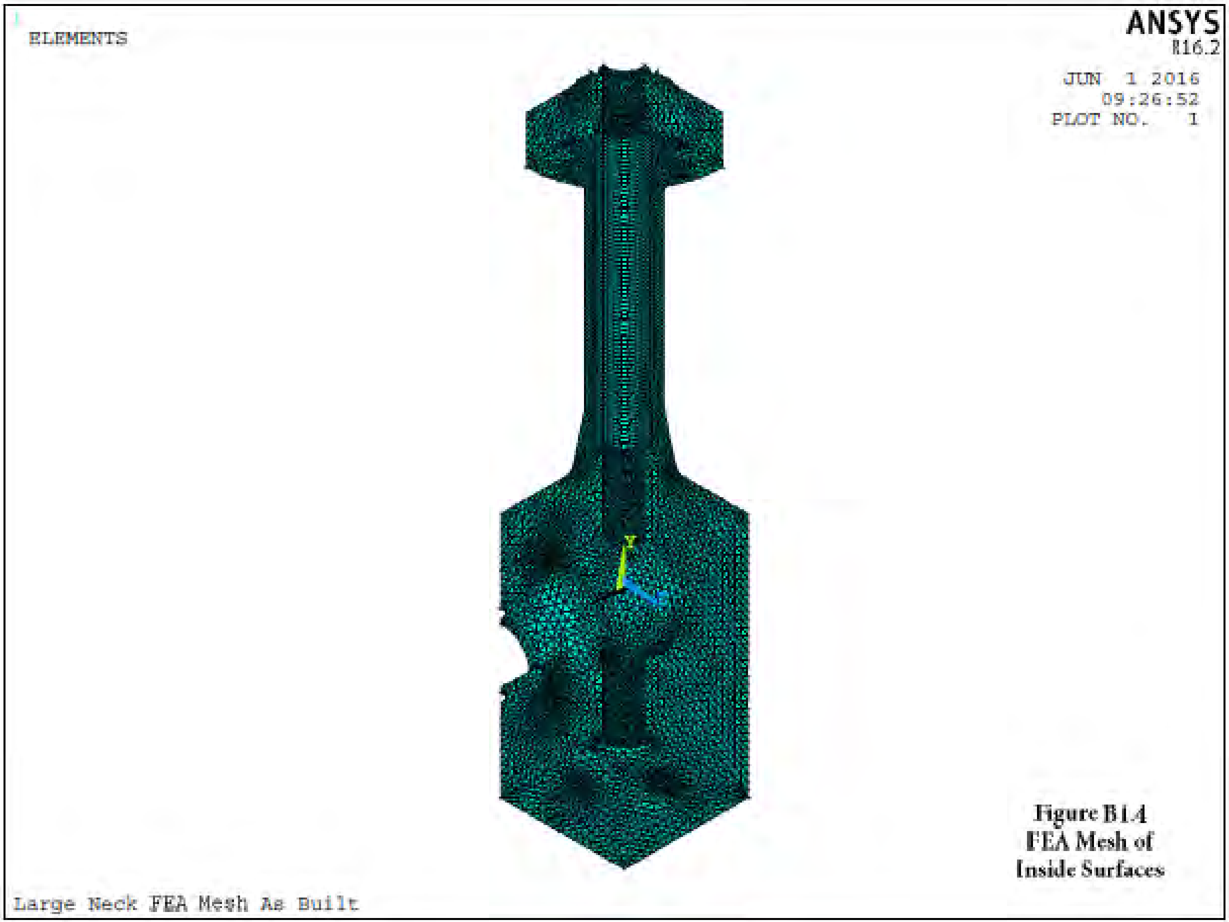


Figure B1.4
FEA Mesh of
Inside Surfaces

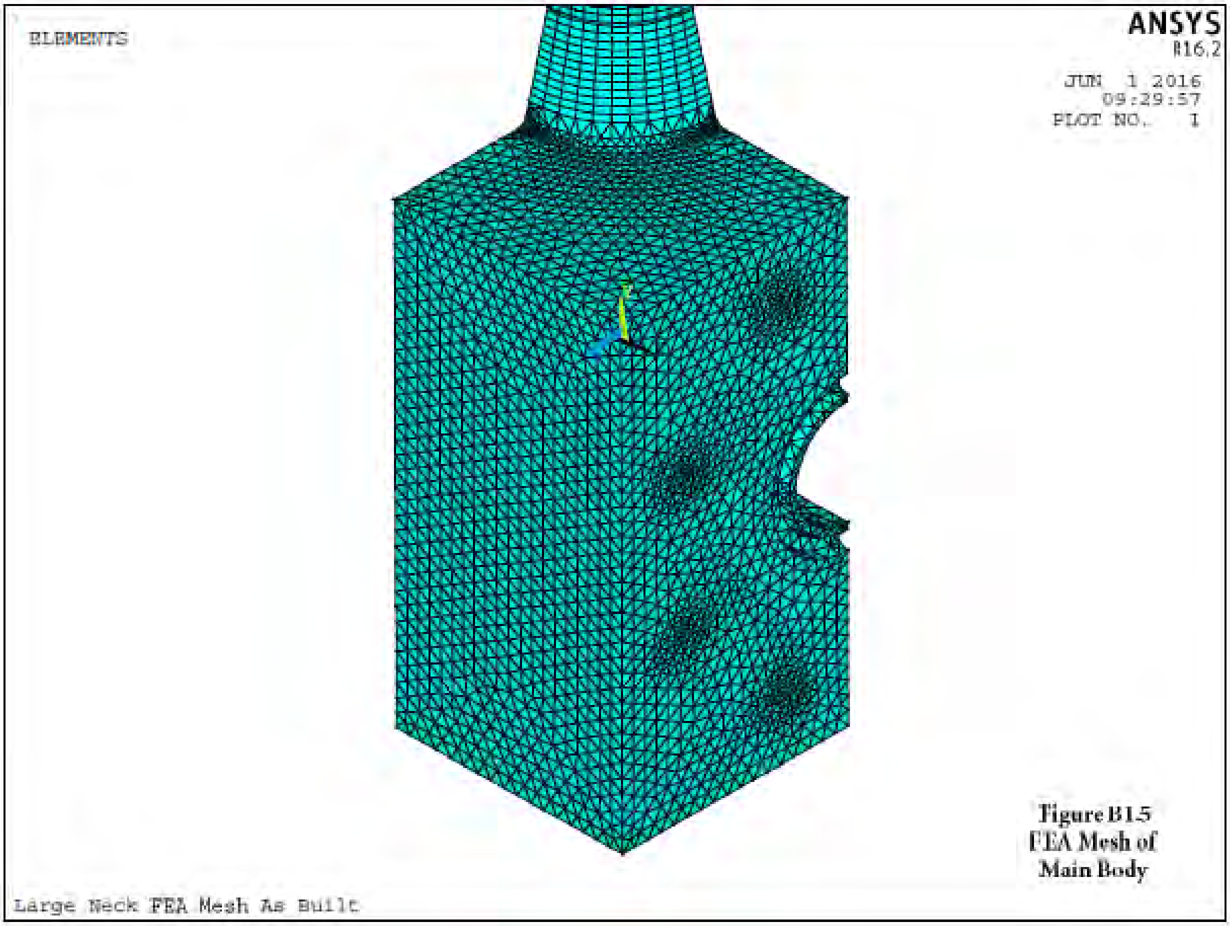


Figure B15
FEA Mesh of
Main Body

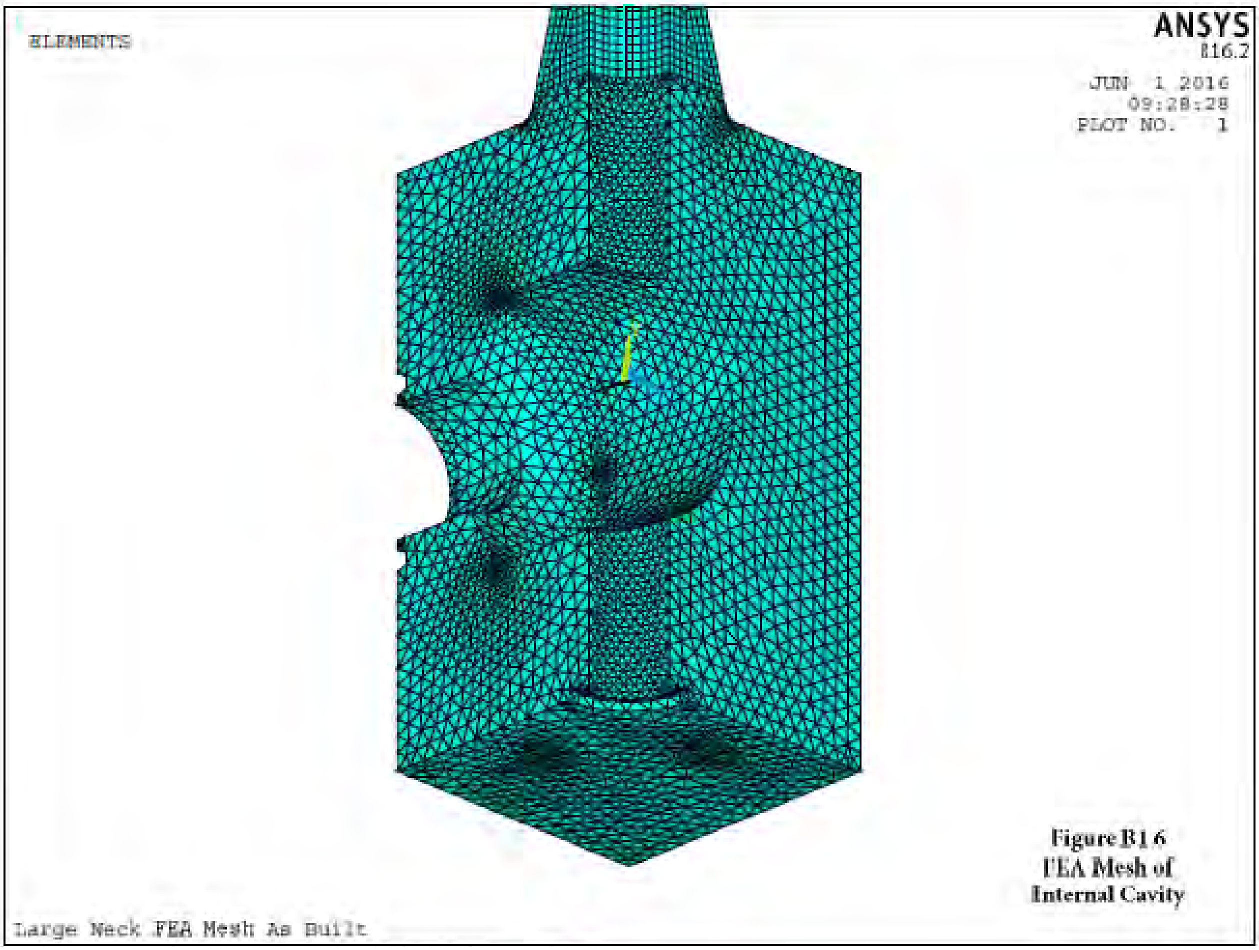


Figure B16
FEA Mesh of
Internal Cavity

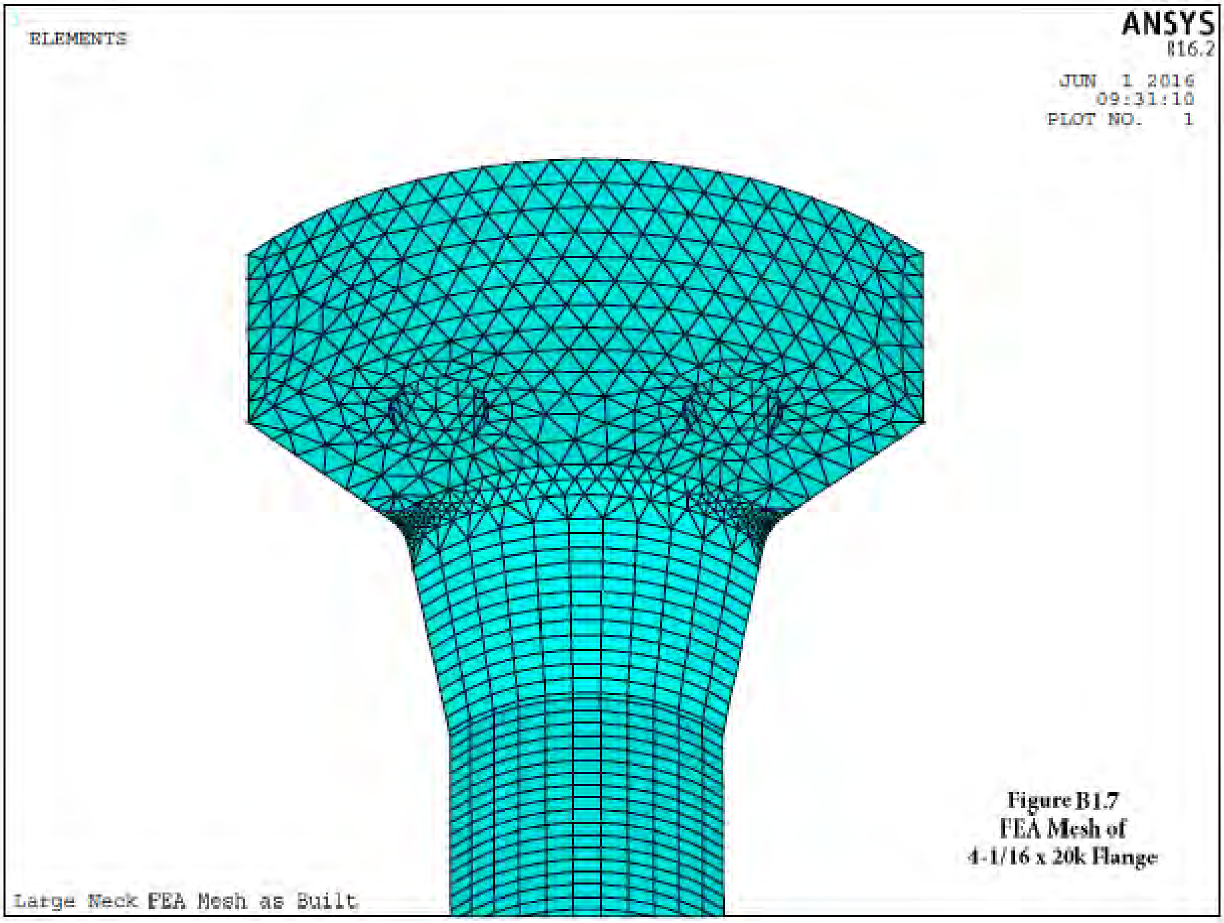


Figure B1.7
FEA Mesh of
4-1/16 x 20k Flange

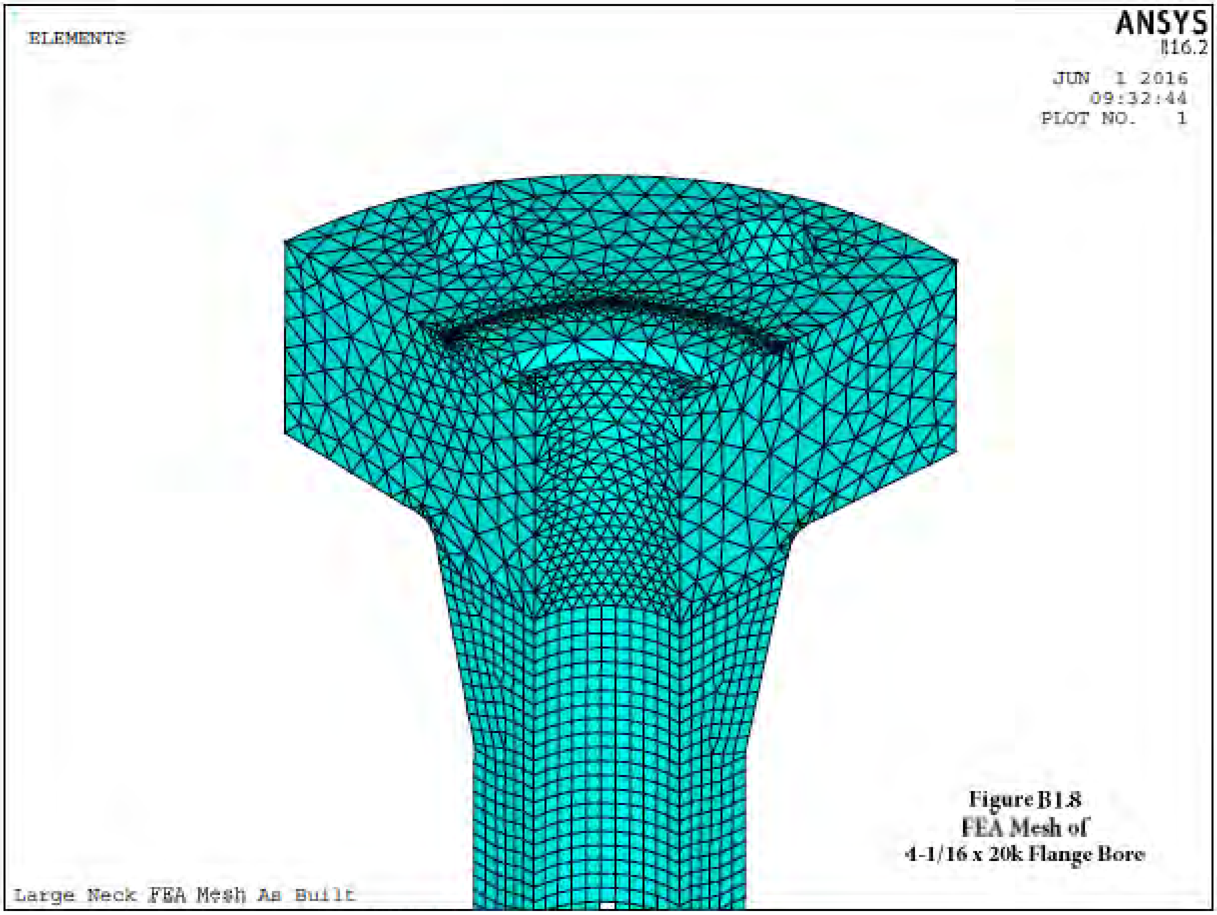
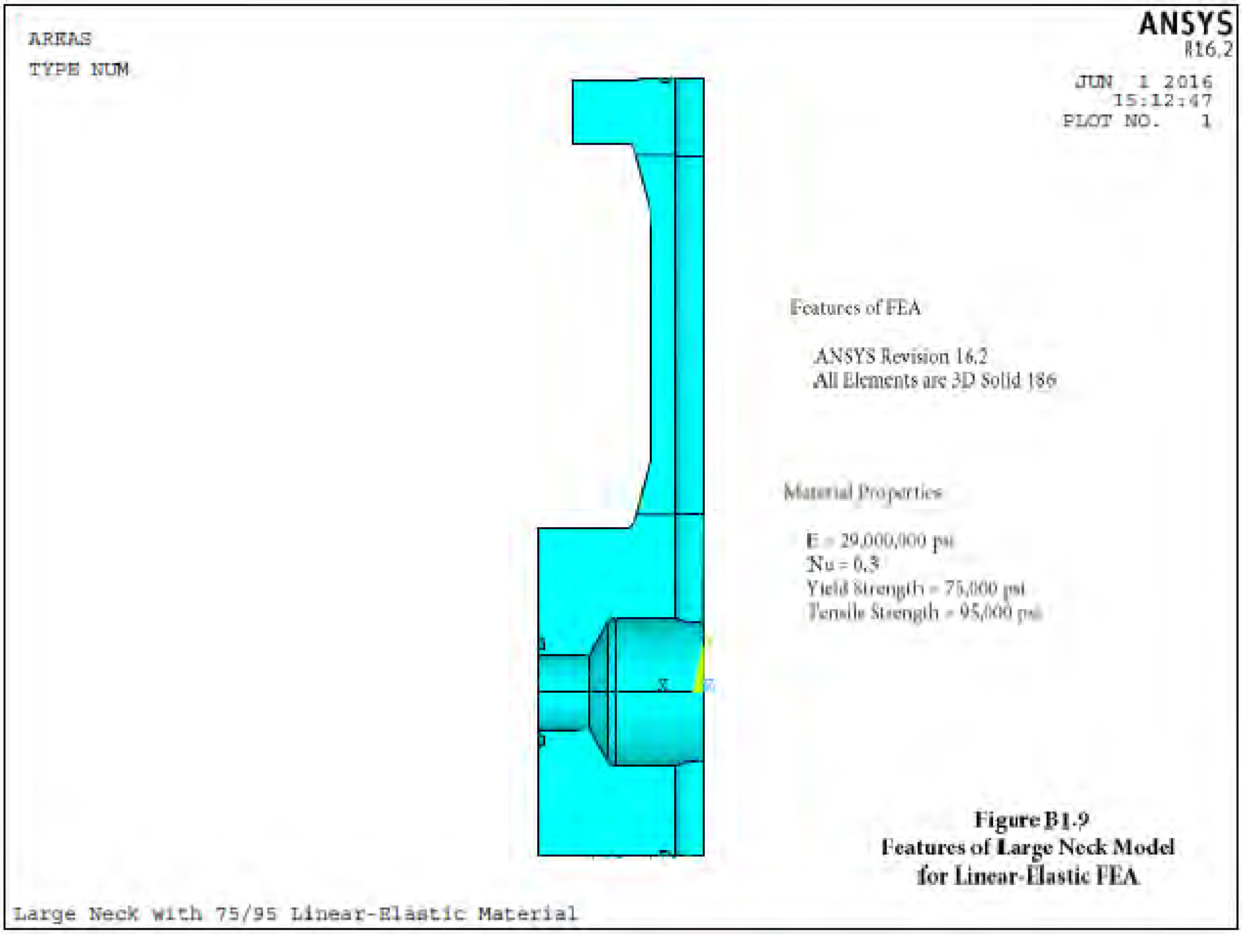


Figure B1.8
FEA Mesh of
4-1/16 x 20k Flange Bore



Features of FEA

ANSYS Revision 16.2
All Elements are 3D Solid 186

Material Properties

E = 29,000,000 psi
Nu = 0.3
Yield Strength = 75,000 psi
Tensile Strength = 95,000 psi

Figure B1.9
Features of Large Neck Model for Linear-Elastic FEA

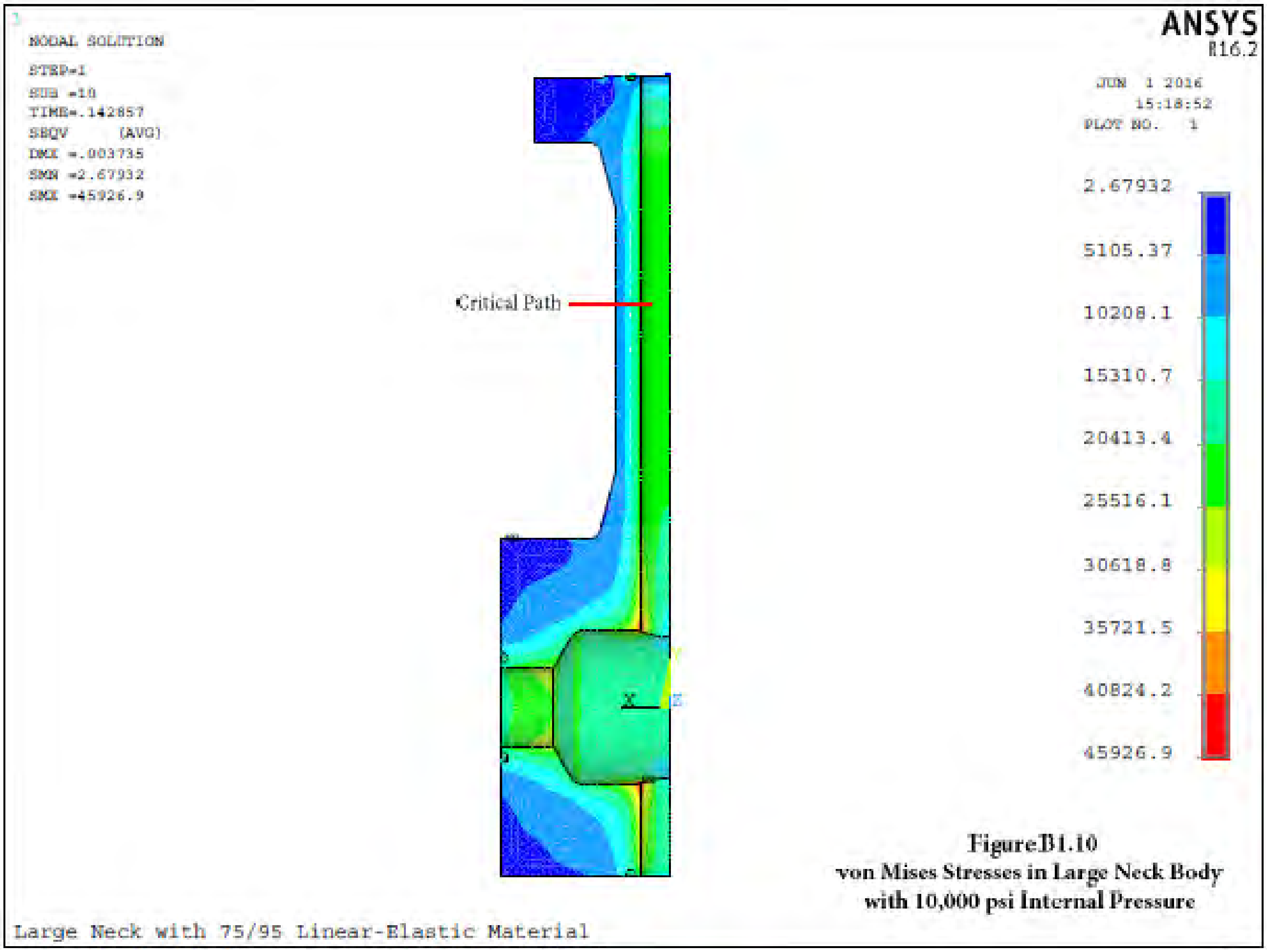


Figure B1.10
von Mises Stresses in Large Neck Body with 10,000 psi Internal Pressure

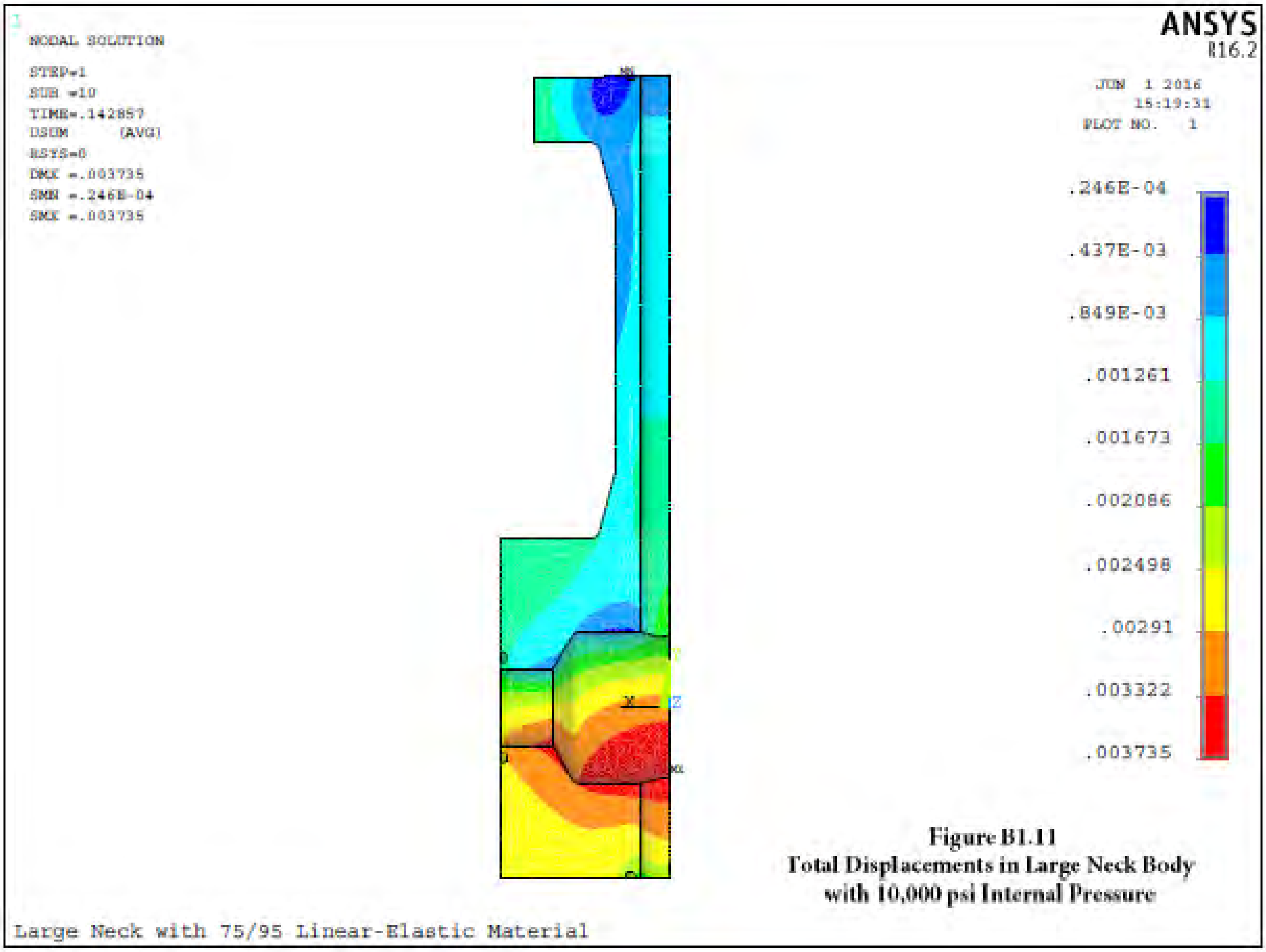


Figure B1.11
Total Displacements in Large Neck Body
with 10,000 psi Internal Pressure

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     Linearized Stresses in Large Neck with Actual Material at 10 ksi Pressure

PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= PATHA      DSYS=  0

  RADIUS OF CURVATURE =   2.0680

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =    316     OUTSIDE NODE =     96

 LOAD STEP     1  SUBSTEP=    10
 TIME=   0.14286         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   2.0680
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ         SXY         SYZ         SXZ
 -3510.       4463.      0.1122E+05  -223.8      -1.256      -44.01
     S1          S2          S3         SINT        SEQV
 0.1122E+05   4469.      -3516.      0.1474E+05  0.1278E+05

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ         SXY         SYZ         SXZ
I  -5765.      -15.97       4879.       0.000       0.000       0.000
C  -1124.      -1.450       465.8       0.000       0.000       0.000
O   3517.       13.07      -3948.       0.000       0.000       0.000
     S1          S2          S3         SINT        SEQV
I   4879.      -15.97      -5765.      0.1064E+05   9228.
C   465.8      -1.450      -1124.       1590.       1415.
O   3517.       13.07      -3948.       7465.       6469.

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ         SXY         SYZ         SXZ
I  -9274.       4447.      0.1610E+05  -223.8      -1.256      -44.01
C  -4634.       4461.      0.1169E+05  -223.8      -1.256      -44.01
O   7.360       4476.       7275.      -223.8      -1.256      -44.01
     S1          S2          S3         SINT        SEQV
I  0.1610E+05   4451.      -9278.      0.2538E+05  0.2200E+05
C  0.1169E+05   4467.      -4639.      0.1633E+05  0.1417E+05
O   7276.       4487.      -4.083       7280.       6362.

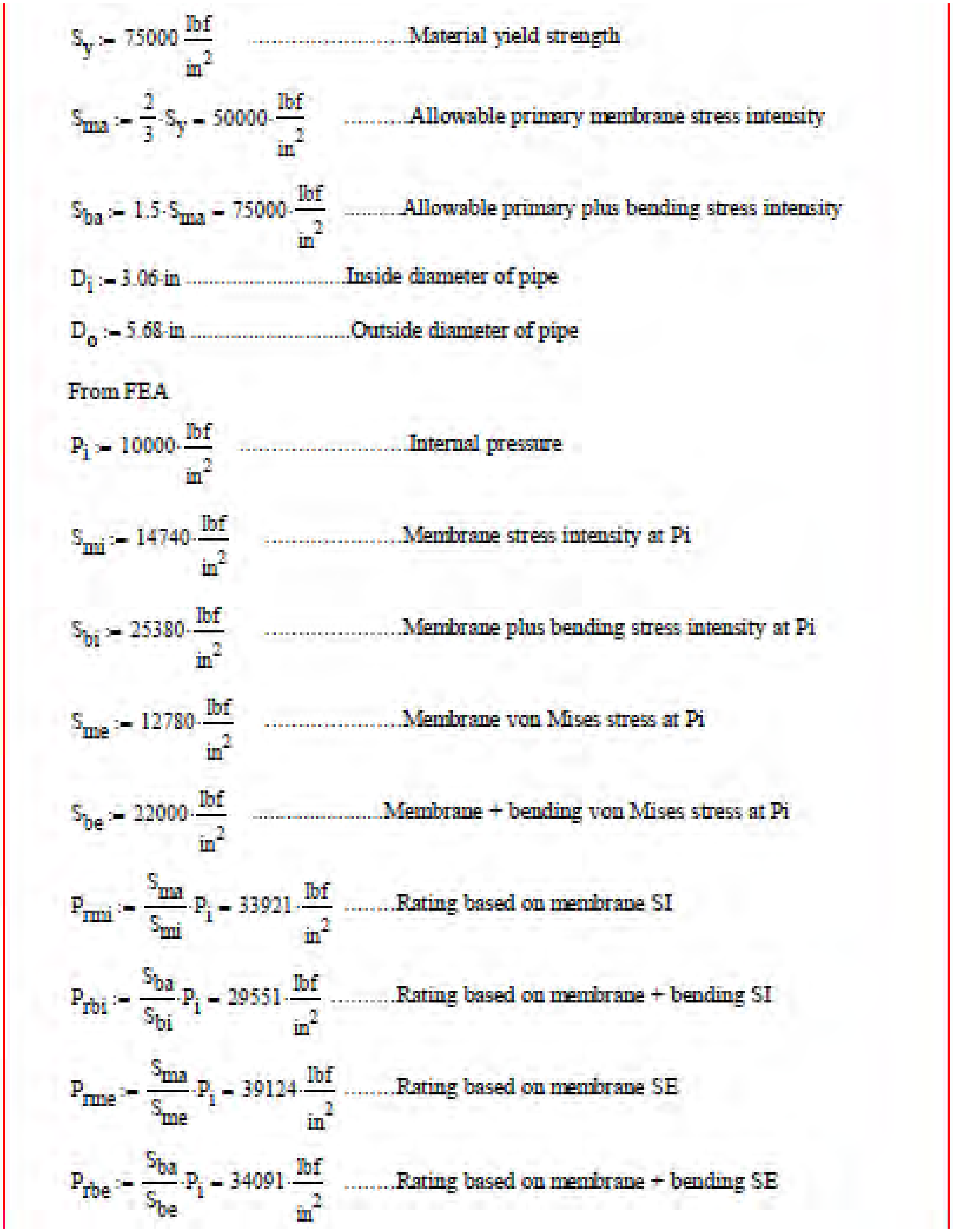
             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ         SXY         SYZ         SXZ
I   0.000      -10.58       1318.      -179.9      -10.78      -378.2
C   1790.       1.752      -644.0       4.594       1.235       43.29
O  0.4974E-13  -1.575       933.2       92.45       1.244       43.58
     S1          S2          S3         SINT        SEQV
I   1420.       126.0      -238.3       1658.       1509.
C   1790.       1.742      -644.8       2435.       2185.
O   935.2       90.47      -94.11       1029.       950.6

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ         SXY         SYZ         SXZ
I  -9274.       4436.      0.1742E+05  -403.7      -12.04      -422.3
C  -2844.       4463.      0.1104E+05  -219.2     -0.2033E-01 -0.7232
O   7.360       4474.       8209.      -131.3     -0.1196E-01 -0.4293
     S1          S2          S3         SINT        SEQV        TEMP
I  0.1743E+05   4448.      -9293.      0.2672E+05  0.2314E+05   0.000
C  0.1104E+05   4470.      -2850.      0.1390E+05  0.1204E+05
O   8209.       4478.       3.503       8205.       7116.       0.000
```

Figure B1.12
Linearized Stresses in Large Neck Body
with 10,000 psi Internal Pressure

Pressure Ratings for Large Neck Body with Spec Material by Linear Elastic FEA

Note: Stresses were calculated with an ANSYS 3D FEA Model.



$S_y := 75000 \frac{lbf}{in^2}$ ....Material yield strength

$S_{ma} := \frac{2}{3} \cdot S_y = 50000 \cdot \frac{lbf}{in^2}$ ....Allowable primary membrane stress intensity

$S_{ba} := 1.5 \cdot S_{ma} = 75000 \cdot \frac{lbf}{in^2}$ ....Allowable primary plus bending stress intensity

$D_i := 3.06 \cdot in$ ....Inside diameter of pipe

$D_o := 5.68 \cdot in$ ....Outside diameter of pipe

From FEA

$P_i := 10000 \cdot \frac{lbf}{in^2}$ ....Internal pressure

$S_{mi} := 14740 \cdot \frac{lbf}{in^2}$ ....Membrane stress intensity at Pi

$S_{bi} := 25380 \cdot \frac{lbf}{in^2}$ ....Membrane plus bending stress intensity at Pi

$S_{me} := 12780 \cdot \frac{lbf}{in^2}$ ....Membrane von Mises stress at Pi

$S_{be} := 22000 \cdot \frac{lbf}{in^2}$ ....Membrane + bending von Mises stress at Pi

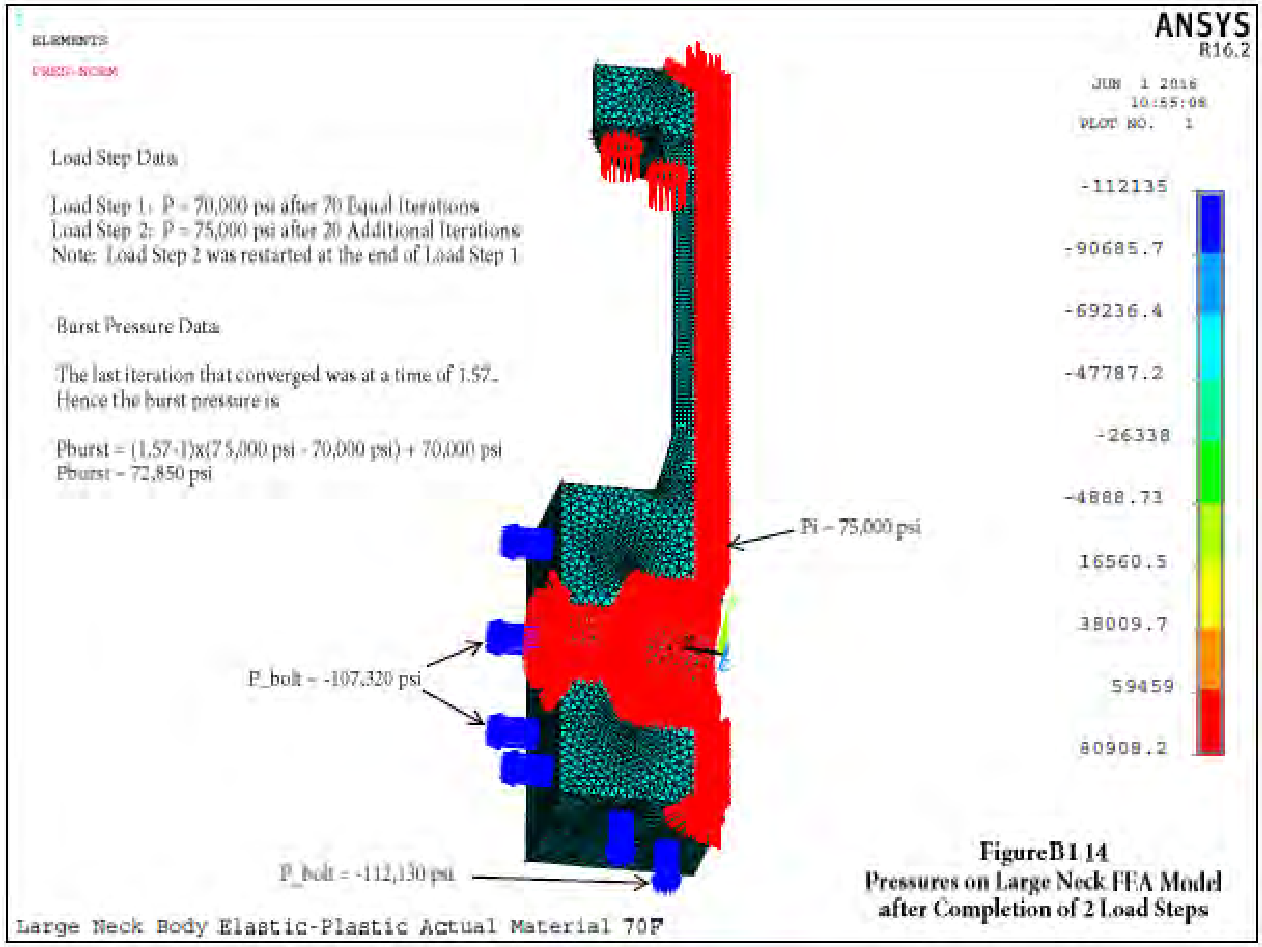
$P_{rmi} := \frac{S_{ma}}{S_{mi}} \cdot P_i = 33921 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane SI

$P_{rbi} := \frac{S_{ba}}{S_{bi}} \cdot P_i = 29551 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane + bending SI

$P_{rme} := \frac{S_{ma}}{S_{me}} \cdot P_i = 39124 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane SE

$P_{rbe} := \frac{S_{ba}}{S_{be}} \cdot P_i = 34091 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane + bending SE

Figure B1.13
Pressure Rating Calculations



Load Step Data

Load Step 1: P = 70,000 psi after 70 Equal Iterations
Load Step 2: P = 75,000 psi after 20 Additional Iterations
Note: Load Step 2 was restarted at the end of Load Step 1

Burst Pressure Data

The last iteration that converged was at a time of 1.57.
Hence the burst pressure is

Pburst = (1.57-1)x(75,000 psi - 70,000 psi) + 70,000 psi
Pburst – 72,850 psi

Figure B1.14
Pressures on Large Neck FEA Model after Completion of 2 Load Steps

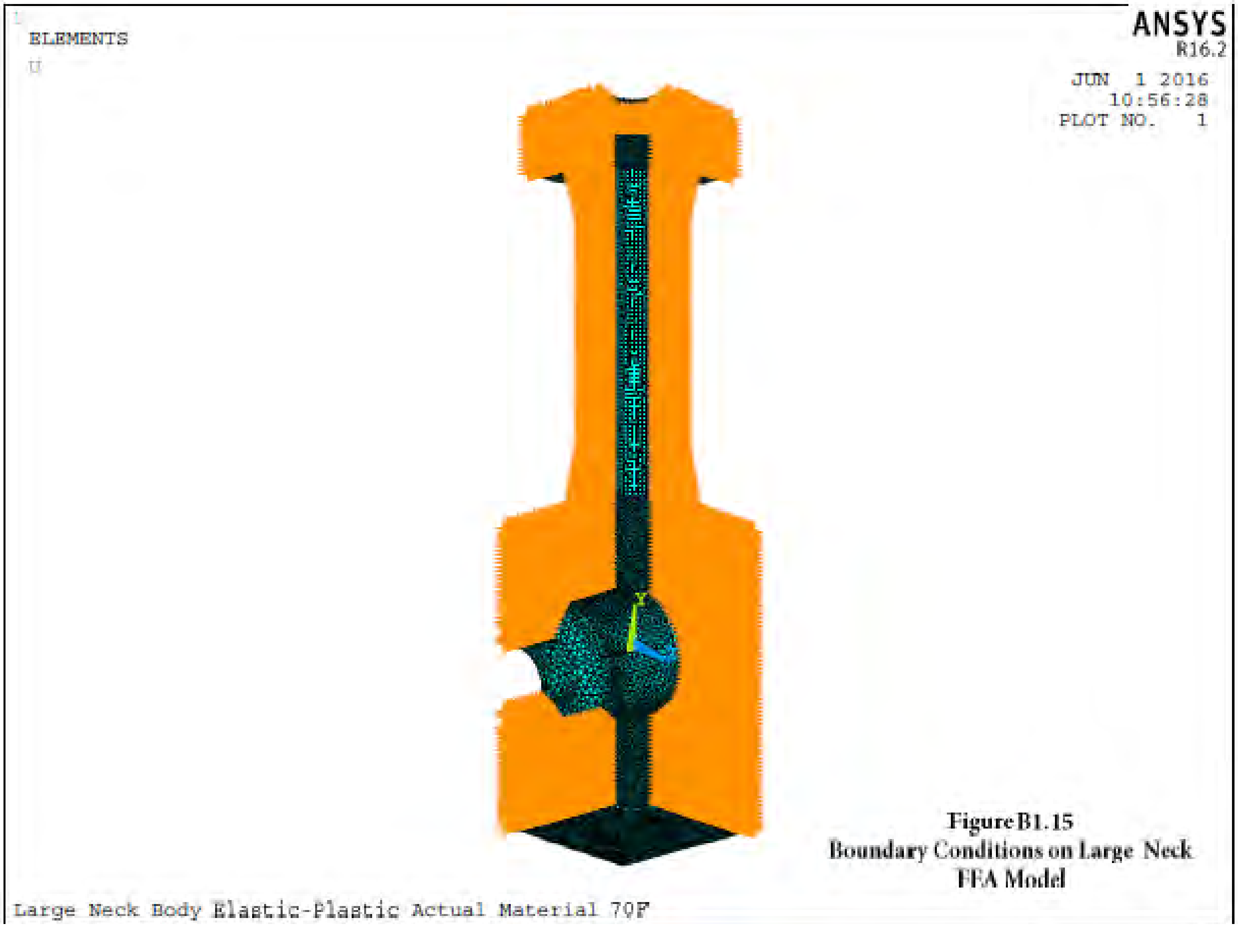


Figure B1.15
Boundary Conditions on Large Neck FEA Model

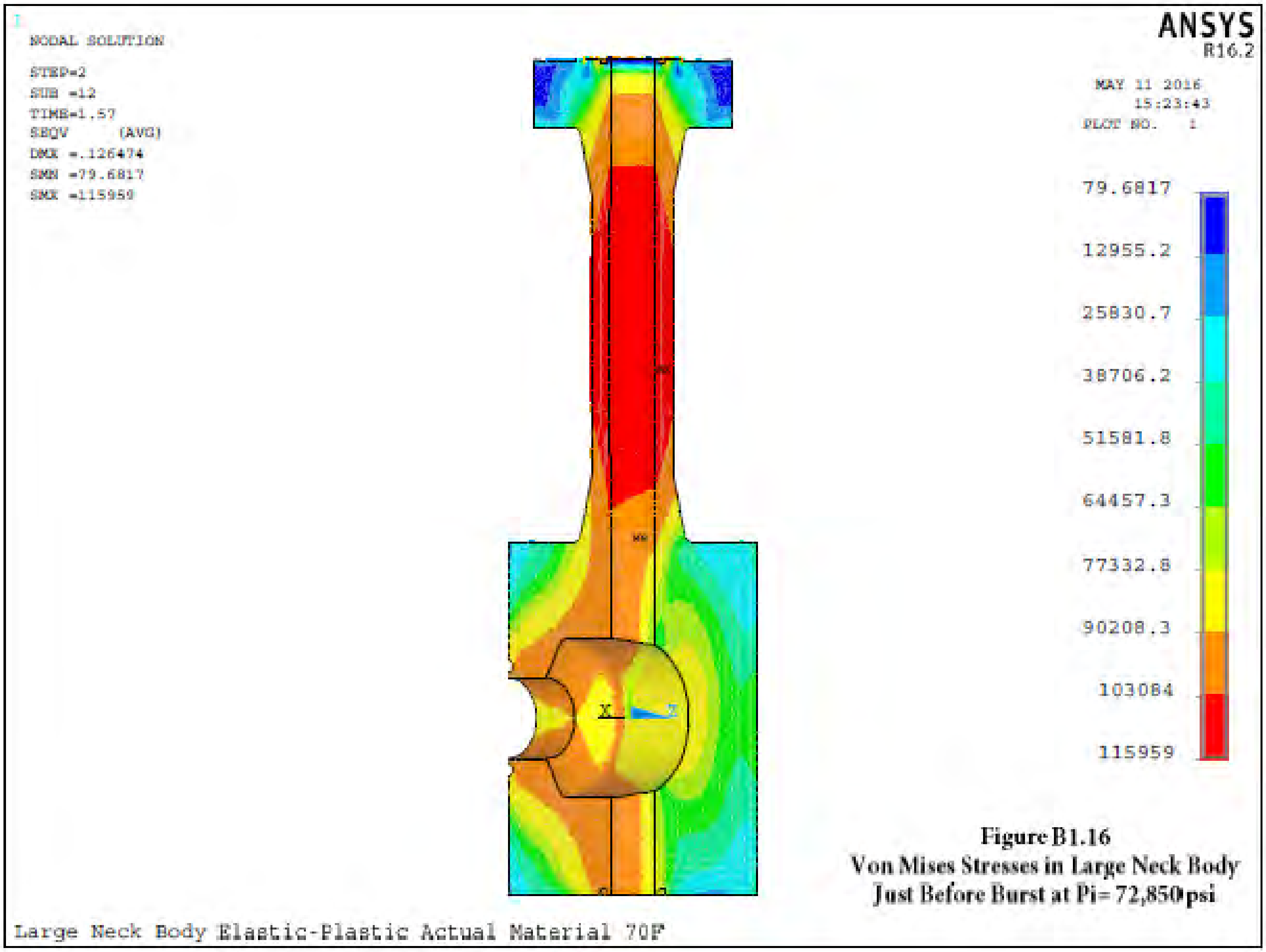
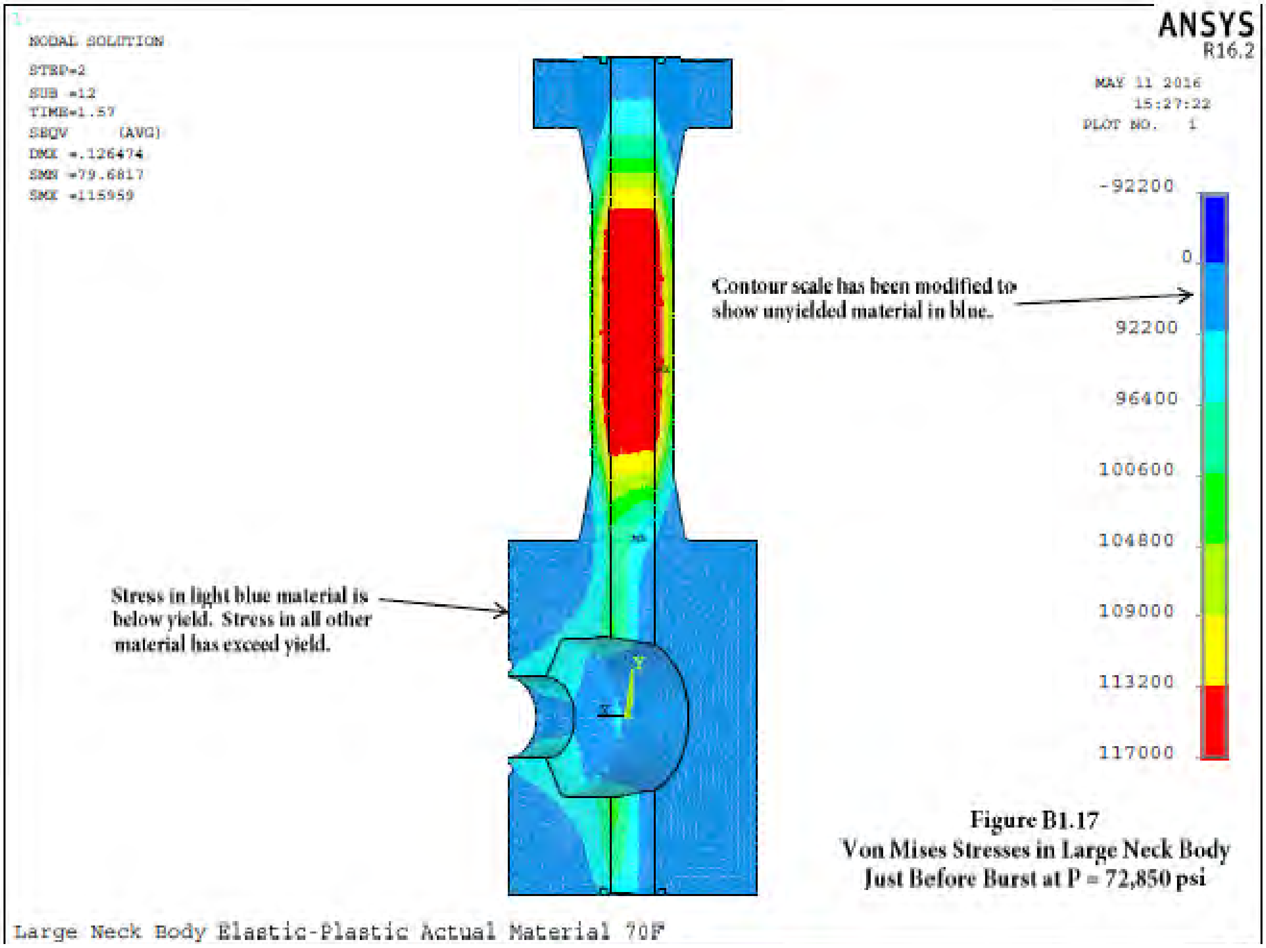


Figure B1.16
Von Mises Stresses in Large Neck Body
Just Before Burst at Pi= 72,850 psi



Contour scale has been modified to show unyielded material in blue.

Stress in light blue material is below yield. Stress in all other material has exceed yield.

Figure B1.17
Von Mises Stresses in Large Neck Body
Just Before Burst at P = 72,850 psi

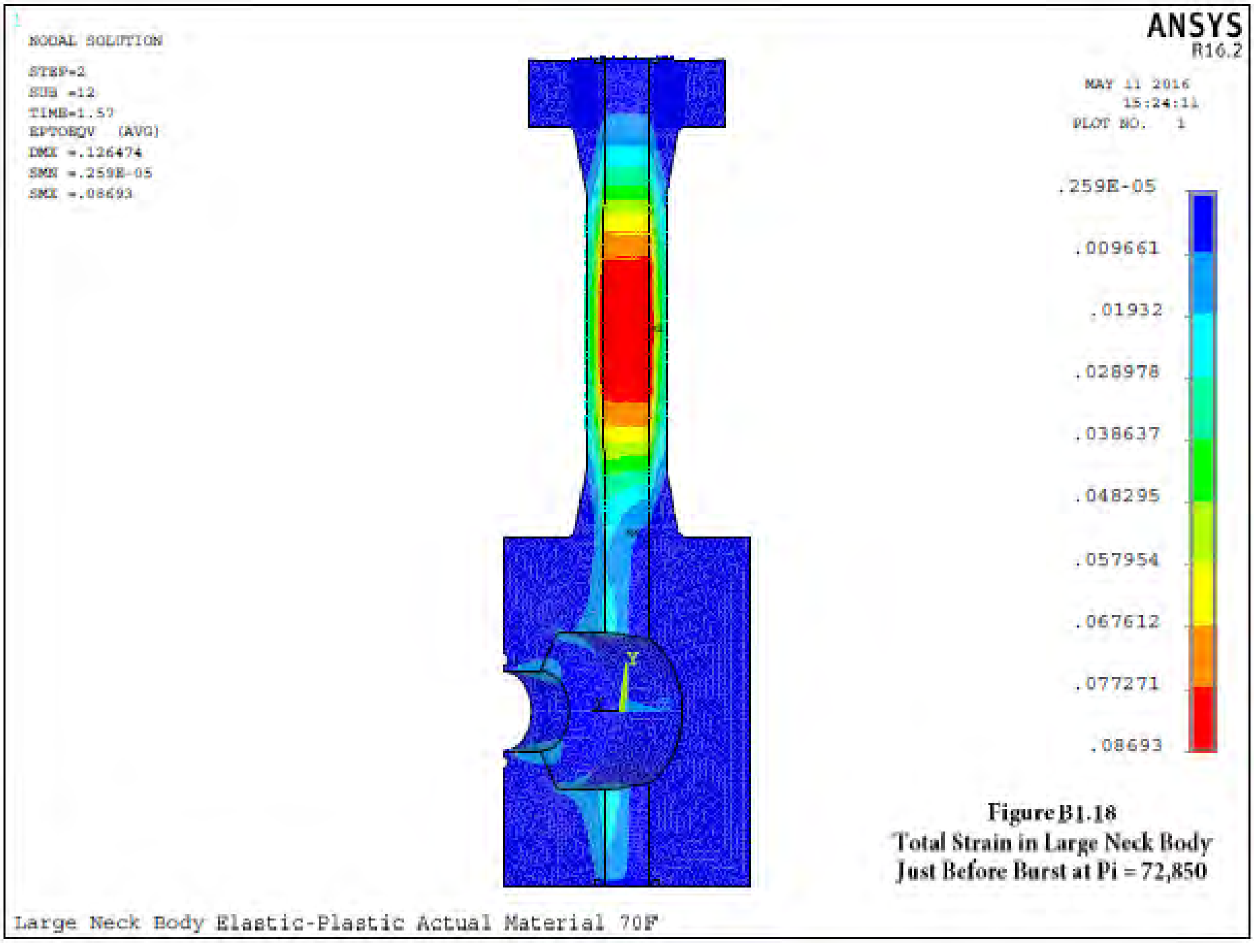
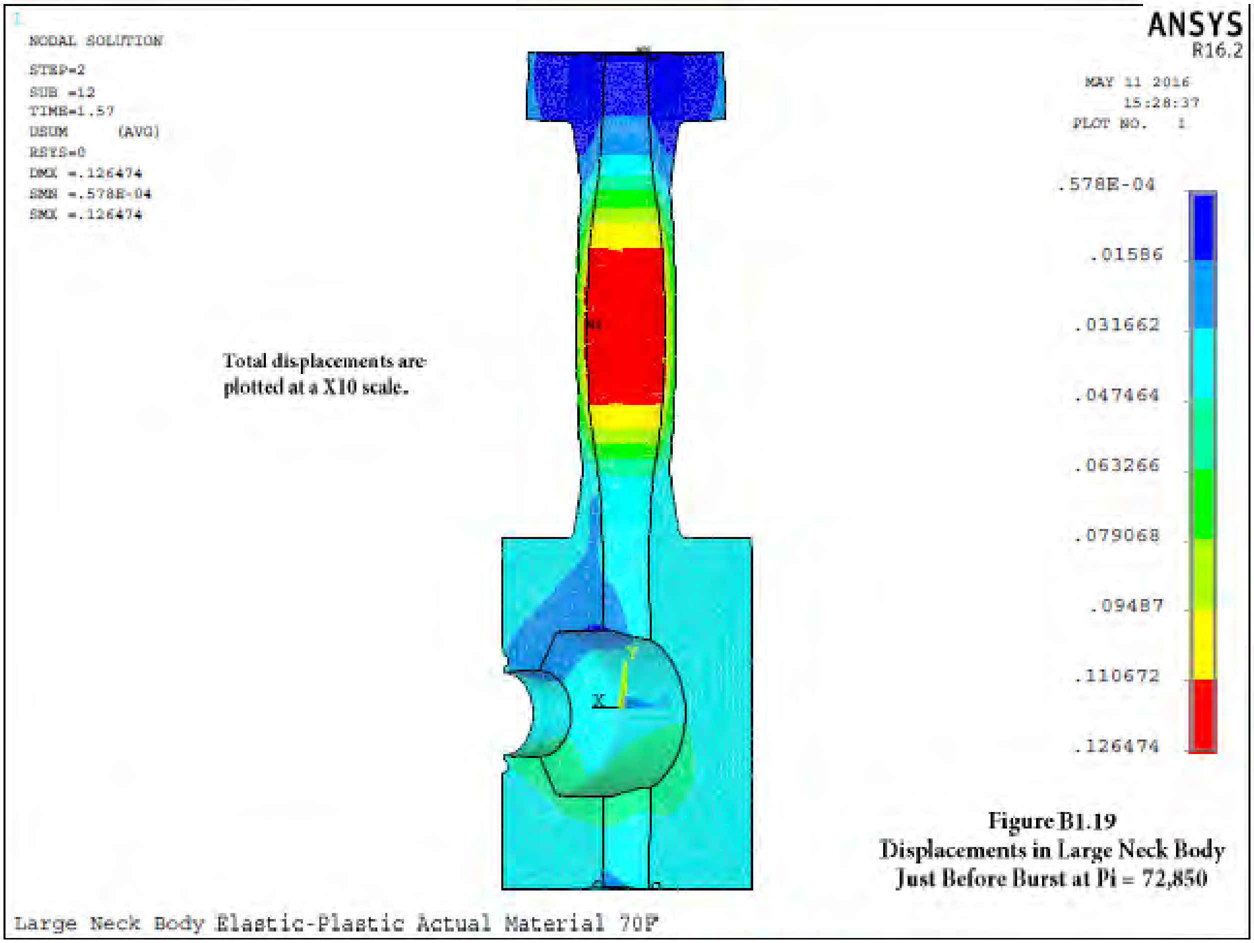
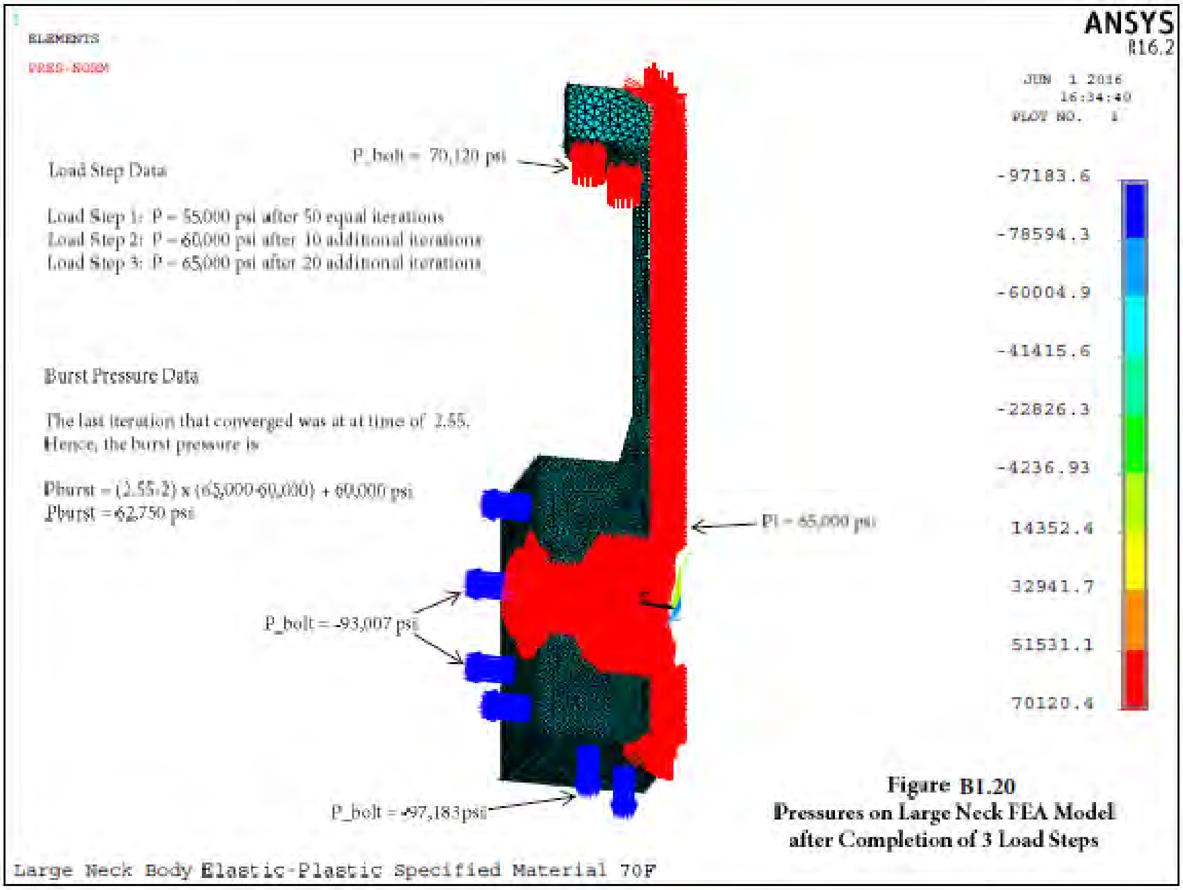


Figure B1.18
Total Strain in Large Neck Body
Just Before Burst at Pi = 72,850



Total displacements are
plotted at a X10 scale.

Figure B1.19
Displacements in Large Neck Body
Just Before Burst at Pi = 72,850



Load Step Data

Load Step 1: P = 55,000 psi after 50 equal iterations
Load Step 2: P = 60,000 psi after 10 additional iterations
Load Step 3: P = 65,000 psi after 20 additional iterations

Burst Pressure Data

The last iteration that converged was at at time of 2.55. Hence, the burst pressure is

Pburst = (2.55-2) x (65,000-60,000) + 60,000 psi
Pburst = 62,750 psi

Figure B1.20
Pressures on Large Neck FEA Model
after Completion of 3 Load Steps

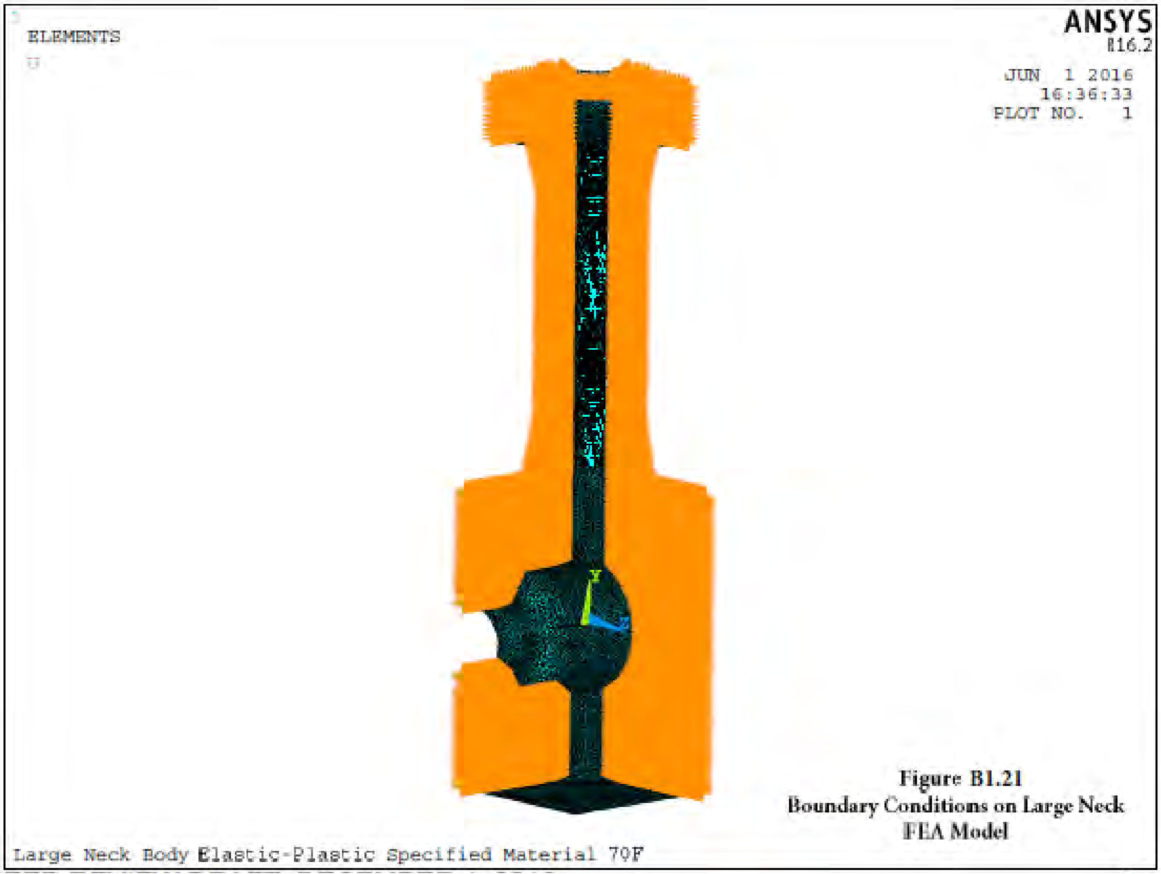


Figure B1.21
Boundary Conditions on Large Neck
FEA Model

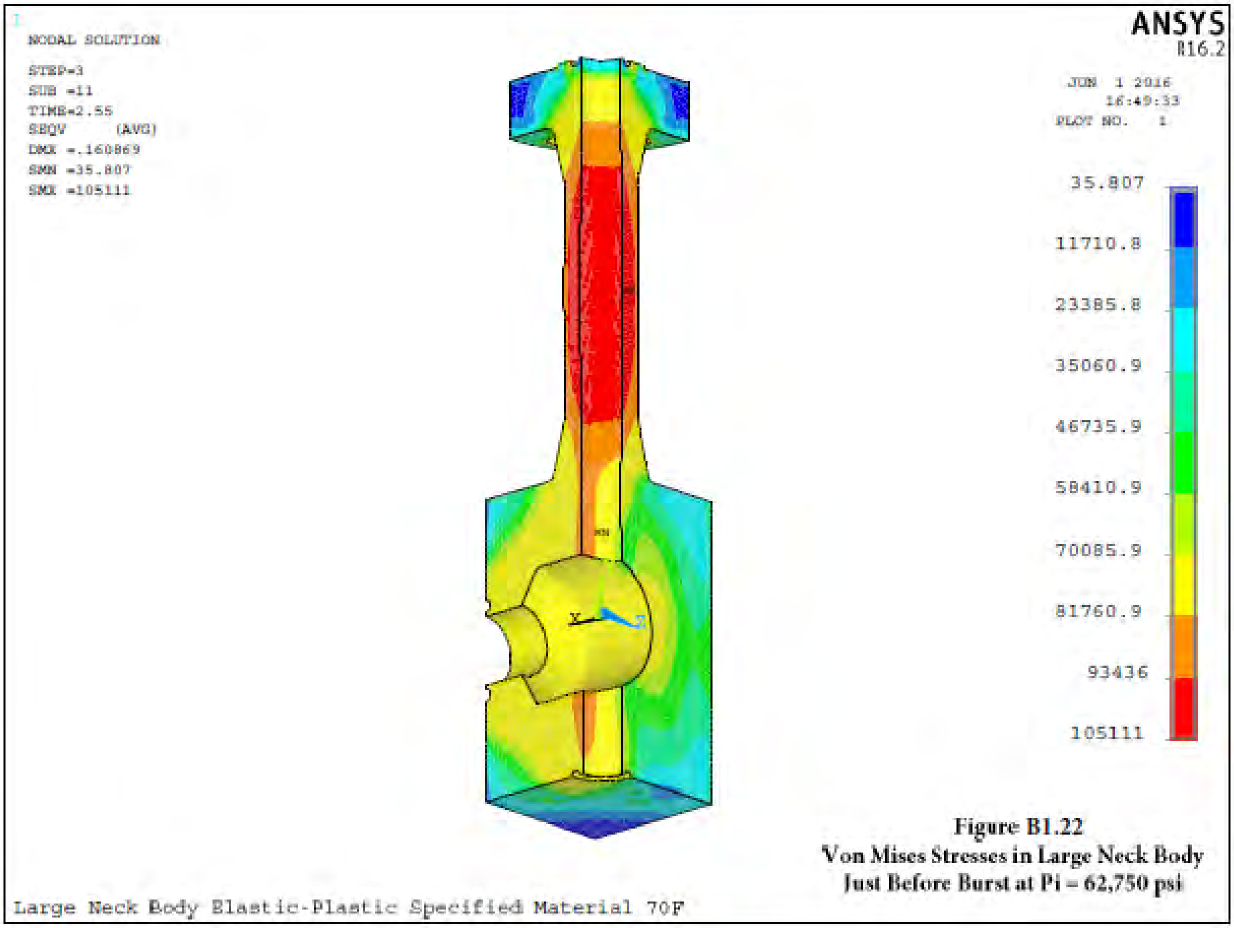


Figure B1.22
Von Mises Stresses in Large Neck Body
Just Before Burst at Pi = 62,750 psi

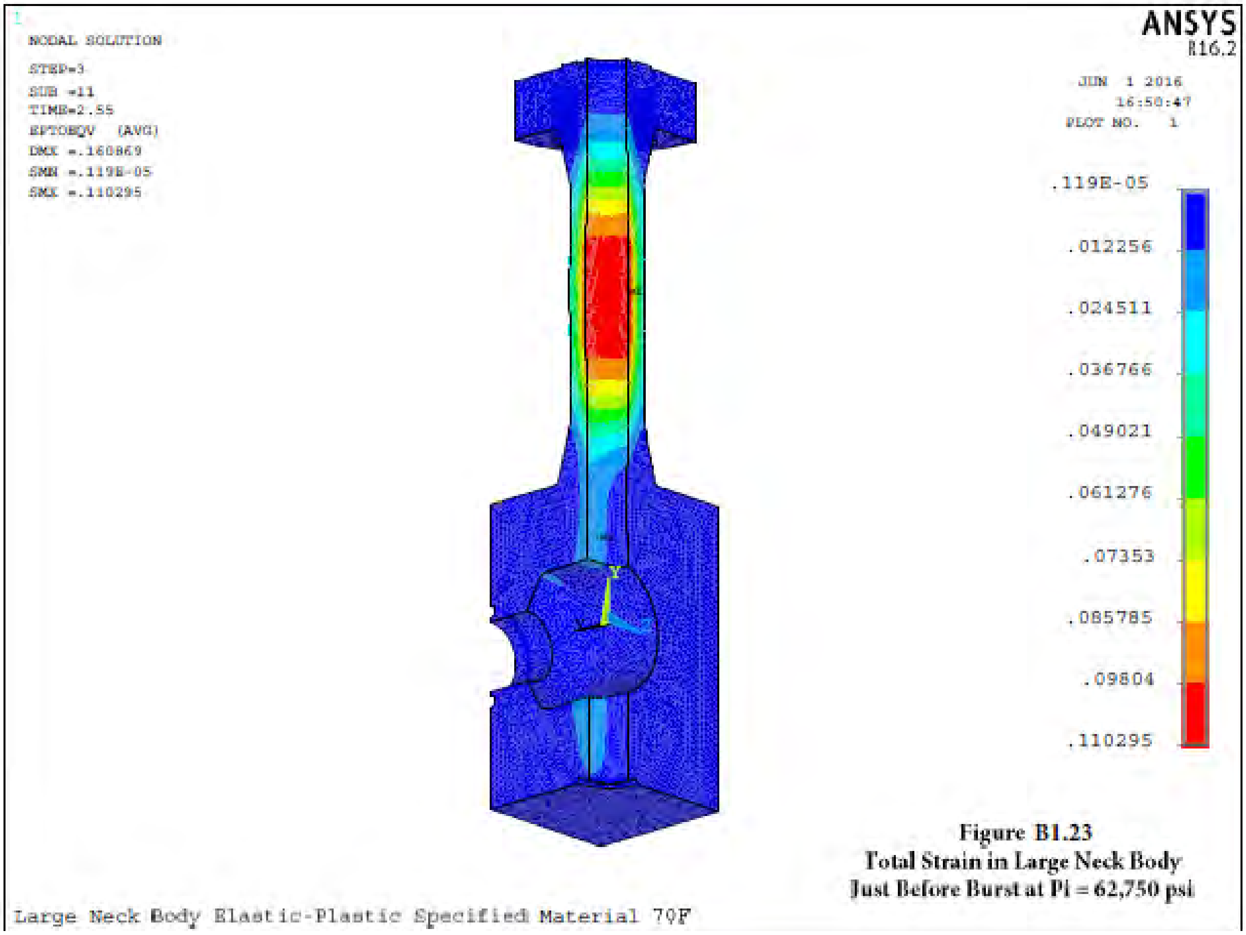


Figure B1.23
Total Strain in Large Neck Body
Just Before Burst at Pi = 62,750 psi

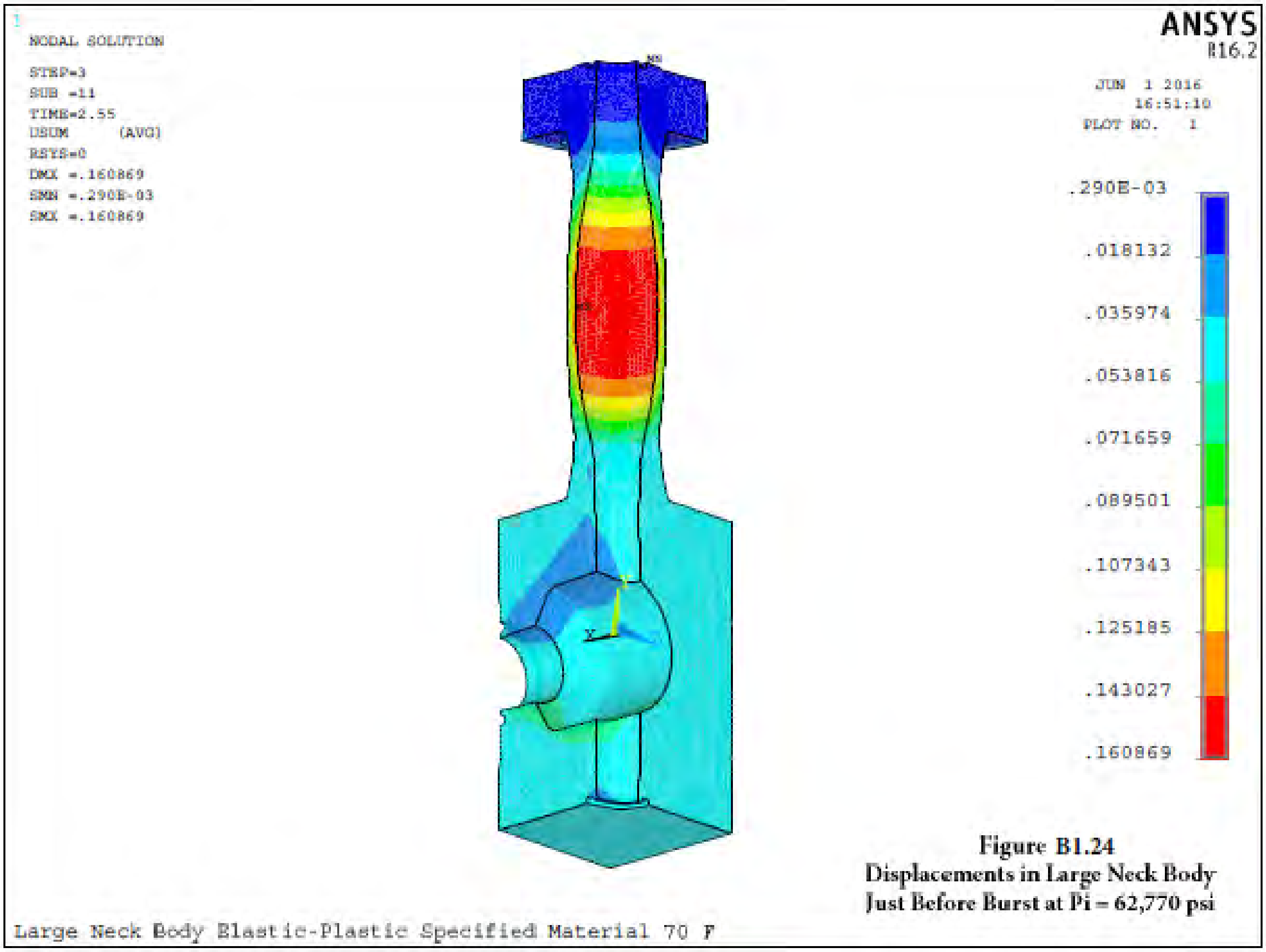


Figure B1.24
Displacements in Large Neck Body
Just Before Burst at Pi = 62,770 psi

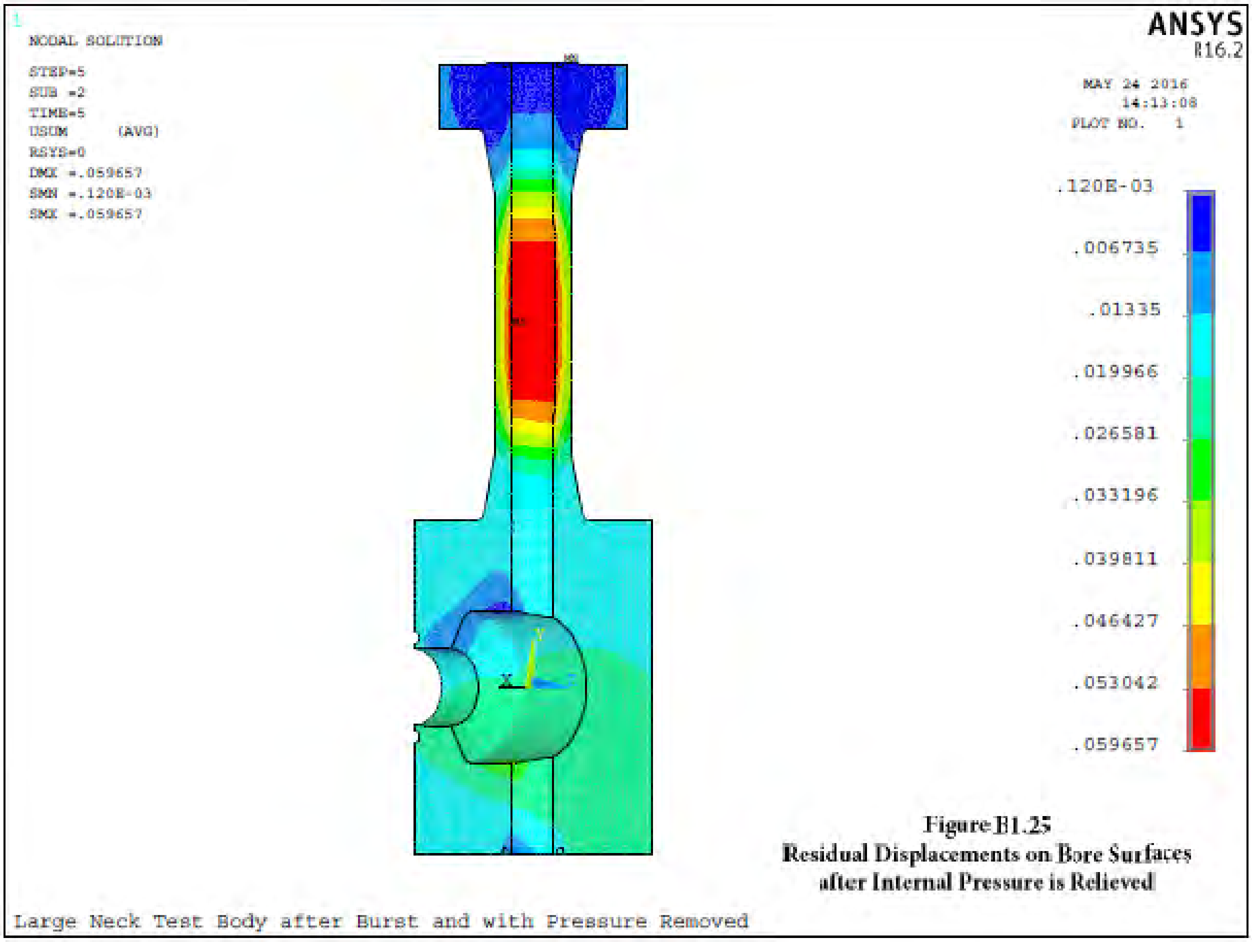


Figure B1.25
Residual Displacements on Bore Surfaces
after Internal Pressure is Relieved

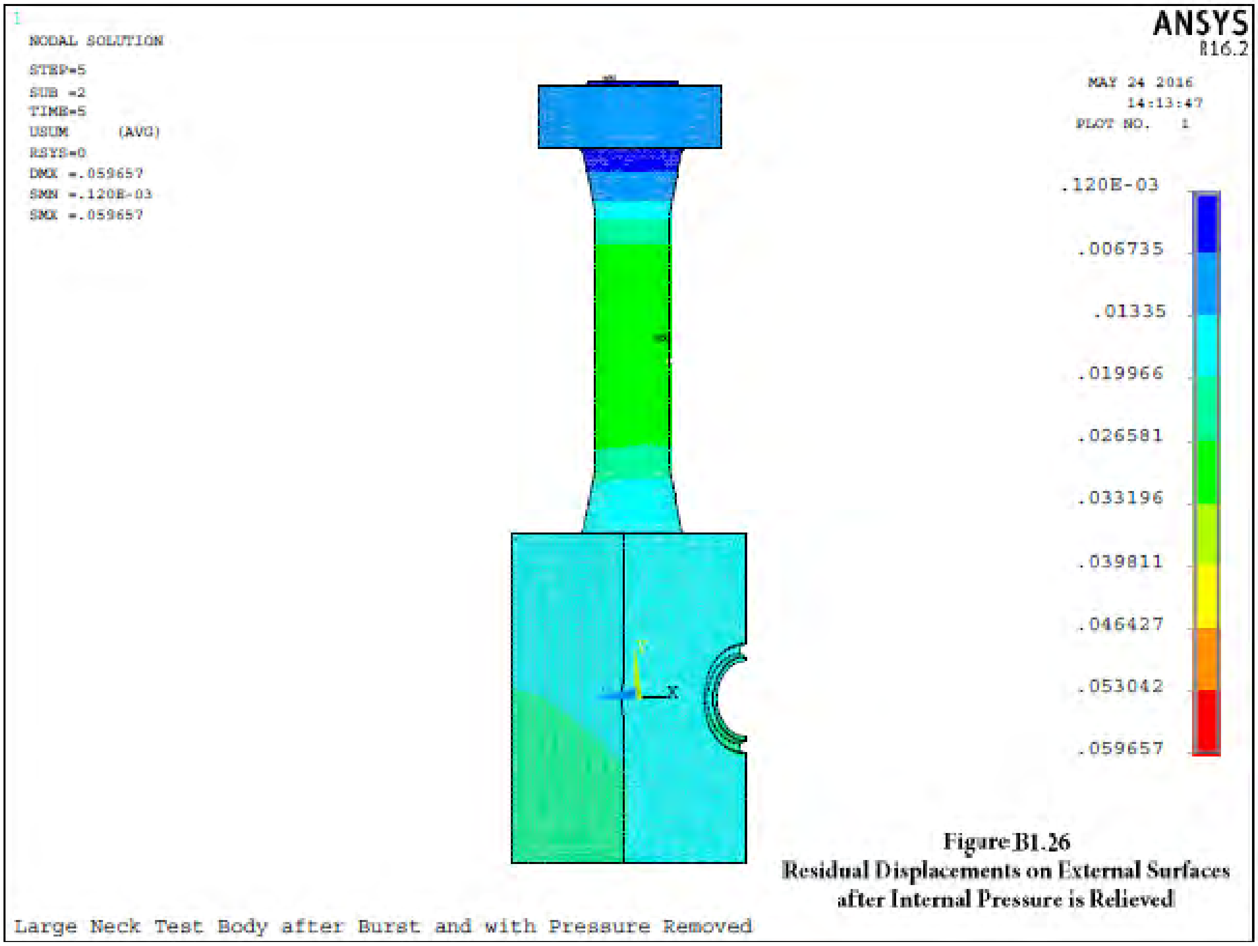


Figure B1.26
Residual Displacements on External Surfaces
after Internal Pressure is Relieved

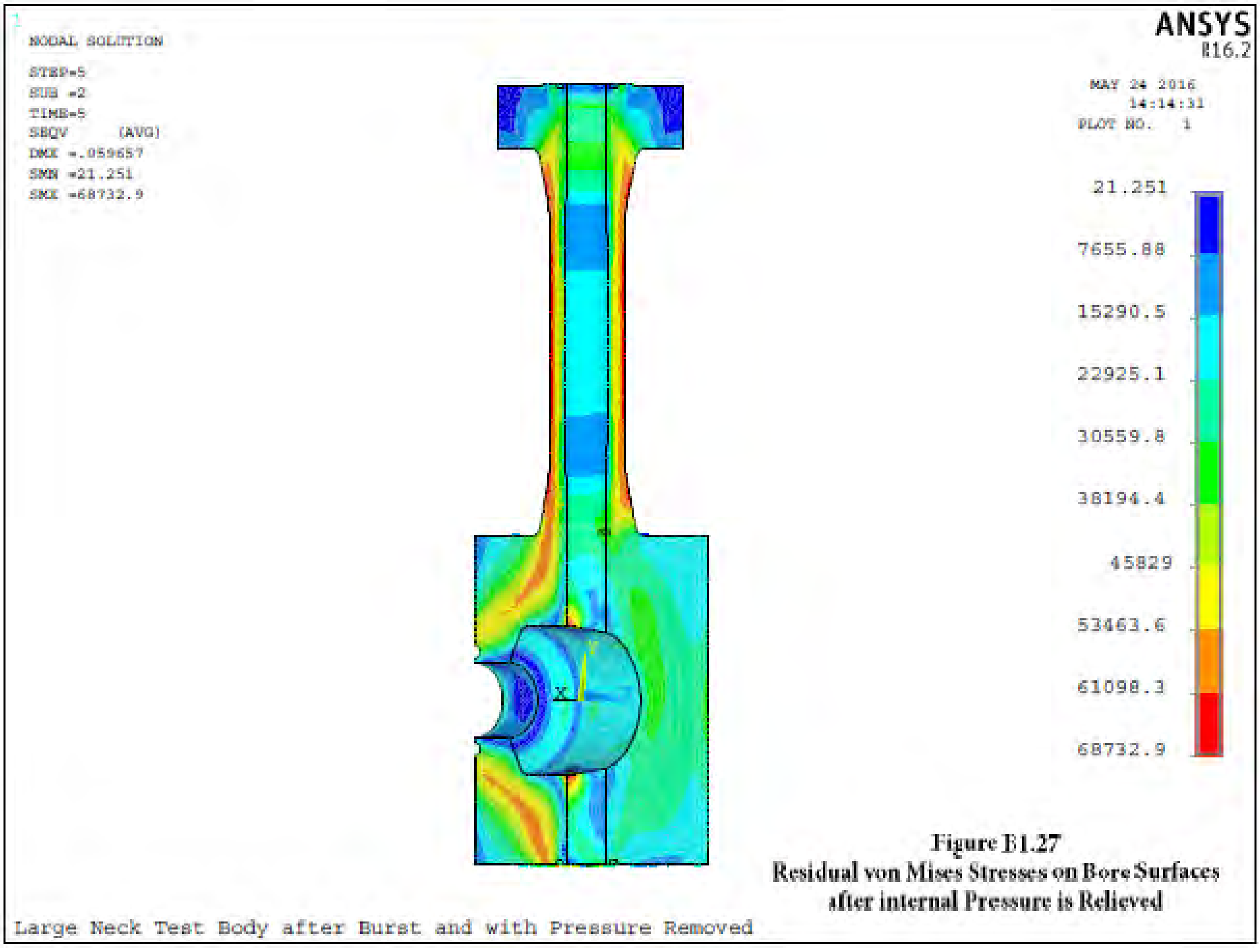


Figure B1.27
Residual von Mises Stresses on Bore Surfaces
after internal Pressure is Relieved

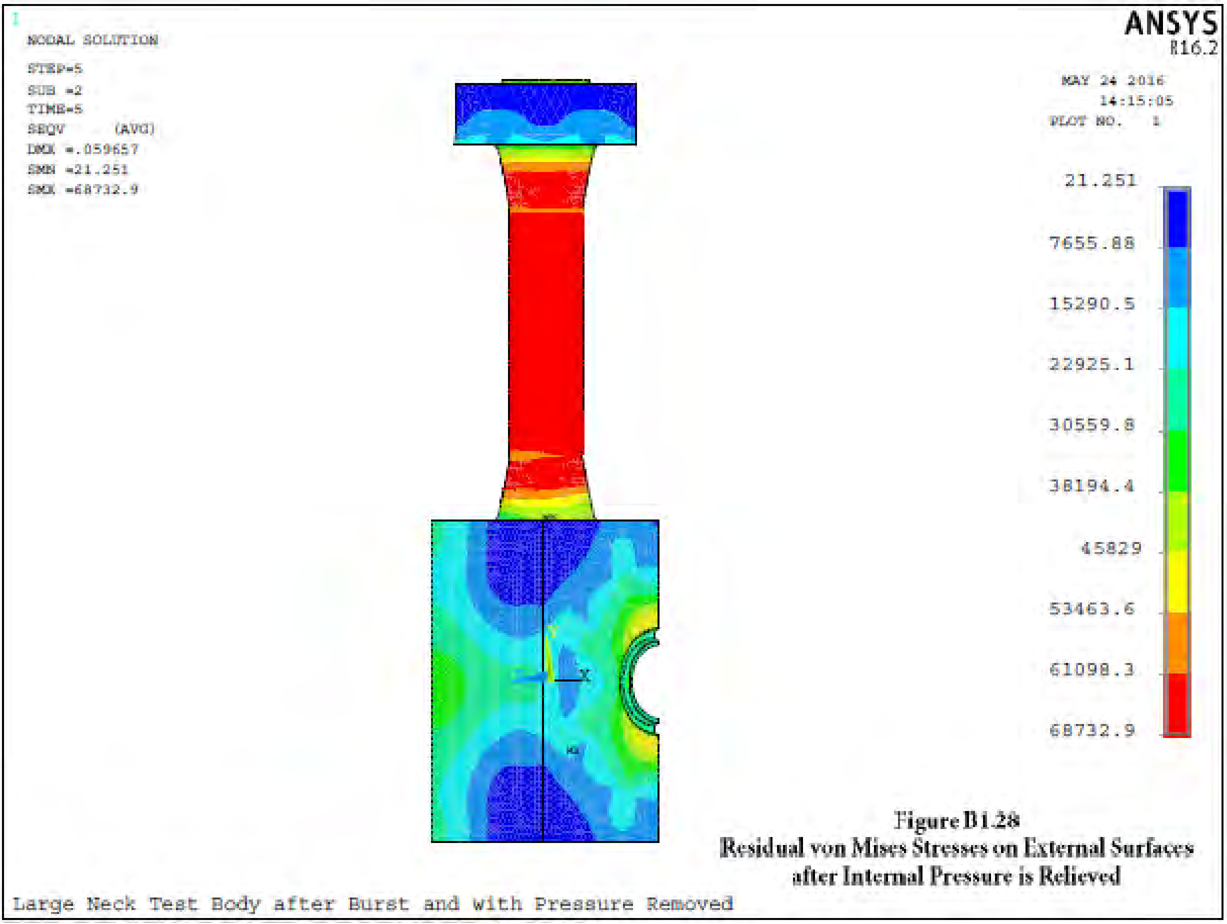


Figure B1.28
Residual von Mises Stresses on External Surfaces
after Internal Pressure is Relieved

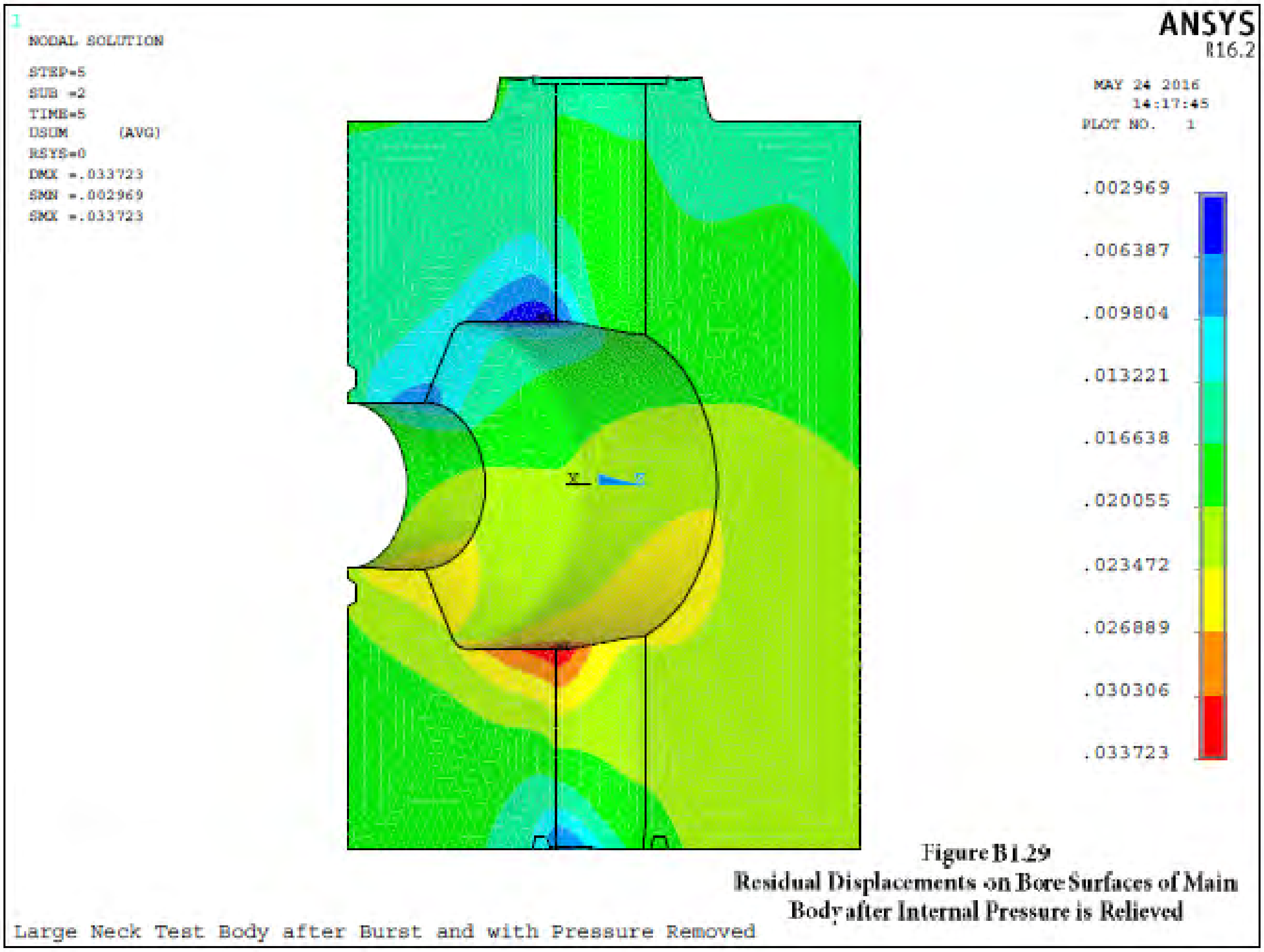


Figure B1.29
Residual Displacements on Bore Surfaces of Main Body after Internal Pressure is Relieved

Figure B1.30
Residual Displacements on External Surfaces of Main Body after Internal Pressure is Relieved

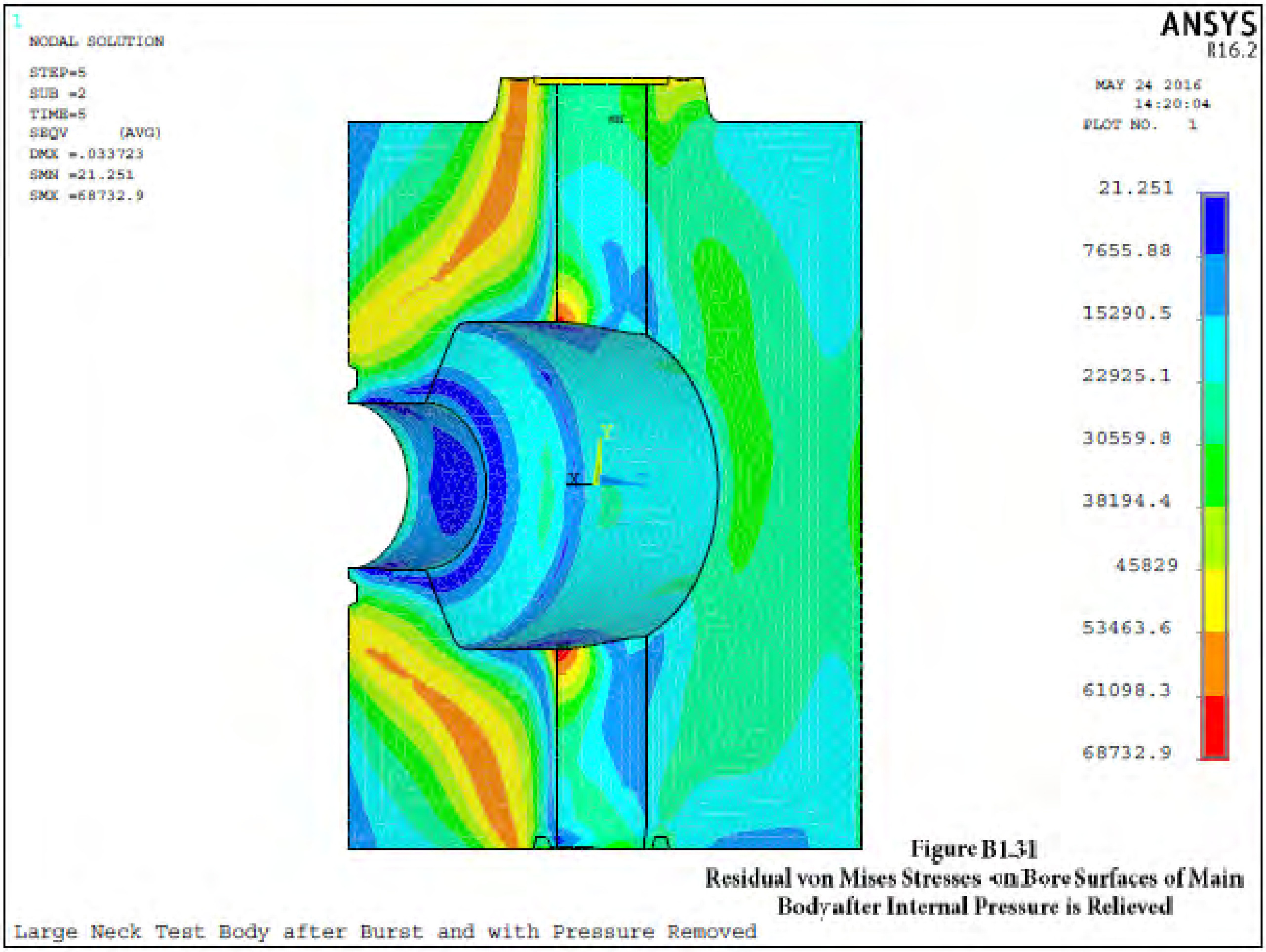


Figure B1.31
Residual von Mises Stresses on Bore Surfaces of Main Body after Internal Pressure is Relieved

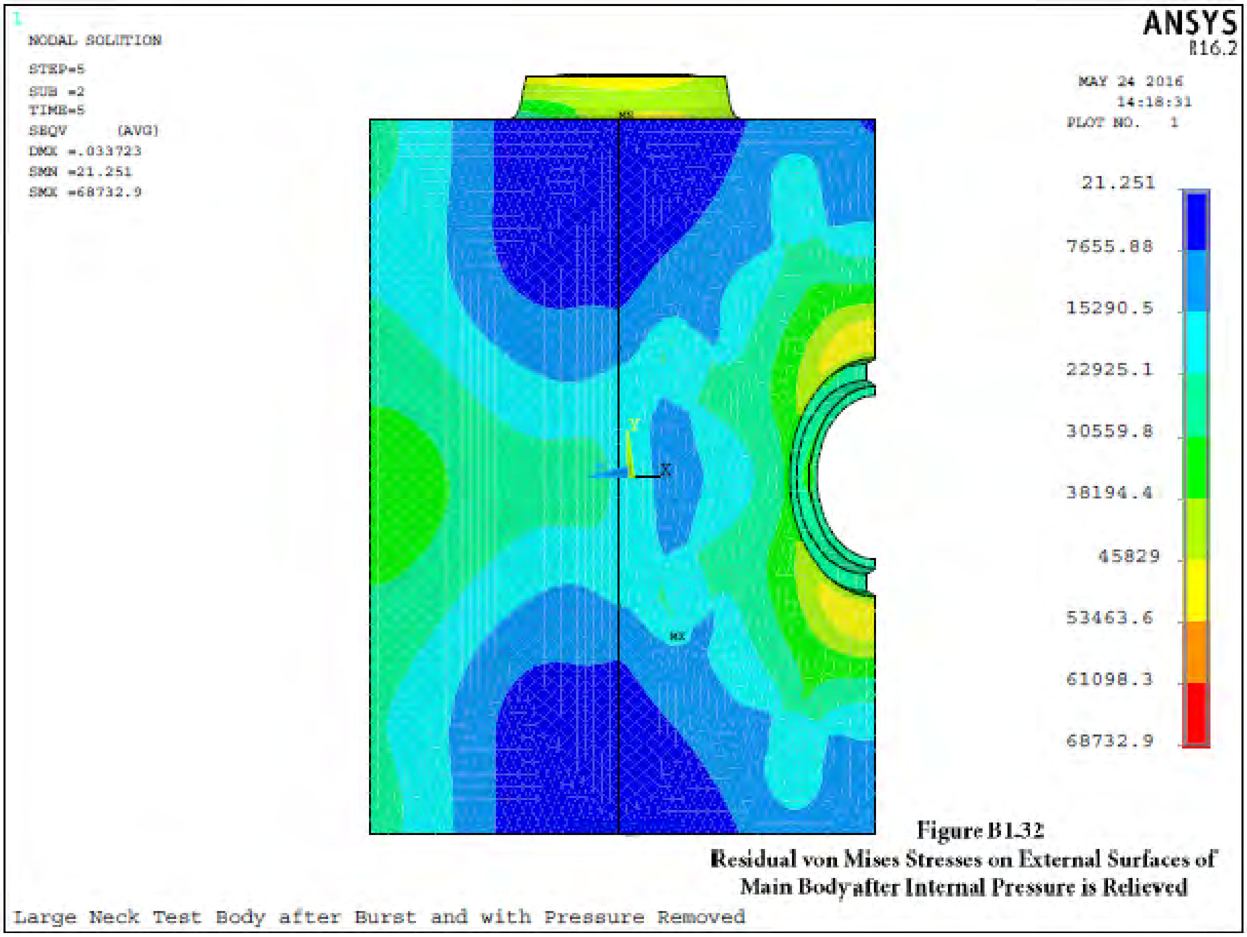


Figure B1.32
Residual von Mises Stresses on External Surfaces of Main Body after Internal Pressure is Relieved

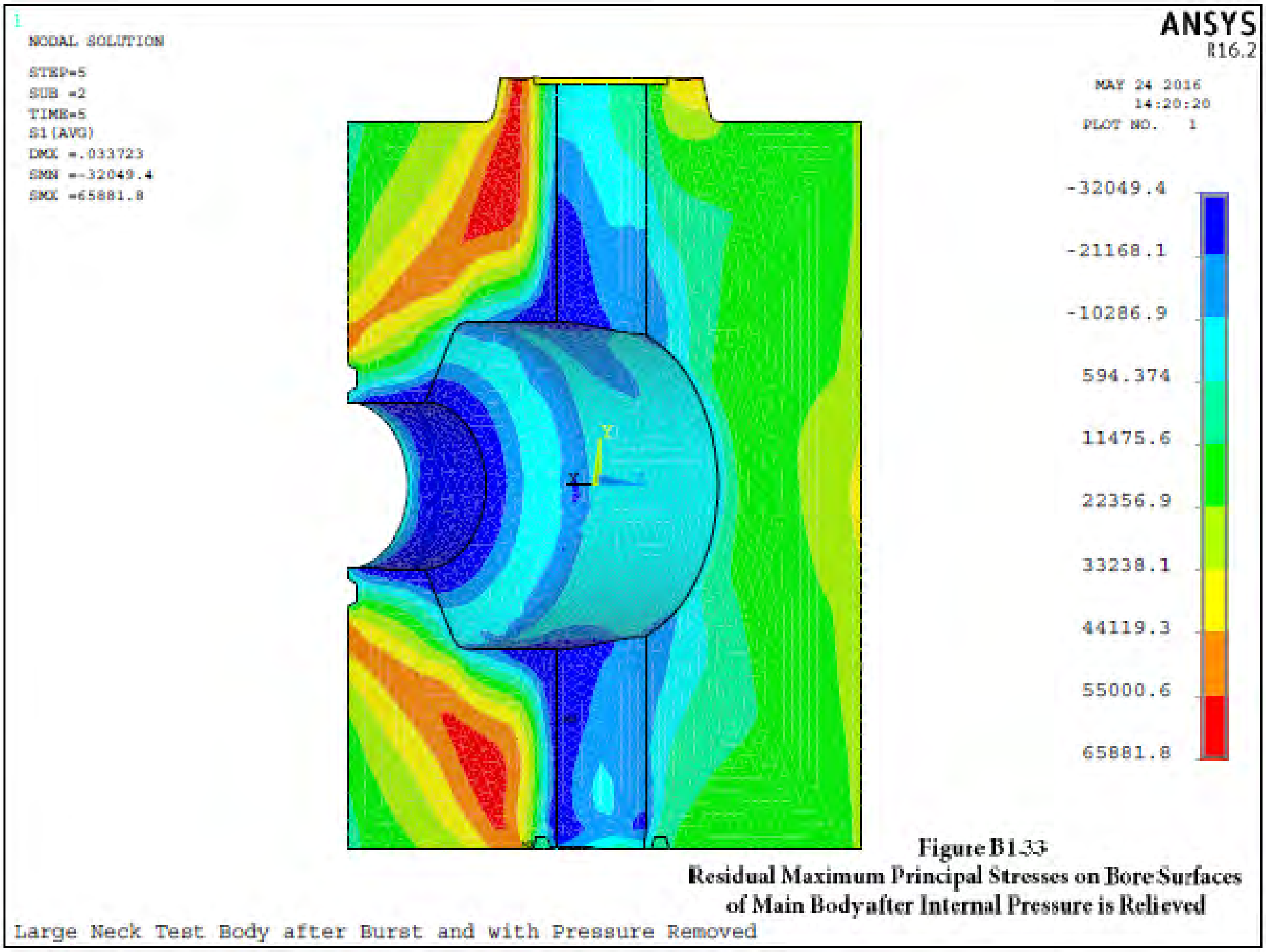


Figure B1.33
Residual Maximum Principal Stresses on Bore Surfaces of Main Body after Internal Pressure is Relieved

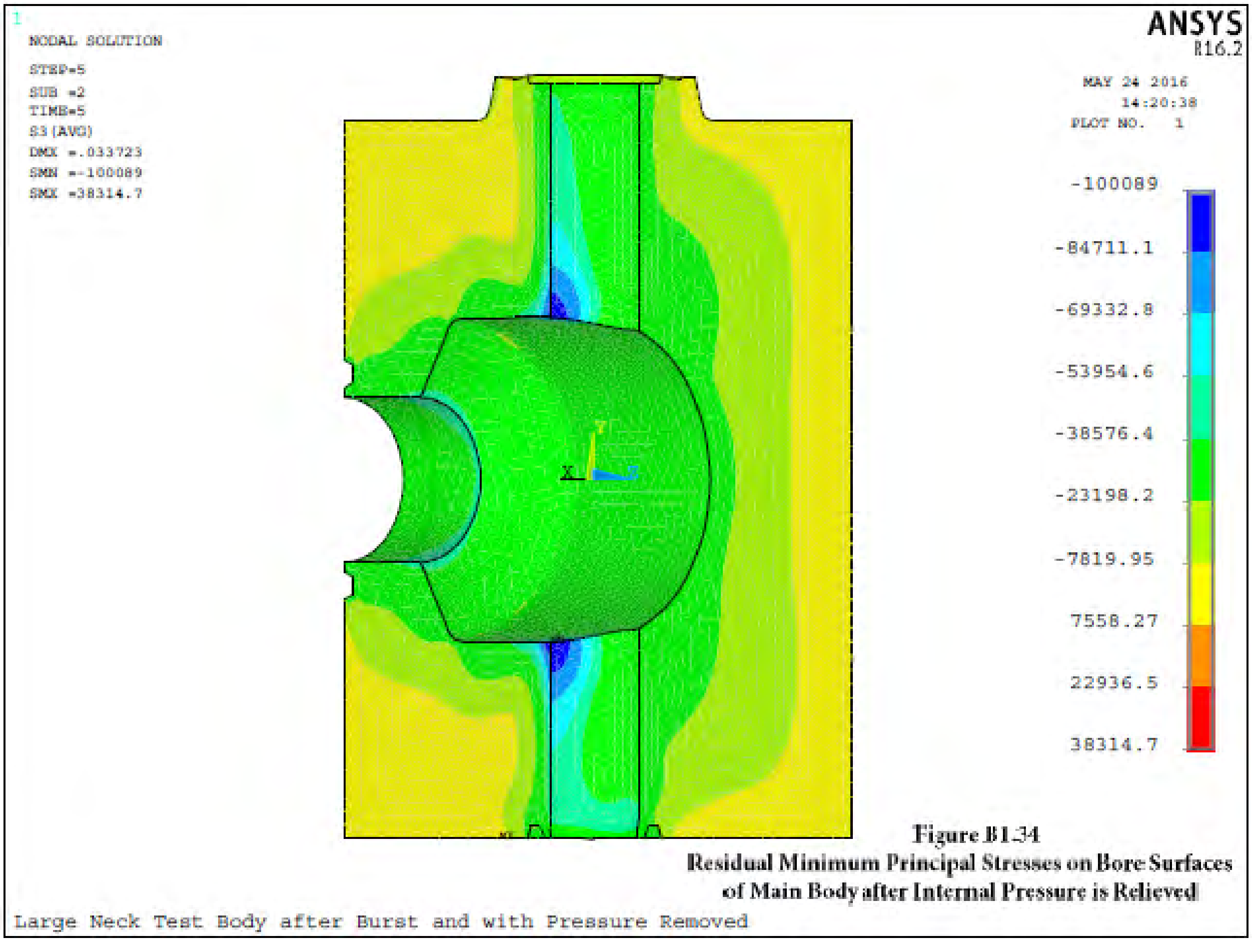


Figure B1.34
Residual Minimum Principal Stresses on Bore Surfaces of Main Body after Internal Pressure is Relieved

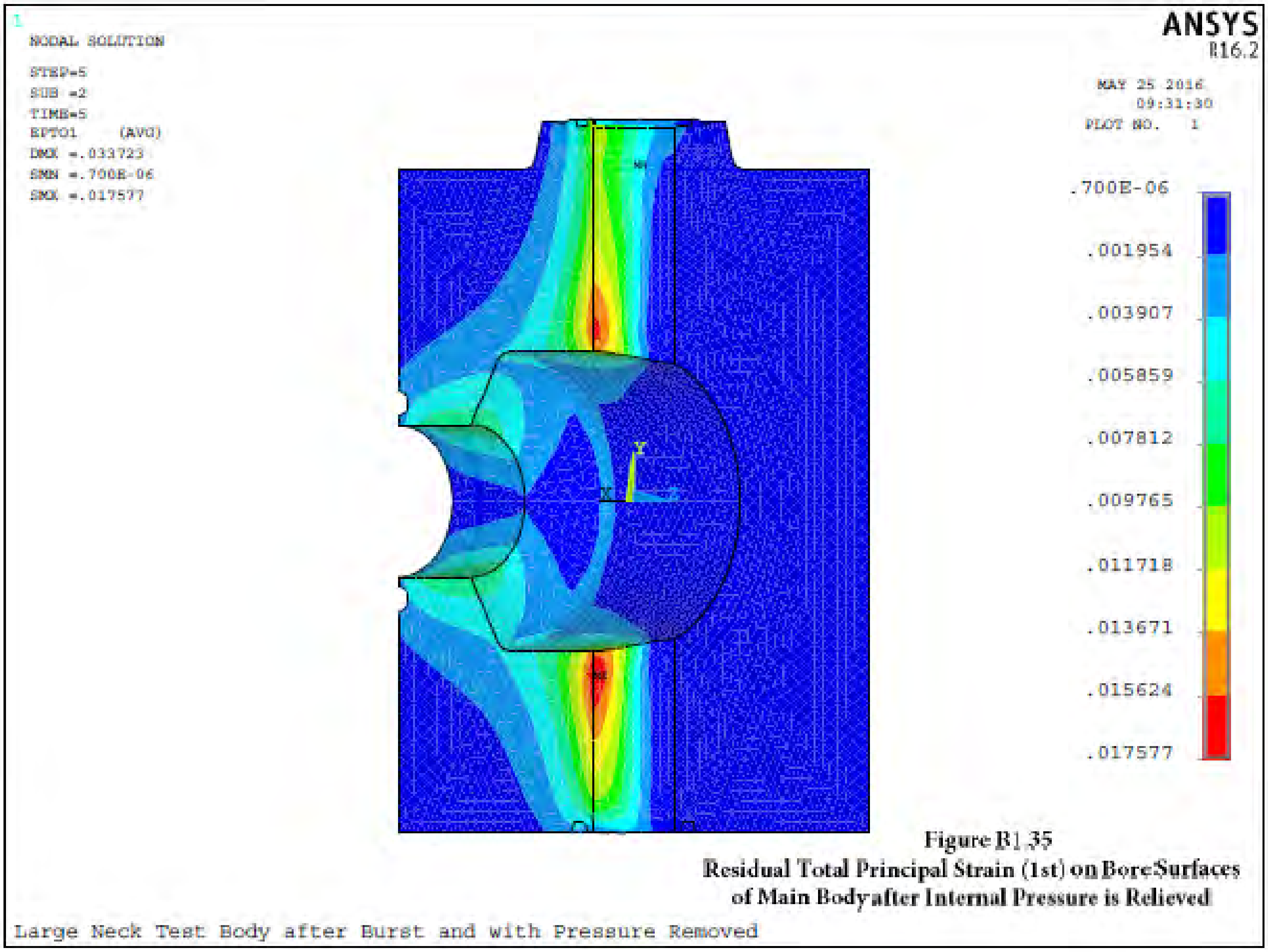


Figure B1.35
Residual Total Principal Strain (1st) on Bore Surfaces
of Main Body after Internal Pressure is Relieved

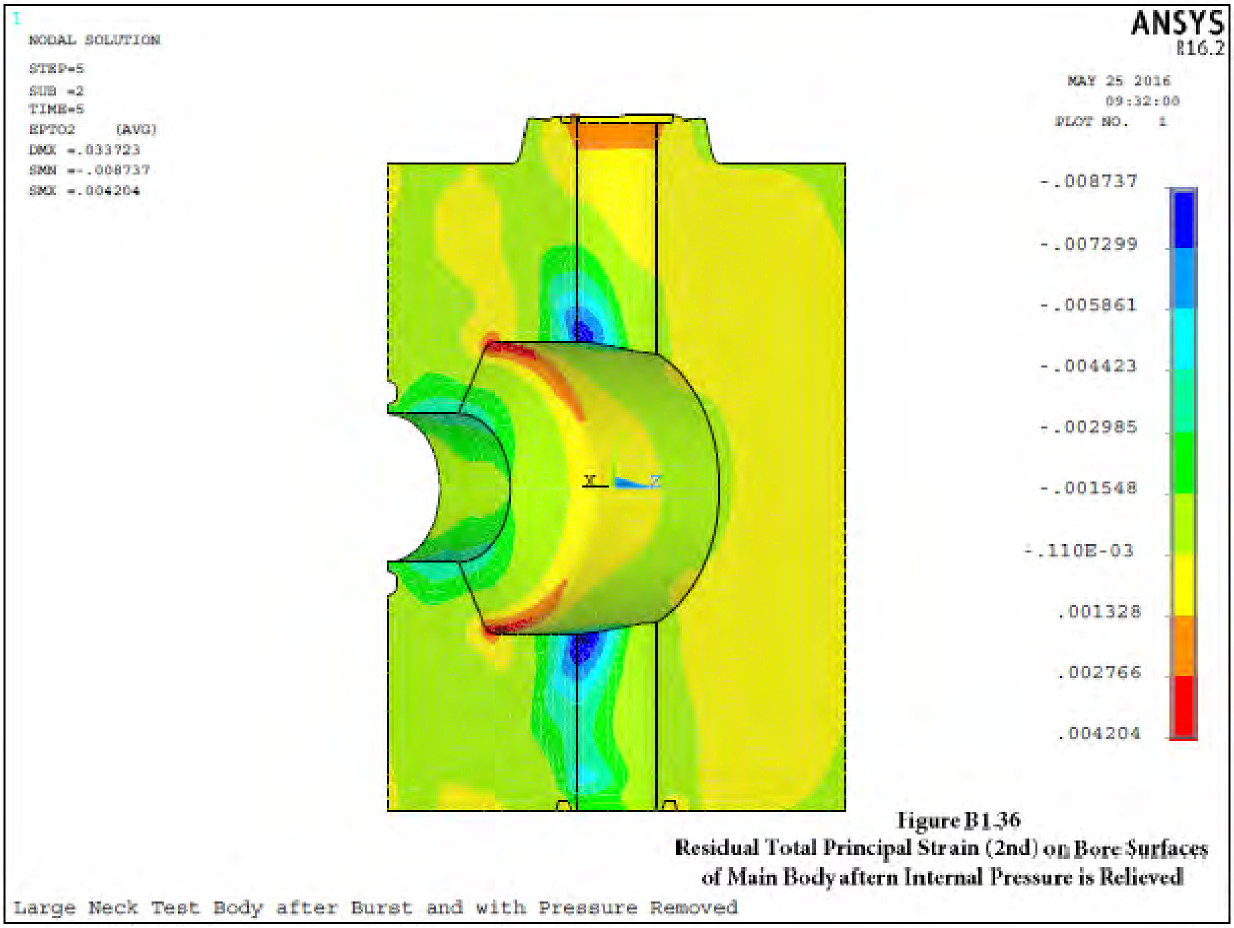


Figure B1.36
Residual Total Principal Strain (2nd) on Bore Surfaces
of Main Body aftern Internal Pressure is Relieved

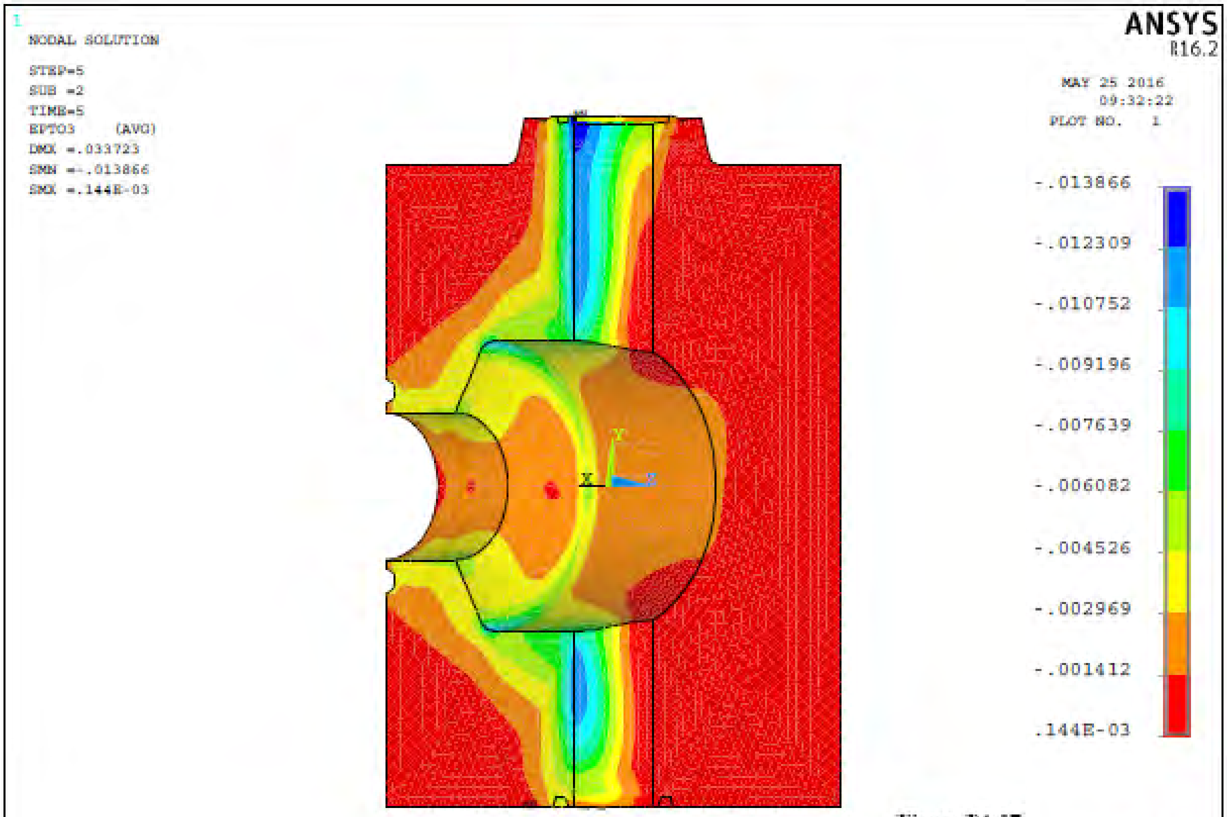


Figure B1.37
Residual Total Principal Strain (3rd) on Bore Surfaces
of Main Body after Internal Pressure is Relieved

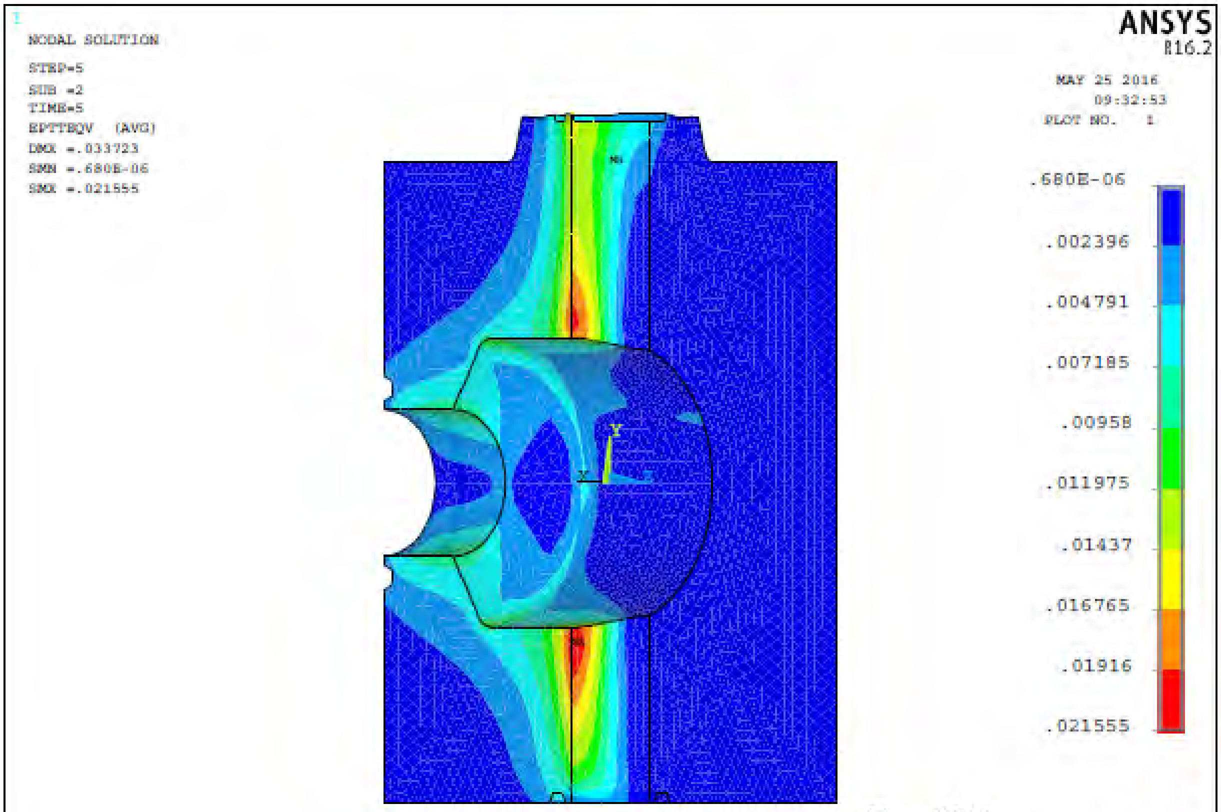


Figure B1.38
Residual Total Principal Strain (EQV) on Bore Surfaces
of Main Body after Internal Pressure is Relieved

Appendix B2
FEA of Small Neck Test Body

Appendix B1 describes FEA of the large neck test body and Appendix B2 describes FEA of the small neck test body. Other than results, the contents of Appendix B1 and Appendix B2 are virtually the same. To make Appendix B2 easier to read, the common text and information in Appendix B1 is repeated in Appendix B2. Hence, there is considerable redundancy in Appendix B2.

Some of the important features of the FEA model of the small neck test body were described in the main body of this report; they will not be further discussed in this Appendix. Plots of the small neck test body model, features, mesh, loads and boundary conditions are presented in the following figures:

The FEA model was solved with the following three material properties:

Linear-elastic properties for the as-specified material
Elastic-plastic properties for the actual material
Elastic-plastic properties for the as-specified material

The results of the solution with linear elastic properties were used to calculate pressure ratings based on the linear-elastic procedures in API 6A and ASME Division 2. The results of the solutions with elastic-plastic properties were used to calculate pressure ratings based on the elastic-plastic rules in ASME Division 2 and Division 3.

The following are discussions of the FEA solutions of the small neck model that were performed, the important results and the pressure ratings based on Code rules.

Linear-Elastic FEA

The small neck FEA model was solved with linear-elastic material properties at the design internal pressure of 10,000 psi. The pressure ratings using stresses from linear-elastic FEA were based on the minimum material strengths of the as-specified material. The linear-elastic analysis methods in API 6A and Division 2 are the same. However, API 6A and Division 2 differ in that API 6A compares stress intensity with the allowable stress whereas Division 2 compares von Mises stress with the allowable stress. In this report, pressure ratings are calculated based on both stress intensity and on von Mises stress.

The following figures of the linear-elastic FEA model and results are included in Appendix B2:

Model and Results of Linear-elastic FEA of Small Neck Test Body

Figure B2.9:	Features of Small Neck Model for Linear Elastic FEA
Figure B2.10:	von Mises Stresses in Small Neck Body with 10 ksi Internal Pressure
Figure B2.11:	Total Displacements in Small Neck Body with 10 ksi Internal Pressure
Figure B2.12:	Linearized Stresses in Small Neck Body with 10 ksi Internal Pressure
Figure B2.13:	Pressure Rating Calculations.

The most important figure is the linearized stress table in Figure B2.12 and the pressure rating calculations in Figure B2.13. The stress table shows the linearized stresses through the critical section. The critical section was found by linearizing section stresses through several paths in the model and choosing the most highly stressed section for pressure rating calculations. The location of the critical path is shown in Figure B2.10.

From the linearized stress table in Figure B2.12, the important linearized stresses in the critical section at an internal pressure of 10 ksi are

Linearize membrane stress intensity = 20,360 psi
Linearized membrane plus bending stress intensity = 31,480 psi
Linearized membrane von Mises stress = 17,650 psi
Linearized membrane plus bending von Mises stress = 27,920 psi

The allowable membrane stress is 2/3 of yield strength and the allowable membrane plus bending stress is the yield strength. Since the minimum yield strength is 75,000 psi, the allowable stresses are

Allowable membrane stress = (2/3) x 75,000) psi = 50,000 psi
Allowable membrane + bending stress = 75,000 psi

For an elastic analysis, stress is linear with pressure. Hence, the allowable pressure ratings for the small neck body based on linear-elastic analysis are calculated using linear interpolation as shown below:

Rating for membrane stress intensity = (50,000/20,360) x 10,000 = 24,558 psi
Rating for membrane + bending stress intensity = (75,000/31,480) x 10,000 = 23,825 psi
Rating for membrane von Mises stress = (50,000/17,650) x 10,000 = 28,329 psi
Rating for membrane + bending von Mises stress = (75,000/27,290) x 10,000 = 27,483 psi

The pressure ratings based on membrane stress are different than those based on membrane plus bending stress. The actual pressure rating is the lessor of the two ratings. Hence, the allowable pressure ratings are

Pressure rating based on stress intensity = 23,825 psi
Pressure rating based on von Mises stress = 27,483 psi

Elastic-Plastic FEA

The FEA model was also solved with elastic-plastic material properties. One elastic-plastic solution used the actual material properties which were determined by tensile tests of a prolongation from the forging. A second elastic-plastic solution used the minimum material properties listed in the material specification. The true-stress strain curve for the as-specified material was calculated based on the methods in Part 5 of ASME Division 2.

Each elastic-plastic solution was solved by incrementally increasing the internal pressures until the solution failed to converge. As required by ASME procedures the internal pressure of the last converged solution was designated as the plastic collapse pressure of the small neck test body.

The following result plots from the elastic-plastic solutions are included at the end of Appendix B1:

Results with Actual Material Properties
Figure B2.14: Pressures on Small Neck FEA Model after Completion of 2 Load Steps
Figure B2.15: Boundary Conditions on Small Neck FEA Model
Figure B2.16: Von Mises Stresses in Small Neck Body Just Before Burst
Figure B2.17: Von Mises Stresses in Small Neck Body Just Before Burst (Modified Scale)
Figure B2.18: Total Strain in Small Neck Body Just Before Burst
Figure B2.19: Displacements in Small Neck Body Just Before Burst

Results with Specified Material Properties
Figure B2.20: Pressures on Small Neck FEA Model after Completion of 3 Load Steps
Figure B2.21: Boundary Conditions on Small Neck FEA Model
Figure B2.22: Von Mises Stresses in Small Neck Body just Before Burst
Figure B2.23: Total Strain in Small Neck Body just Before Burst
Figure B2.24: Displacements in Small Neck Body just Before Burst.

Plastic Collapse Pressures and ASME Pressure Ratings

As previously stated by ASME rules the plastic collapse pressure is the pressure at the last converged solution of the FEA model. The following paragraphs describe the procedure for calculation of the plastic collapse pressure using the elastic-plastic FEA model. Collapse pressure calculations are performed for the small neck test body with actual material properties and with specified material properties.

A solution consists of starting with a zero internal pressure and slowly ramping the pressure up in small increments until the solution does not converge. The pressure at the end of the solution and the pressure increment are specified at the onset of the solution. If the solution converges when the maximum pressure is reached a second load step must be performed. The second load step is a continuation of the first load step but with an increased value for the final pressure and possibly a different pressure increment. If the solution still converges at the end of second load step then a third load step must be performed. This process must be continued until non-convergence is achieved.

The ANSYS program lists the time and/or the iteration number at the last converged solution. The internal pressure at the last converged is easily calculated using simple linear interpolation based on either time or iteration number. The following are calculations for the collapse pressures and pressure ratings.

Small Neck Body with Actual Material Properties

Plastic Collapse Iteration History

Load Step 1: 50,000 psi internal pressure after 50 equal iterations (time = 1.0)

Load Step 2: 55,000 psi internal pressure after 10 additional iterations (time = 2.0)

Load Step 3: 60,000 psi internal pressure after 20 additional iterations (time = 3.0)

Time = 2.10 at last converged solution

Plastic Collapse Pressure

Plastic collapse pressure = (2.07 - 2.0) x (60,000 – 55,000) + 55,000 psi

Plastic collapse pressure = 55,375 psi for small neck body

ASME Pressure Ratings

Division 2 Pressure Rating = 55,375 psi / 2. 4 = 23,073 psi

Division 3 Pressure Rating = 55,375 psi / 1.8 = 30,764 psi

Small Neck Body with Specified Material Properties

Plastic Collapse Iteration

Load Step 1: 45,000 psi internal pressure after 45 equal iteration (t = 1.0)

Load Step 2: 50,000 psi internal pressure after 20 additional iterations (t = 2.0)

Time =1.57 at last converged solution

Plastic Collapse Pressure

Plastic collapse pressure = (1.57 - 1.0) x (50,000 – 45,000) + 45,000 psi

Plastic collapse pressure = 47,850 psi for small neck body

ASME Pressure Ratings

Division 2 Pressure Rating = 47,850 psi / 2. 4 = 19,937 psi

Division 3 Pressure Rating = 47,850 psi / 1.8 = 26,583 psi

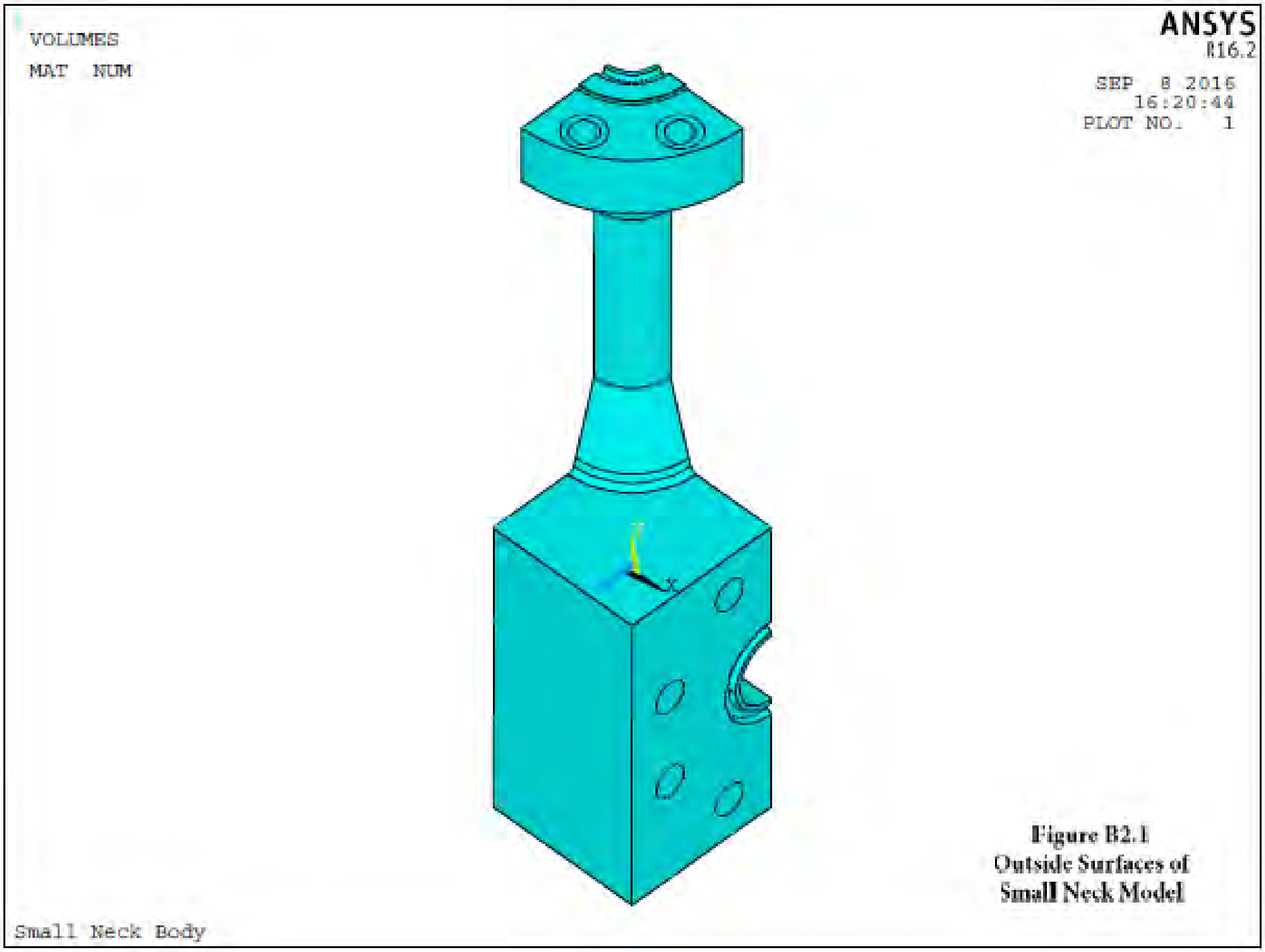


Figure B2.1
Outside Surfaces of
Small Neck Model

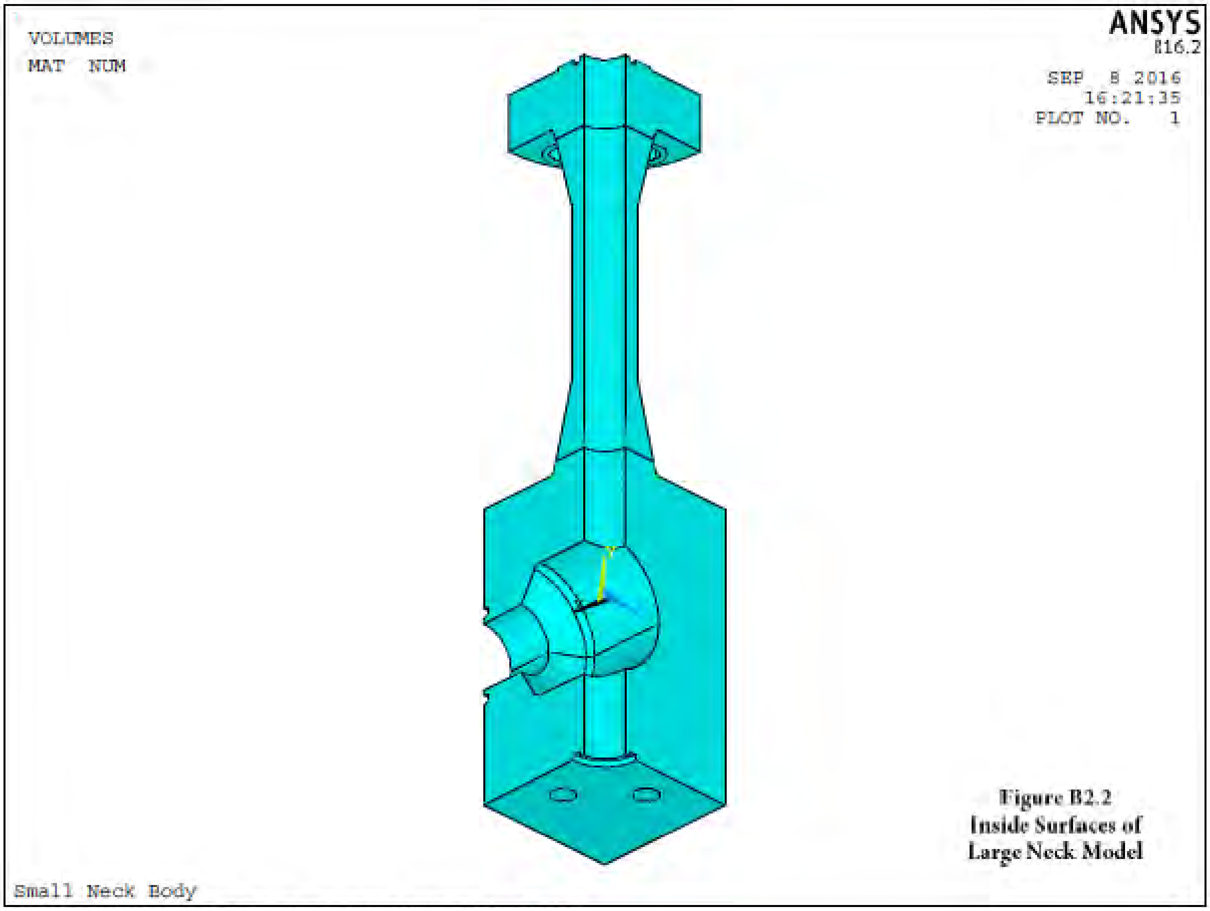


Figure B2.2
Inside Surfaces of
Large Neck Model

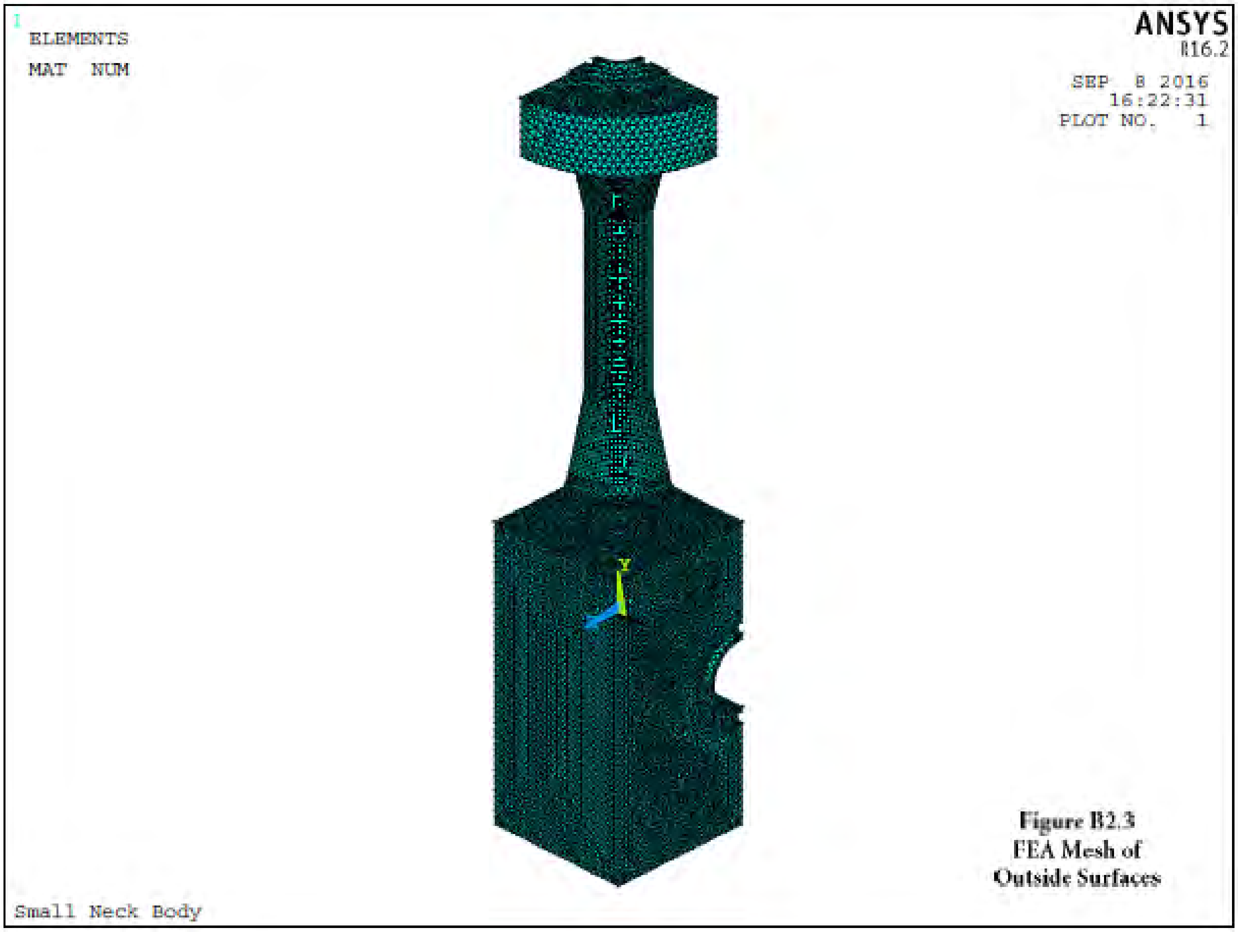


Figure B2.3
FEA Mesh of
Outside Surfaces

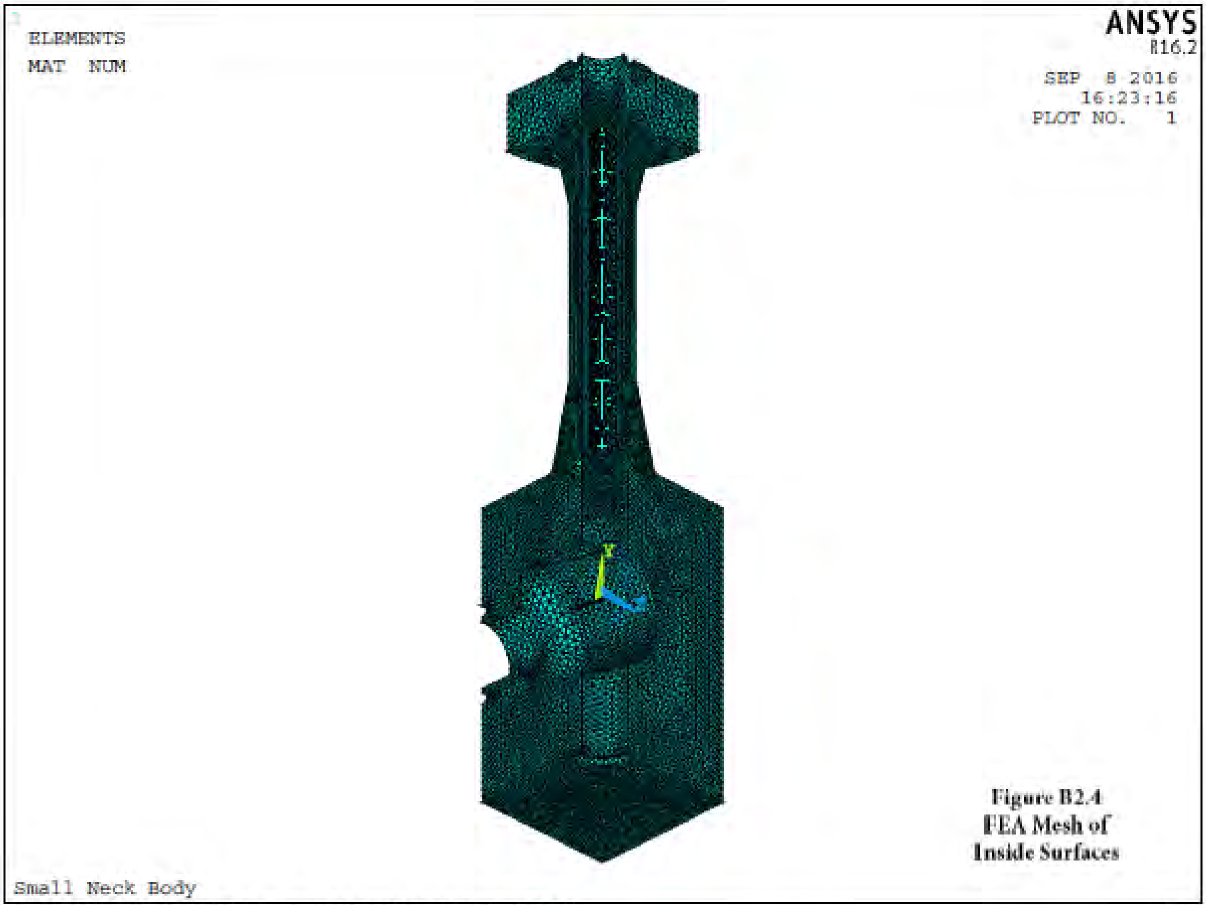


Figure B2.4
FEA Mesh of
Inside Surfaces

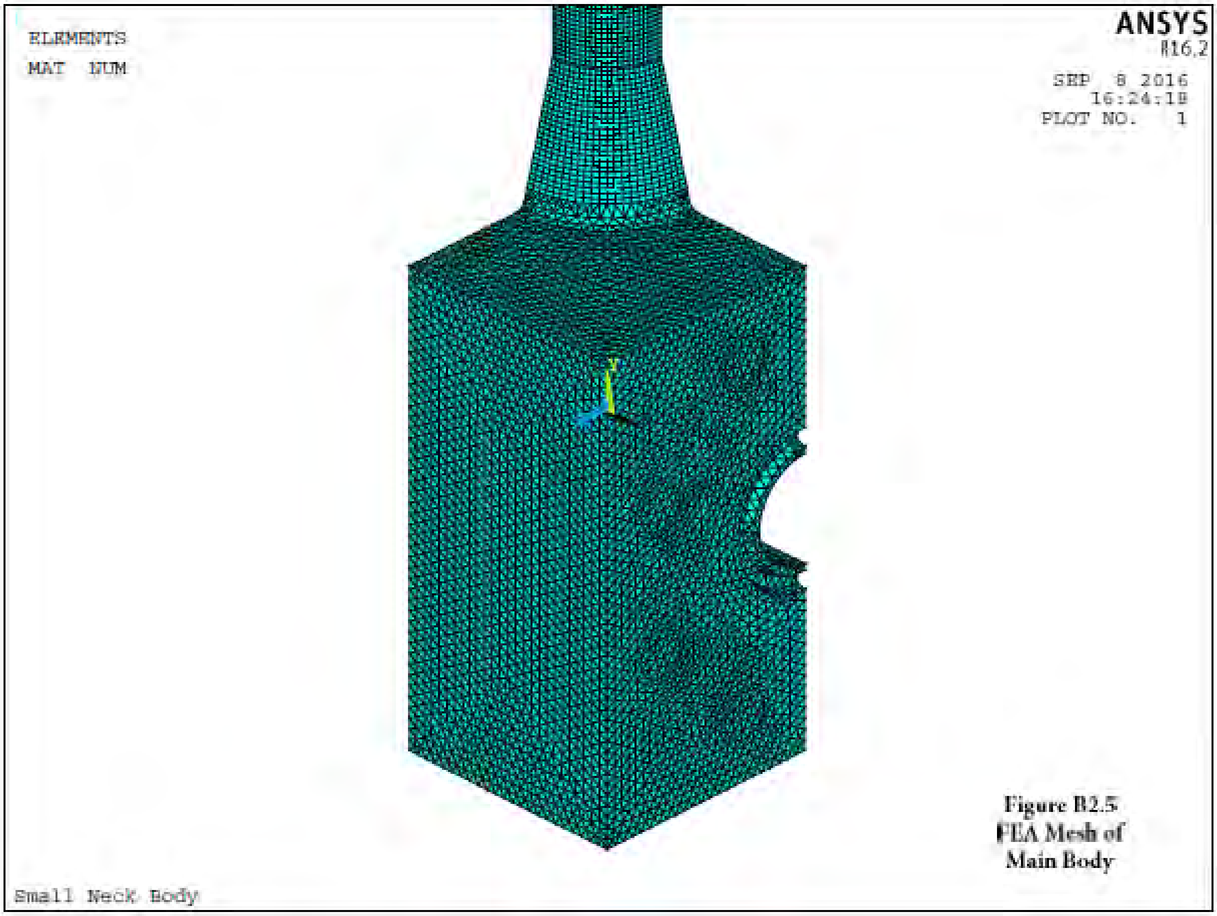


Figure B2.5
FEA Mesh of
Main Body

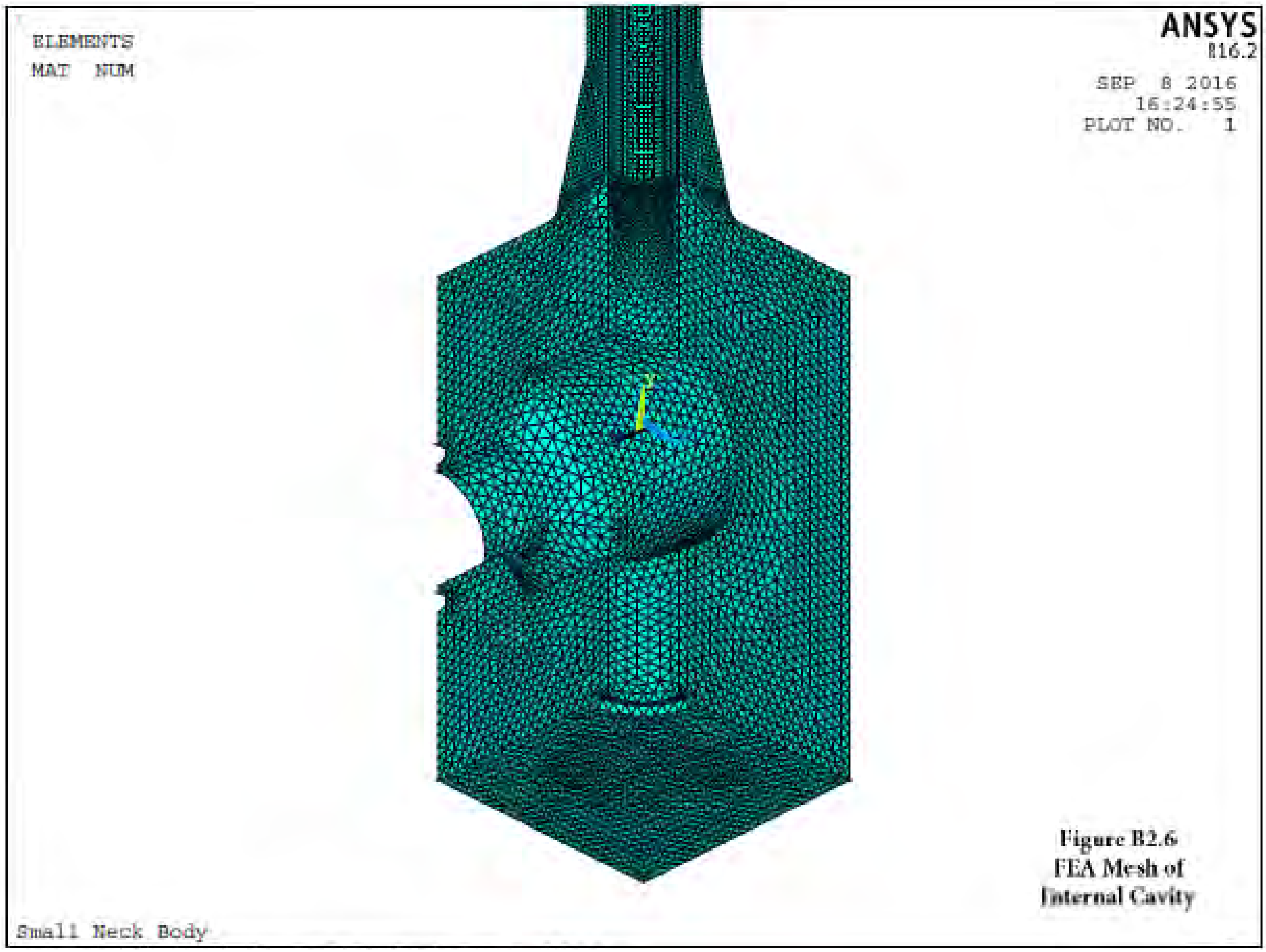


Figure B2.6
FEA Mesh of
Internal Cavity

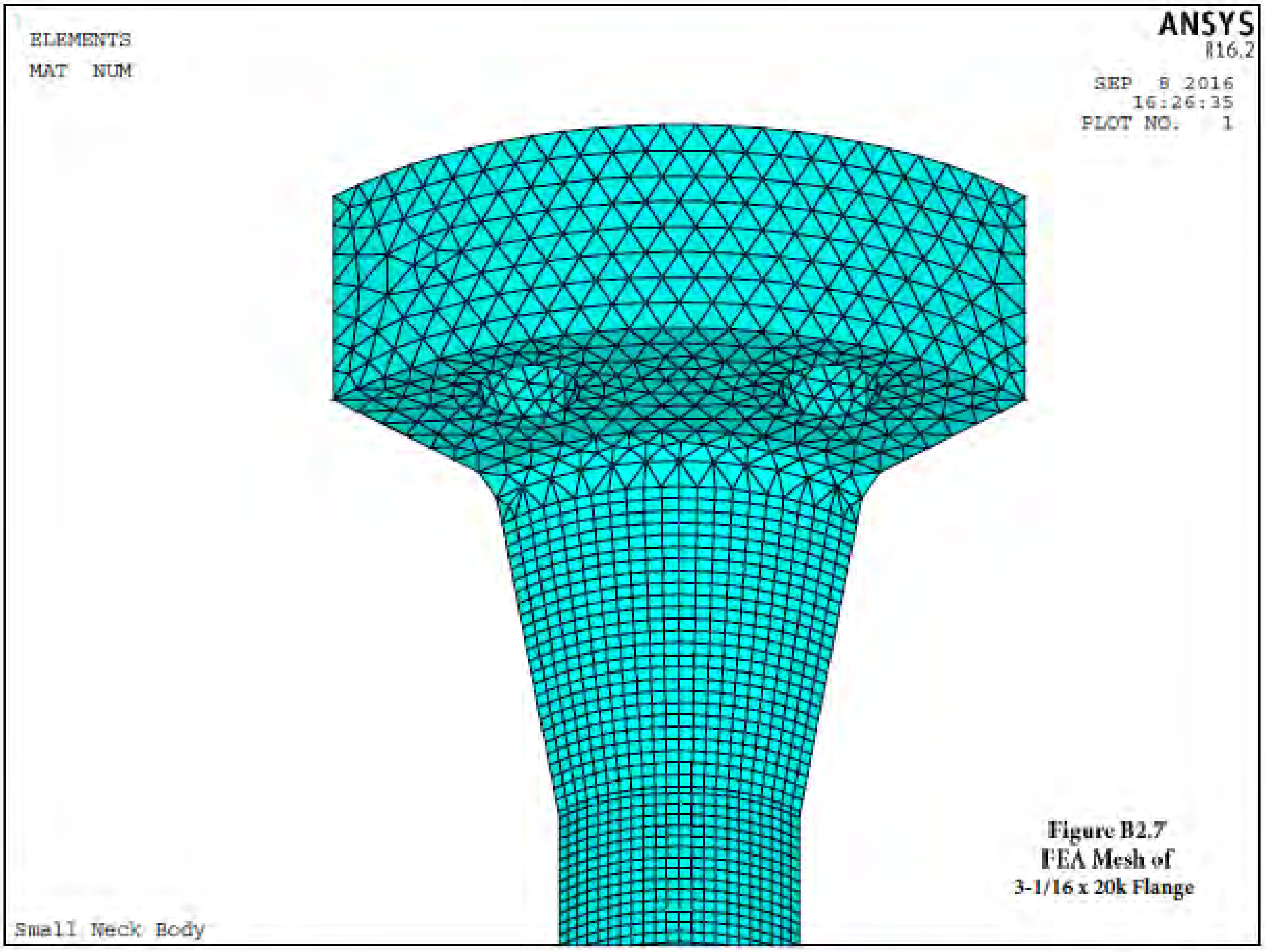


Figure B2.7
FEA Mesh of
3-1/16 x 20k Flange

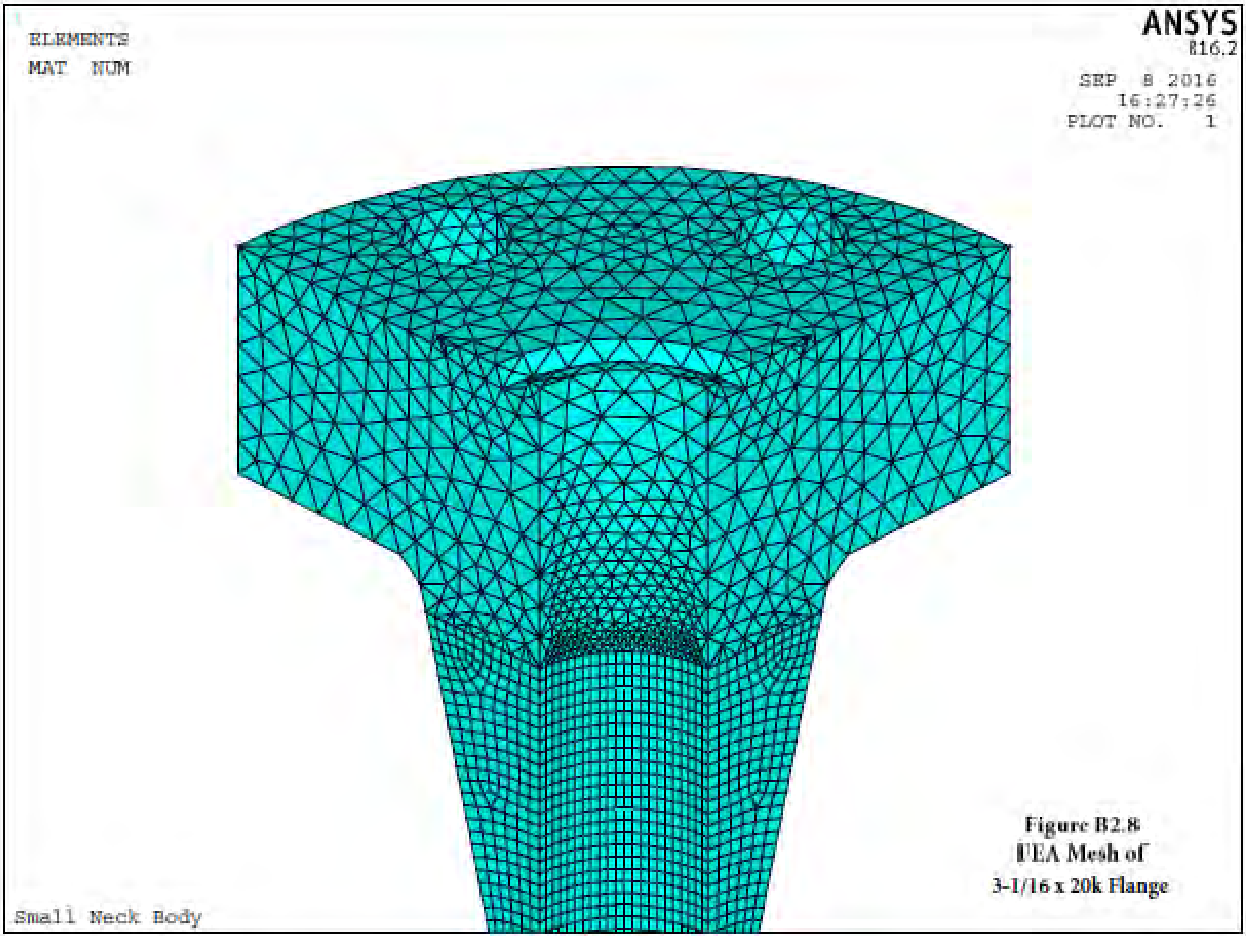
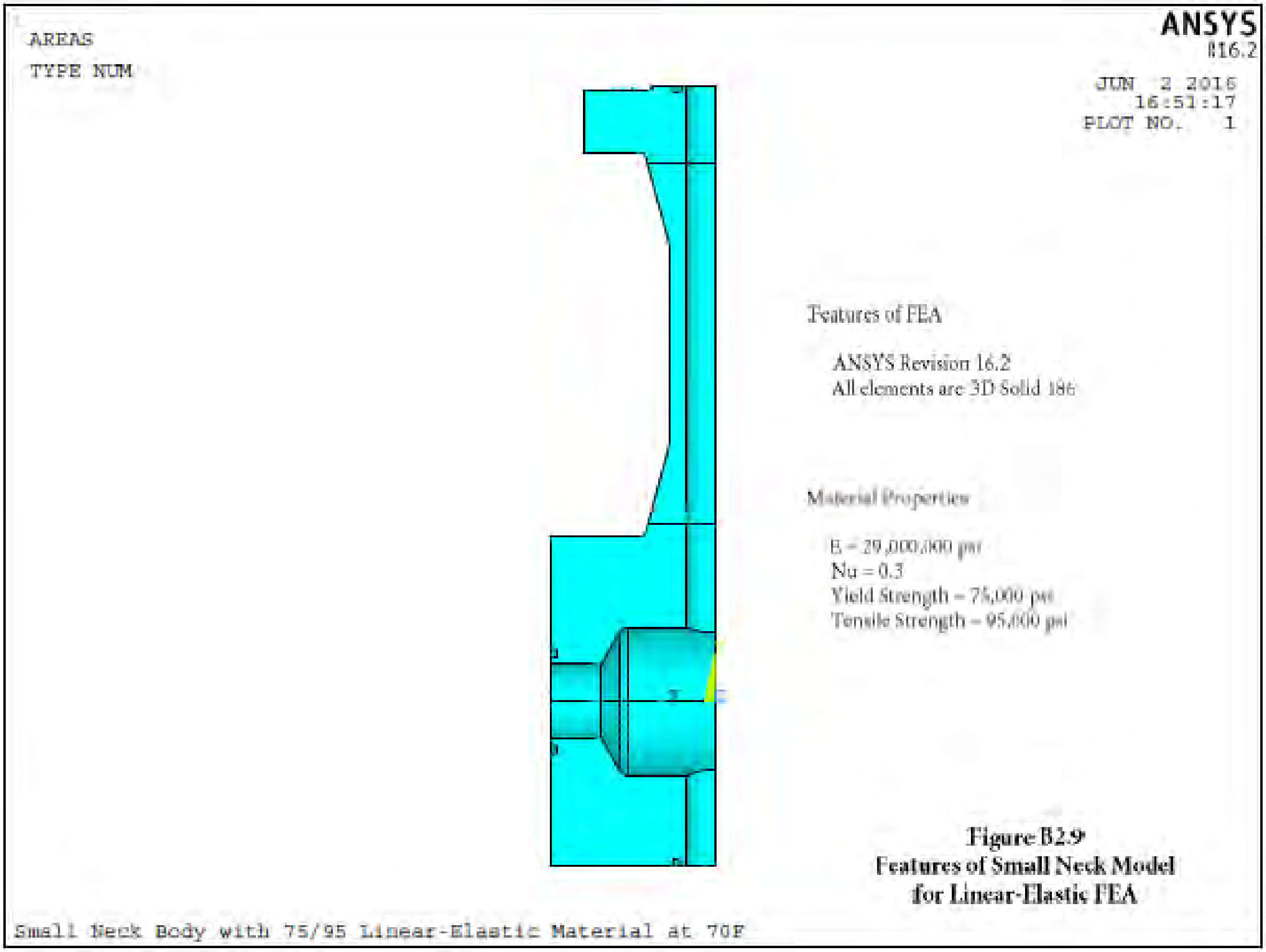


Figure B2.8
FEA Mesh of
3-1/16 x 20k Flange



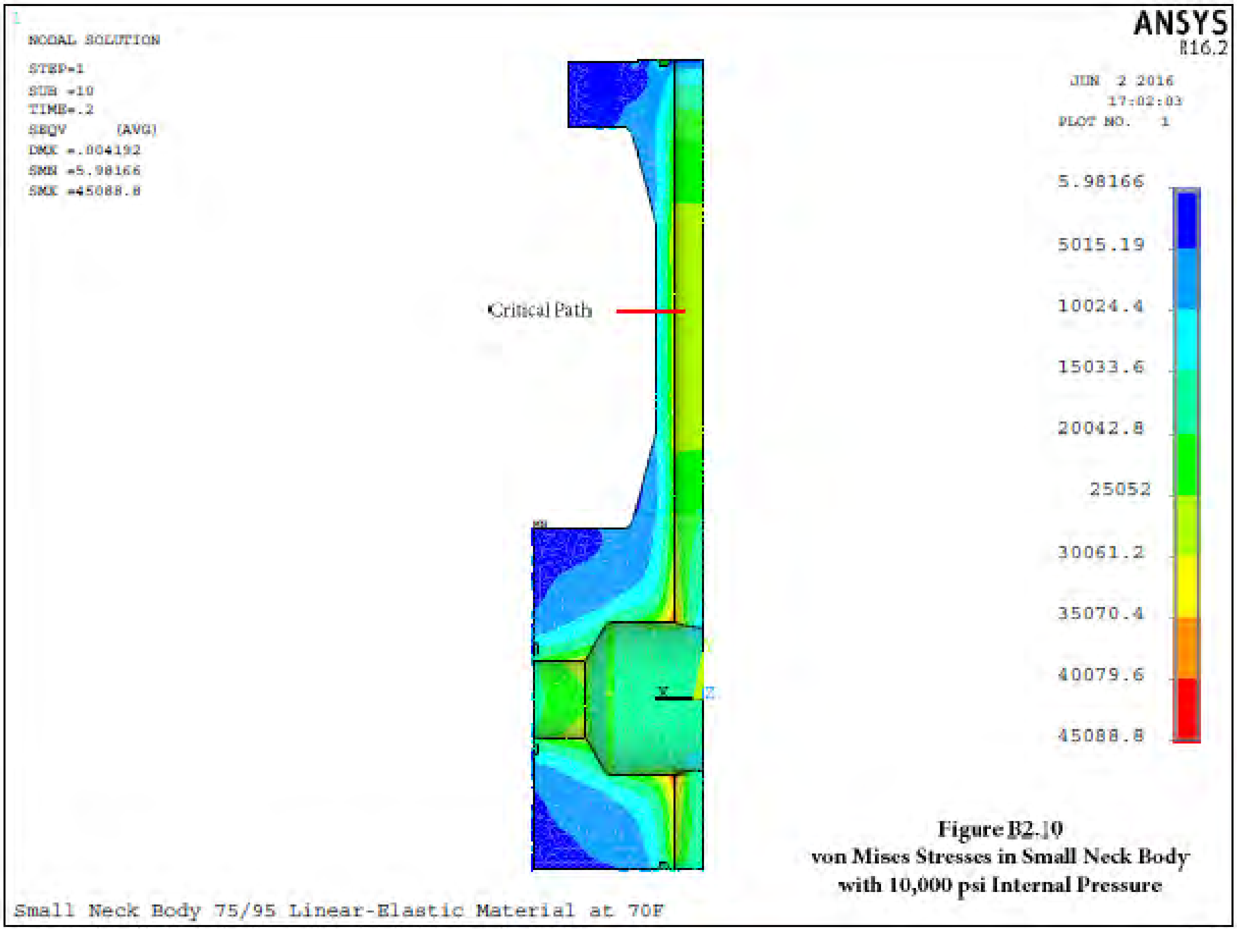
Features of FEA

ANSYS Revision 16.2
All elements are 3D Solid 186

Material Properties

E = 29,000,000 psi
Nu = 0.3
Yield Strength = 75,000 psi
Tensile Strength = 95,000 psi

Figure B2.9
Features of Small Neck Model
for Linear-Elastic FEA


```
NODAL SOLUTION

STEP=1
SUB =10
TIME=.2
SEQV       (AVG)
DMX =.004192
SMN =5.98166
SMX =45088.8
```

Figure B2.10
von Mises Stresses in Small Neck Body
with 10,000 psi Internal Pressure

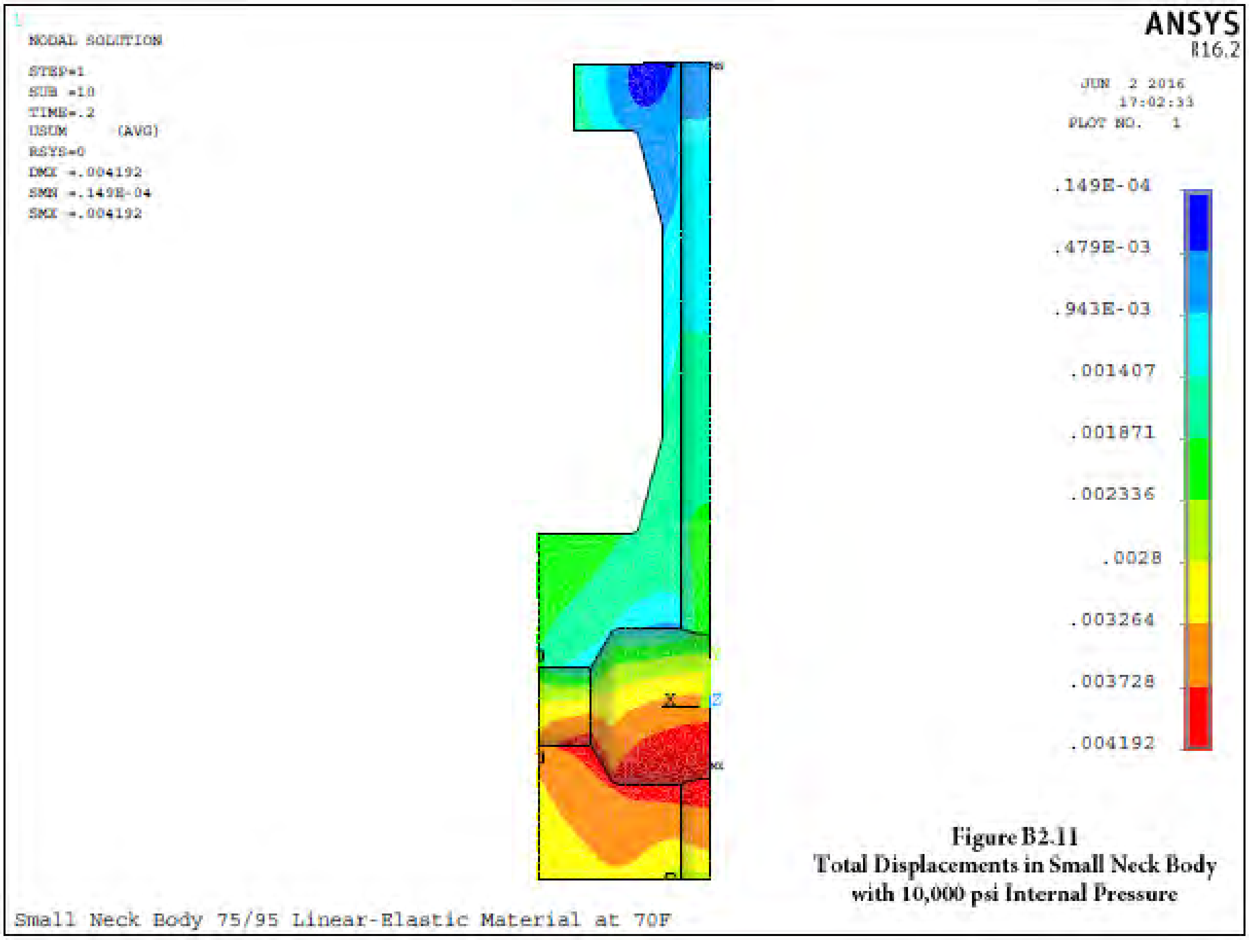


Figure B2.11
Total Displacements in Small Neck Body
with 10,000 psi Internal Pressure

```
      Linearized Stresses in Small Neck with Spec Material at 10 ksi Pressure

PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= PATHA      DSYS=  0

  RADIUS OF CURVATURE =   1.9030

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =  12623     OUTSIDE NODE =  12861

 LOAD STEP     1  SUBSTEP=    10
 TIME=   0.22222         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   1.9030
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 -3848.       7050.      0.1648E+05   528.4      0.4653E-01 -0.9084
     S1          S2          S3          SINT        SEQV
 0.1648E+05   7075.      -3874.      0.2036E+05  0.1765E+05

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -6081.      0.2452       5047.       0.000       0.000       0.000
C  -1108.      0.1738E-01   372.6       0.000       0.000       0.000
O   3865.     -0.2104      -4302.       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   5047.      0.2452      -6081.      0.1113E+05   9651.
C   372.6      0.1738E-01  -1108.       1480.       1334.
O   3865.     -0.2104      -4302.       8167.       7076.

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -9929.       7050.      0.2153E+05   528.4      0.4653E-01 -0.9084
C  -4956.       7050.      0.1686E+05   528.4      0.4653E-01 -0.9084
O   16.83       7049.      0.1218E+05   528.4      0.4653E-01 -0.9084
     S1          S2          S3          SINT        SEQV
I  0.2153E+05   7066.      -9945.      0.3148E+05  0.2729E+05
C  0.1686E+05   7073.      -4979.      0.2183E+05  0.1894E+05
O  0.1218E+05   7089.      -22.66      0.1220E+05  0.1062E+05

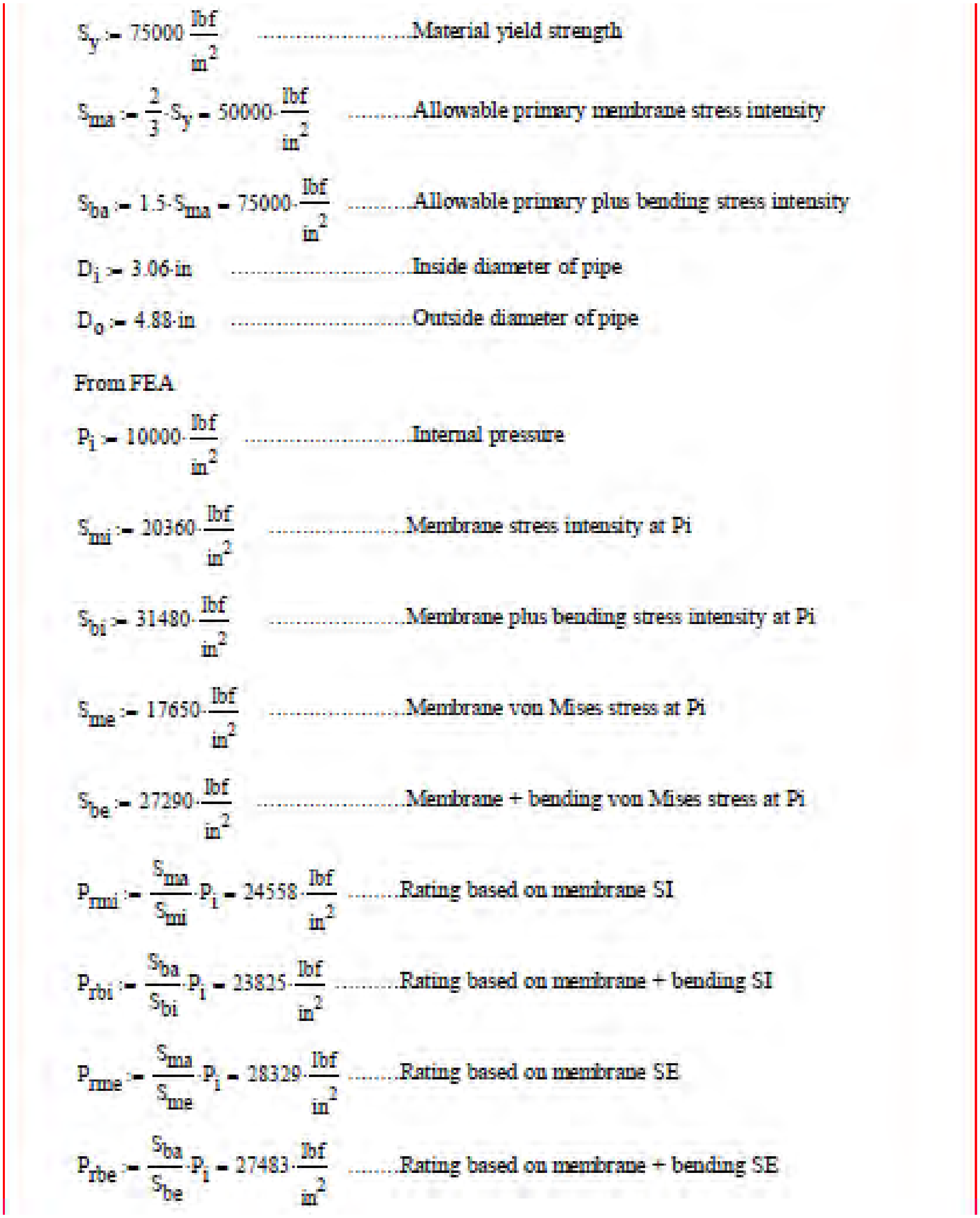
             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I   0.000      -6.447       1414.       333.4      0.3186E-01 -0.5947
C   1639.       1.790      -524.3      -11.54     -0.9110E-03  0.1530E-01
O -0.6217E-12  -1.565       823.7      -171.5     -0.1671E-01  0.3179
     S1          S2          S3          SINT        SEQV
I   1414.       330.1      -336.6       1750.       1530.
C   1639.       1.708      -524.3       2164.       1954.
O   823.7       170.7      -172.2       995.9       876.3

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -9929.       7043.      0.2294E+05   861.8      0.7839E-01  -1.503
C  -3317.       7051.      0.1633E+05   516.9      0.4562E-01 -0.8931
O   16.83       7048.      0.1300E+05   357.0      0.2982E-01 -0.5906
     S1          S2          S3          SINT        SEQV        TEMP
I  0.2294E+05   7087.      -9973.      0.3292E+05  0.2851E+05   0.000
C  0.1633E+05   7077.      -3343.      0.1967E+05  0.1705E+05
O  0.1300E+05   7066.      -1.249      0.1301E+05  0.1128E+05   0.000
```

Figure B2.12
Linearized Stresses in Small Neck
Body with 10,000 psi Internal pressure

Pressure Ratings for Small Neck Body with Specified Material by Linear Elastic FEA

Note: Stresses were calculated with an ANSYS 3D FEA Model.



$S_y := 75000 \cdot \frac{lbf}{in^2}$ ....Material yield strength

$S_{ma} := \frac{2}{3} \cdot S_y = 50000 \cdot \frac{lbf}{in^2}$ ....Allowable primary membrane stress intensity

$S_{ba} := 1.5 \cdot S_{ma} = 75000 \cdot \frac{lbf}{in^2}$ ....Allowable primary plus bending stress intensity

$D_i := 3.06 \cdot in$ ....Inside diameter of pipe

$D_o := 4.88 \cdot in$ ....Outside diameter of pipe

From FEA

$P_i := 10000 \cdot \frac{lbf}{in^2}$ ....Internal pressure

$S_{mi} := 20360 \cdot \frac{lbf}{in^2}$ ....Membrane stress intensity at Pi

$S_{bi} := 31480 \cdot \frac{lbf}{in^2}$ ....Membrane plus bending stress intensity at Pi

$S_{me} := 17650 \cdot \frac{lbf}{in^2}$ ....Membrane von Mises stress at Pi

$S_{be} := 27290 \cdot \frac{lbf}{in^2}$ ....Membrane + bending von Mises stress at Pi

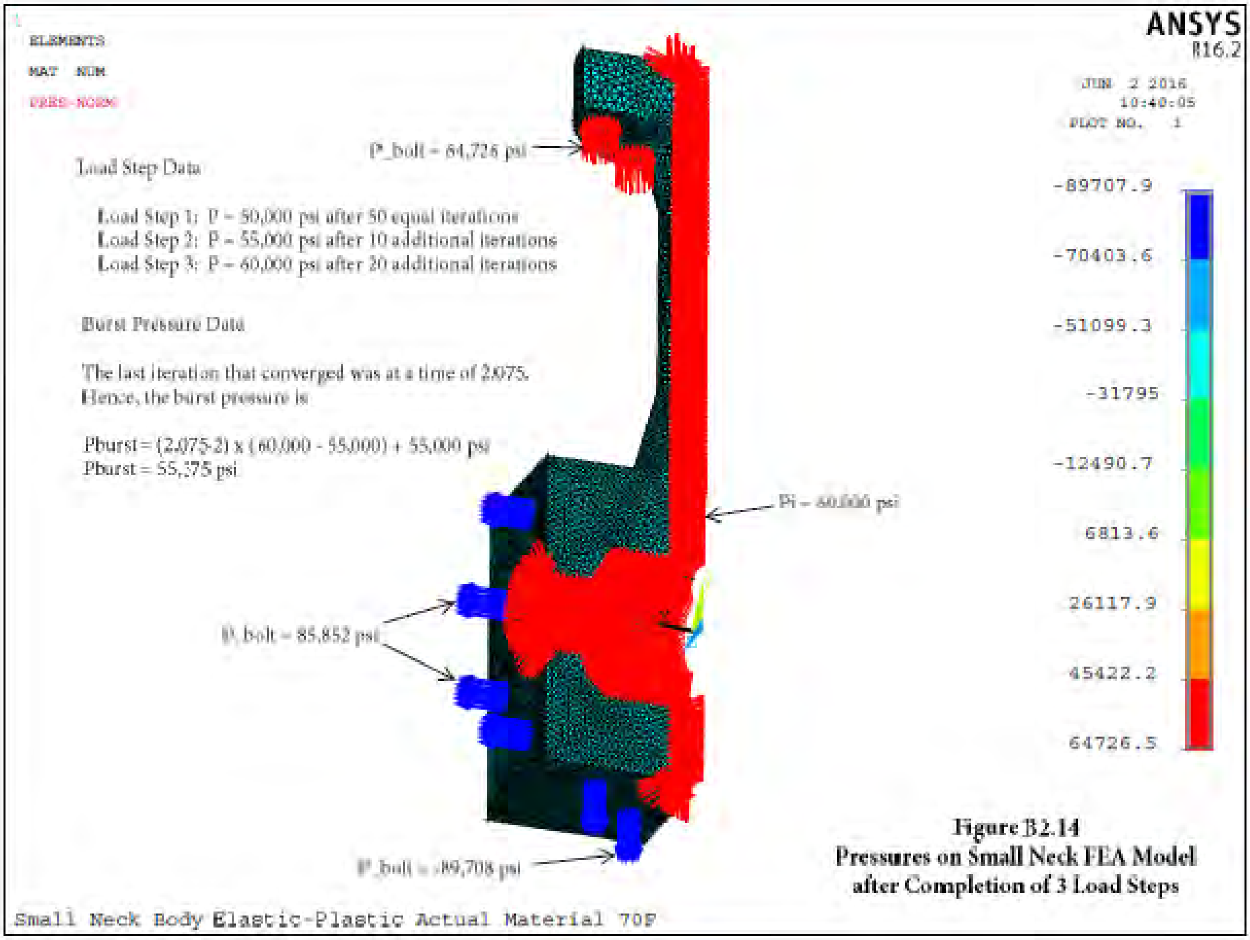
$P_{rmi} := \frac{S_{ma}}{S_{mi}} \cdot P_i = 24558 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane SI

$P_{rbi} := \frac{S_{ba}}{S_{bi}} \cdot P_i = 23825 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane + bending SI

$P_{rme} := \frac{S_{ma}}{S_{me}} \cdot P_i = 28329 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane SE

$P_{rbe} := \frac{S_{ba}}{S_{be}} \cdot P_i = 27483 \cdot \frac{lbf}{in^2}$ ....Rating based on membrane + bending SE

Figure B2.13
Pressure Rating Calculations



Load Step Data

Load Step 1: P = 50,000 psi after 50 equal iterations
Load Step 2: P = 55,000 psi after 10 additional iterations
Load Step 3: P = 60,000 psi after 20 additional iterations

Burst Pressure Data

The last iteration that converged was at a time of 2.075. Hence, the burst pressure is

Pburst = (2.075-2) x (60,000 - 55,000) + 55,000 psi
Pburst = 55,375 psi

Figure B2.14
Pressures on Small Neck FEA Model after Completion of 3 Load Steps

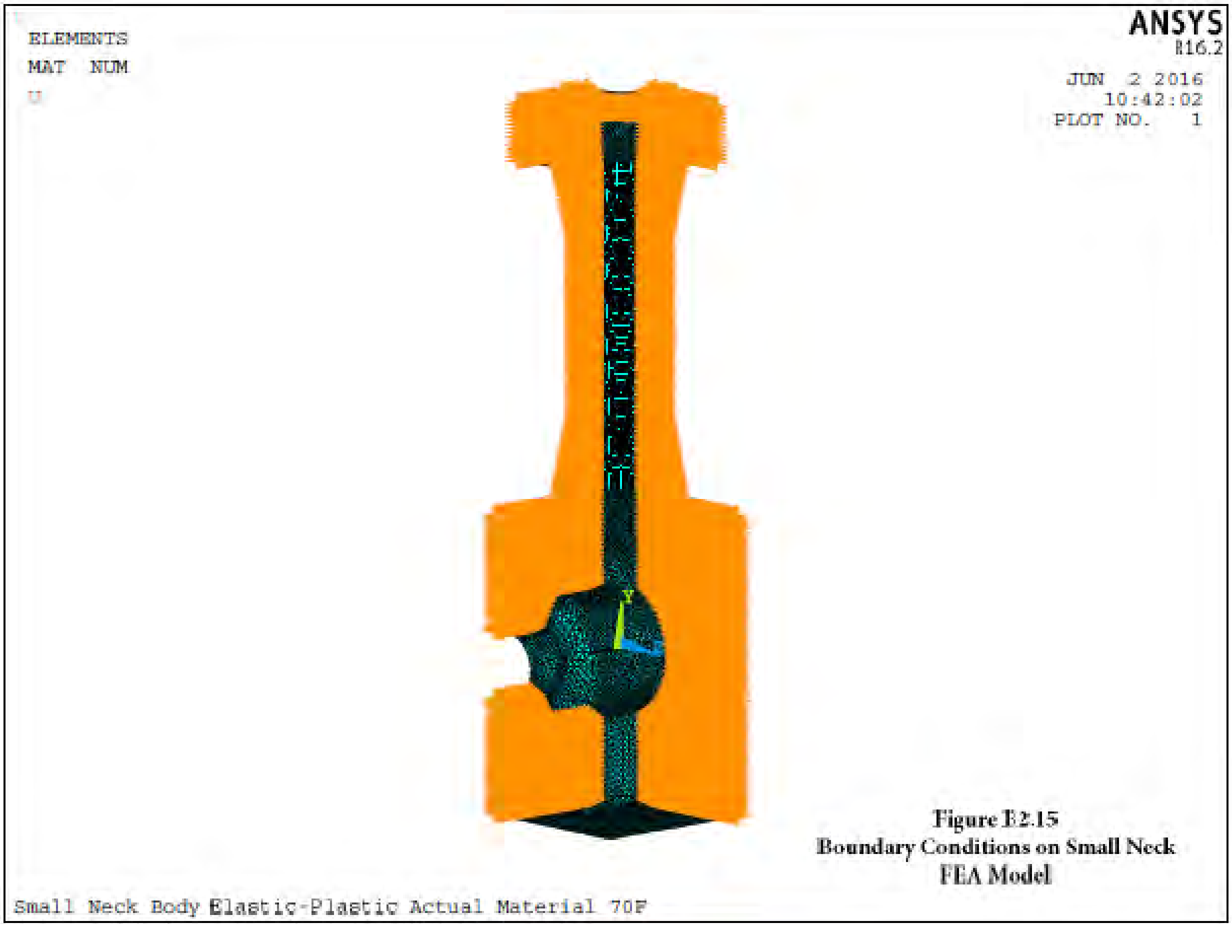


Figure B2.15
Boundary Conditions on Small Neck FEA Model

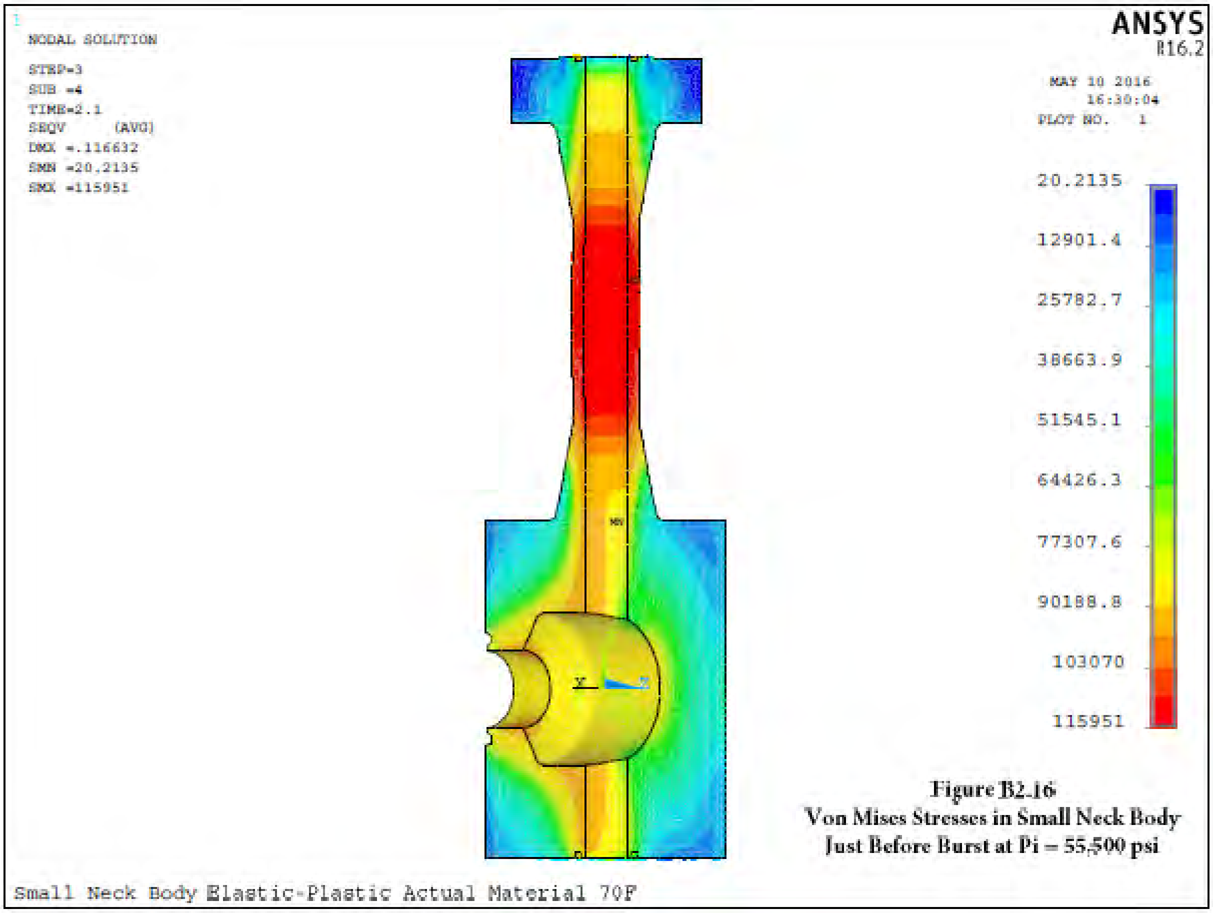
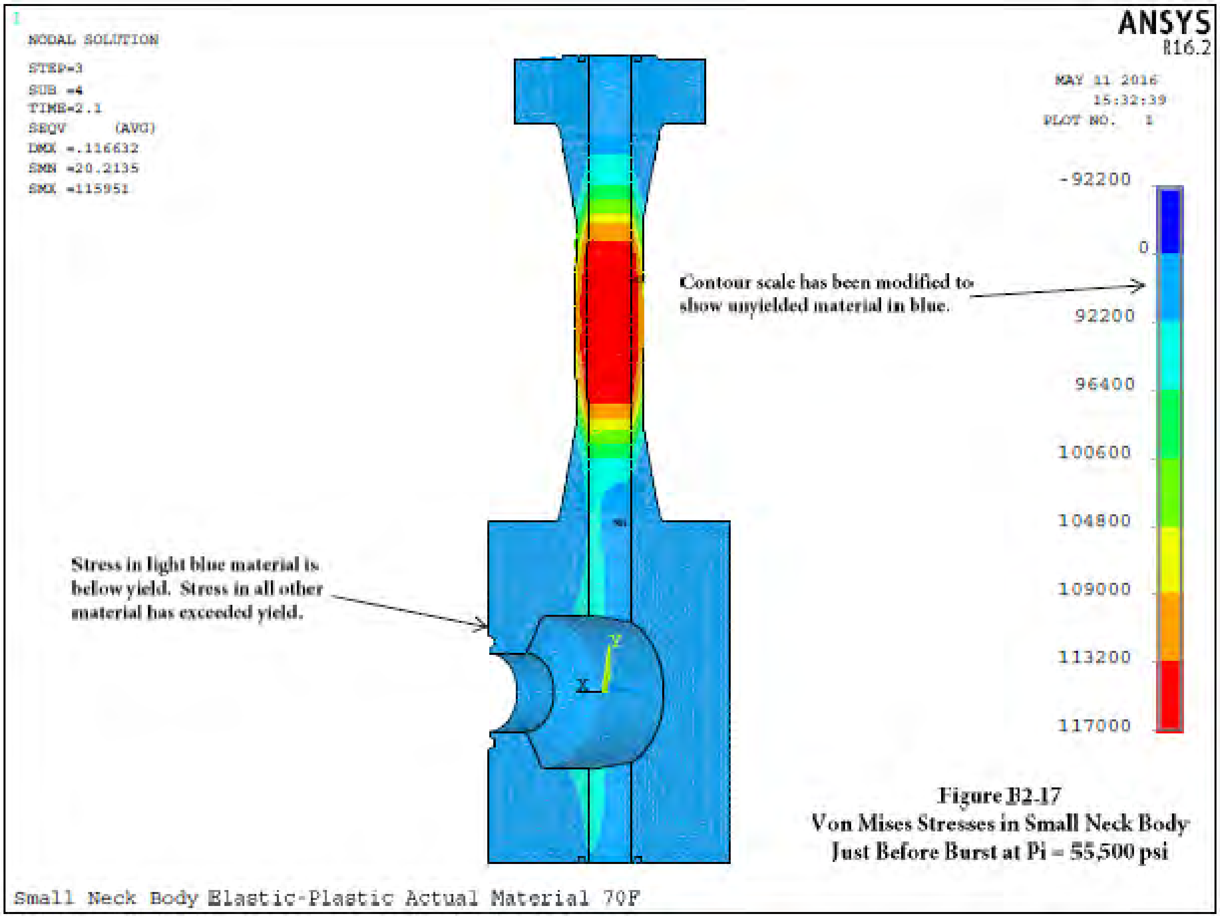


Figure B2.16
Von Mises Stresses in Small Neck Body
Just Before Burst at Pi = 55,500 psi



Contour scale has been modified to show unyielded material in blue.

Stress in light blue material is below yield. Stress in all other material has exceeded yield.

Figure B2.17
Von Mises Stresses in Small Neck Body
Just Before Burst at Pi = 55,500 psi

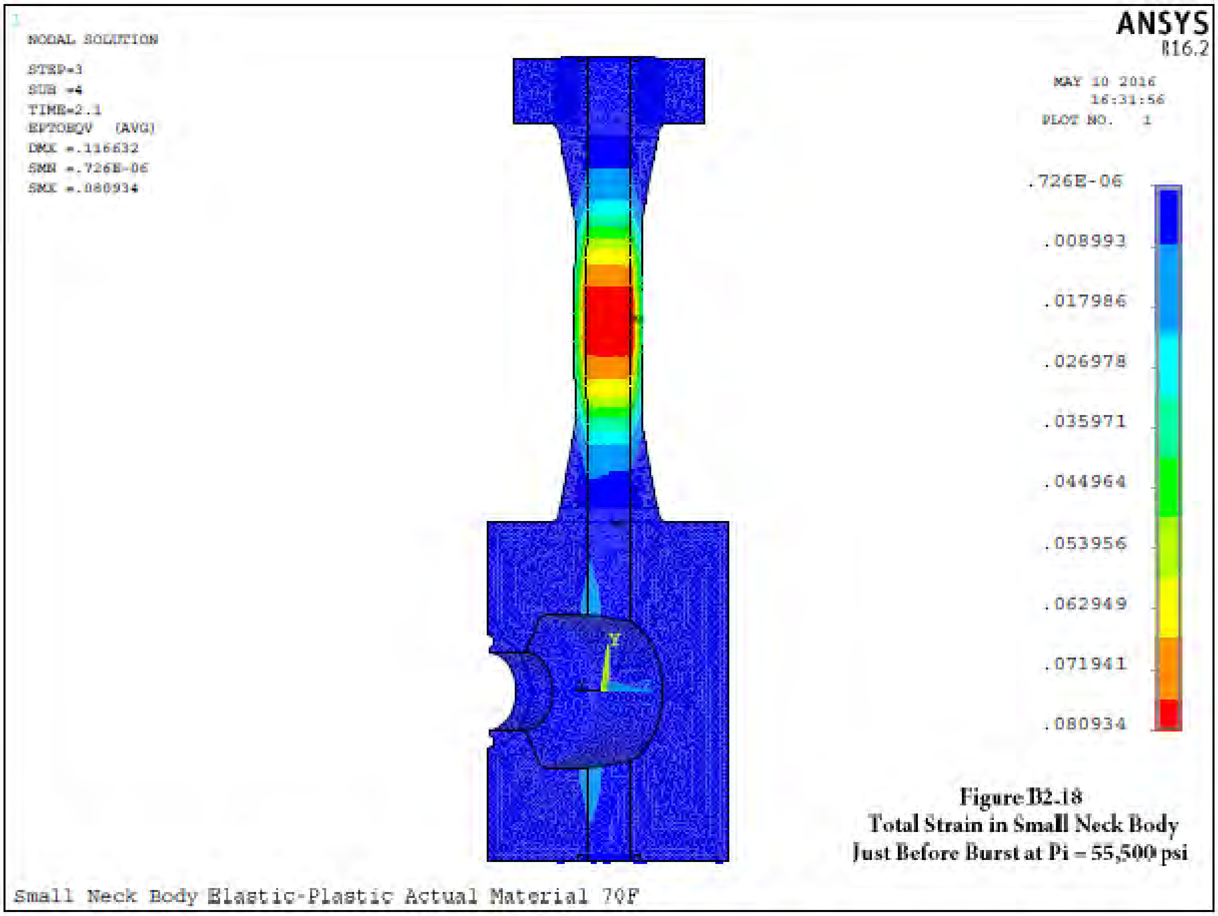
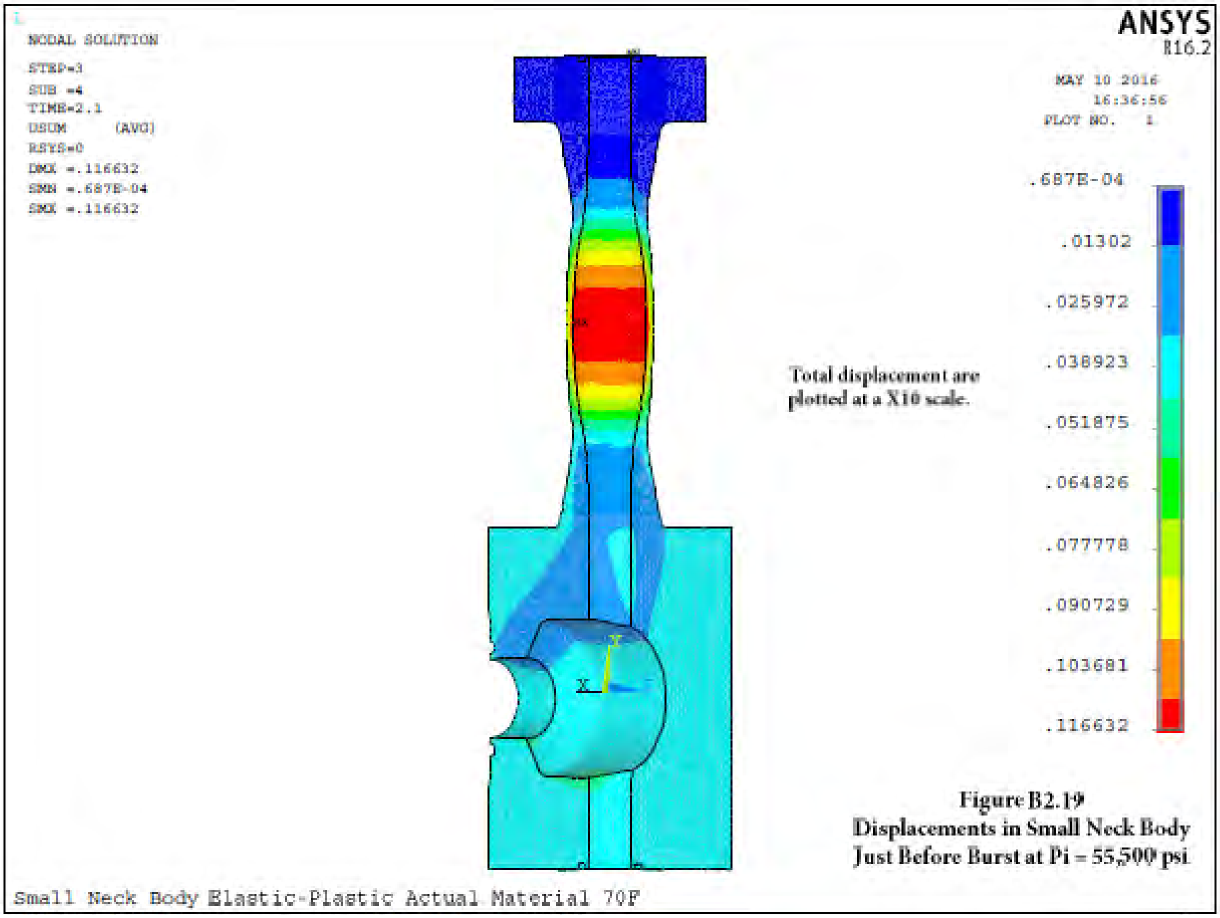
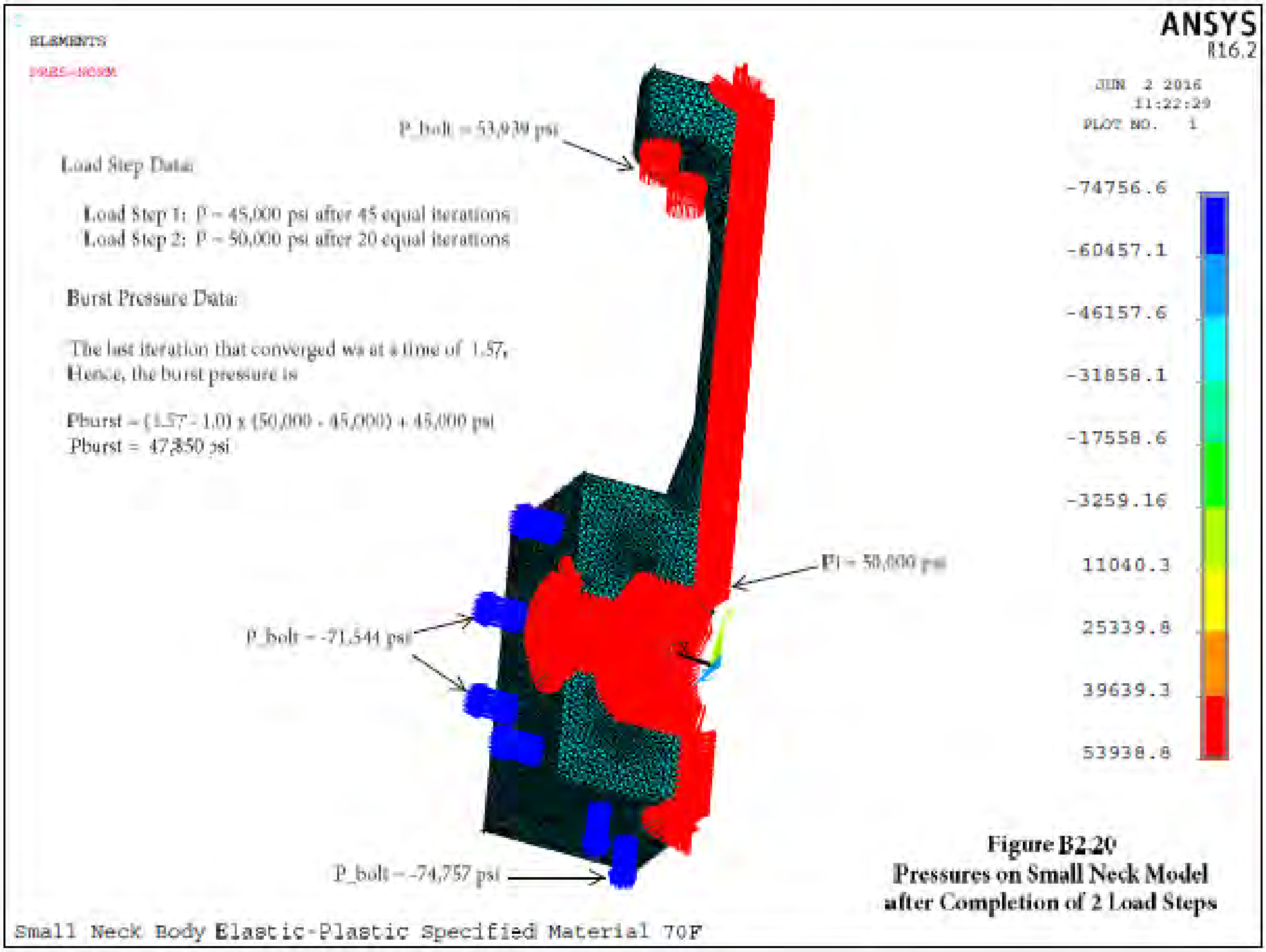


Figure B2.18
Total Strain in Small Neck Body
Just Before Burst at Pi = 55,500 psi



Total displacement are plotted at a X10 scale.

Figure B2.19
Displacements in Small Neck Body
Just Before Burst at Pi = 55,500 psi



Load Step Data:

Load Step 1: P = 45,000 psi after 45 equal iterations
Load Step 2: P = 50,000 psi after 20 equal iterations

Burst Pressure Data:

The last iteration that converged wa at a time of 1.57,
Hence, the burst pressure is

Pburst = (1.57 - 1.0) x (50,000 - 45,000) + 45,000 psi
Pburst = 47,850 psi

Figure B2-20
Pressures on Small Neck Model
after Completion of 2 Load Steps

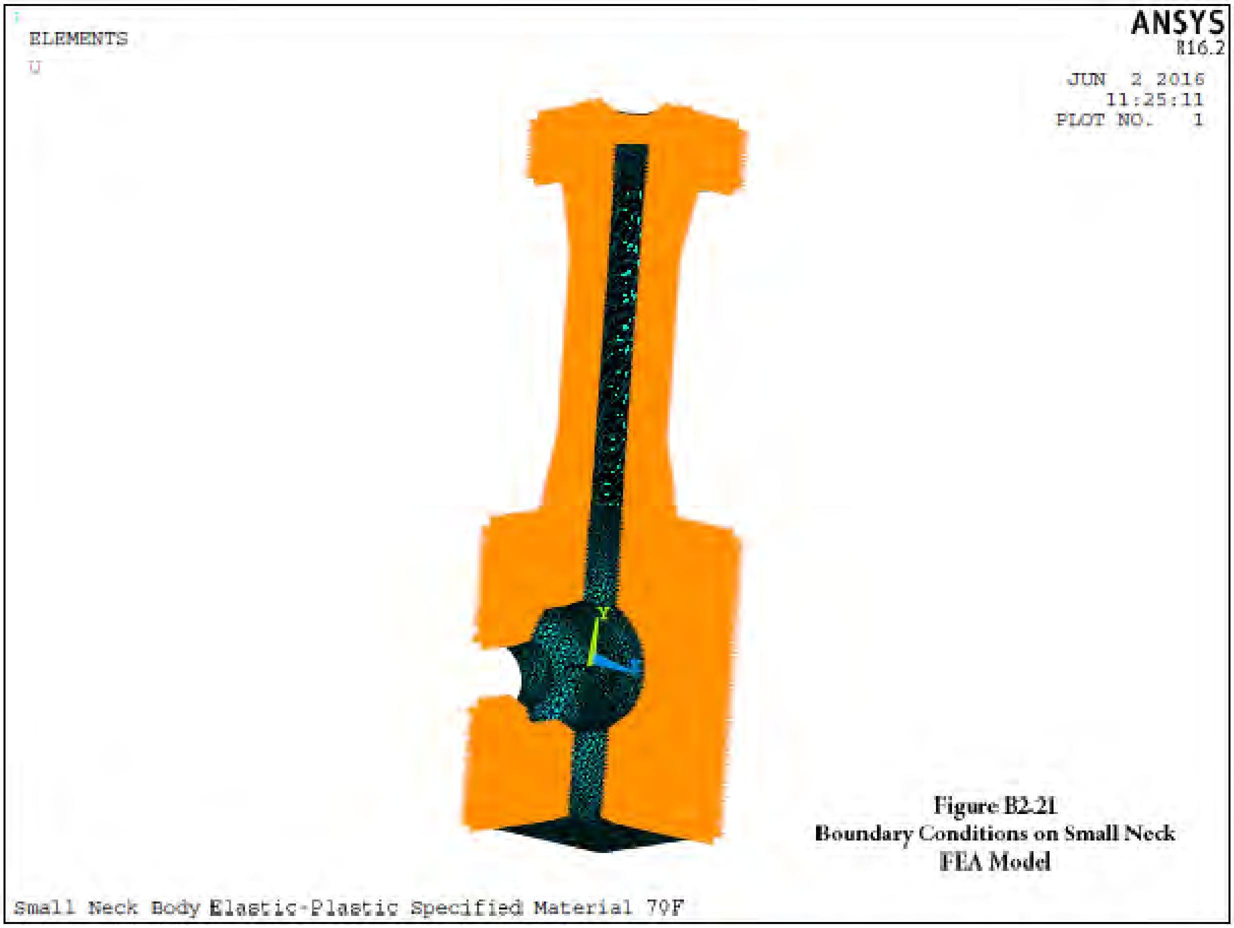


Figure B2-21
Boundary Conditions on Small Neck
FEA Model

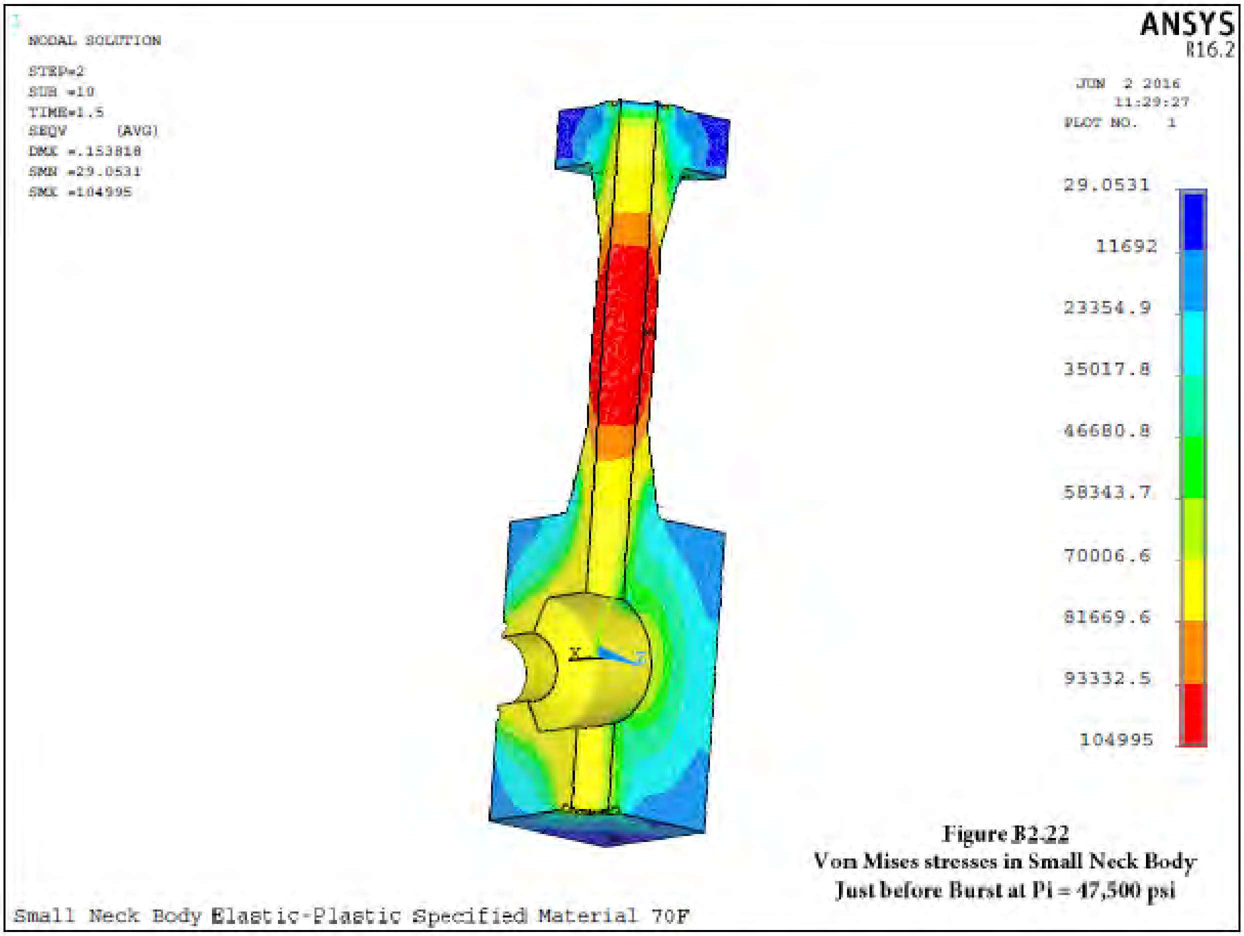


Figure B2.22
Von Mises stresses in Small Neck Body
Just before Burst at Pi = 47,500 psi

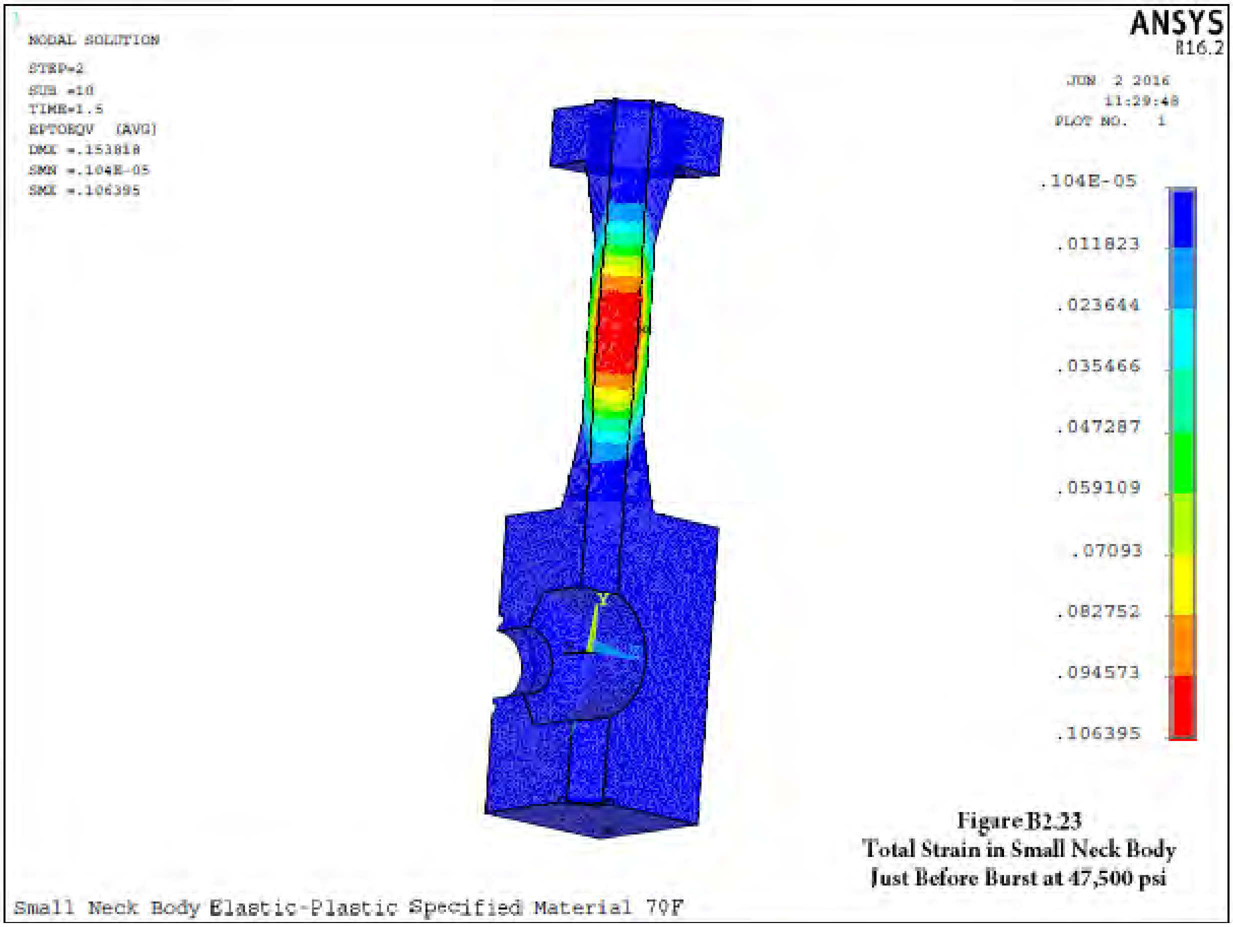


Figure B2.23
Total Strain in Small Neck Body
Just Before Burst at 47,500 psi

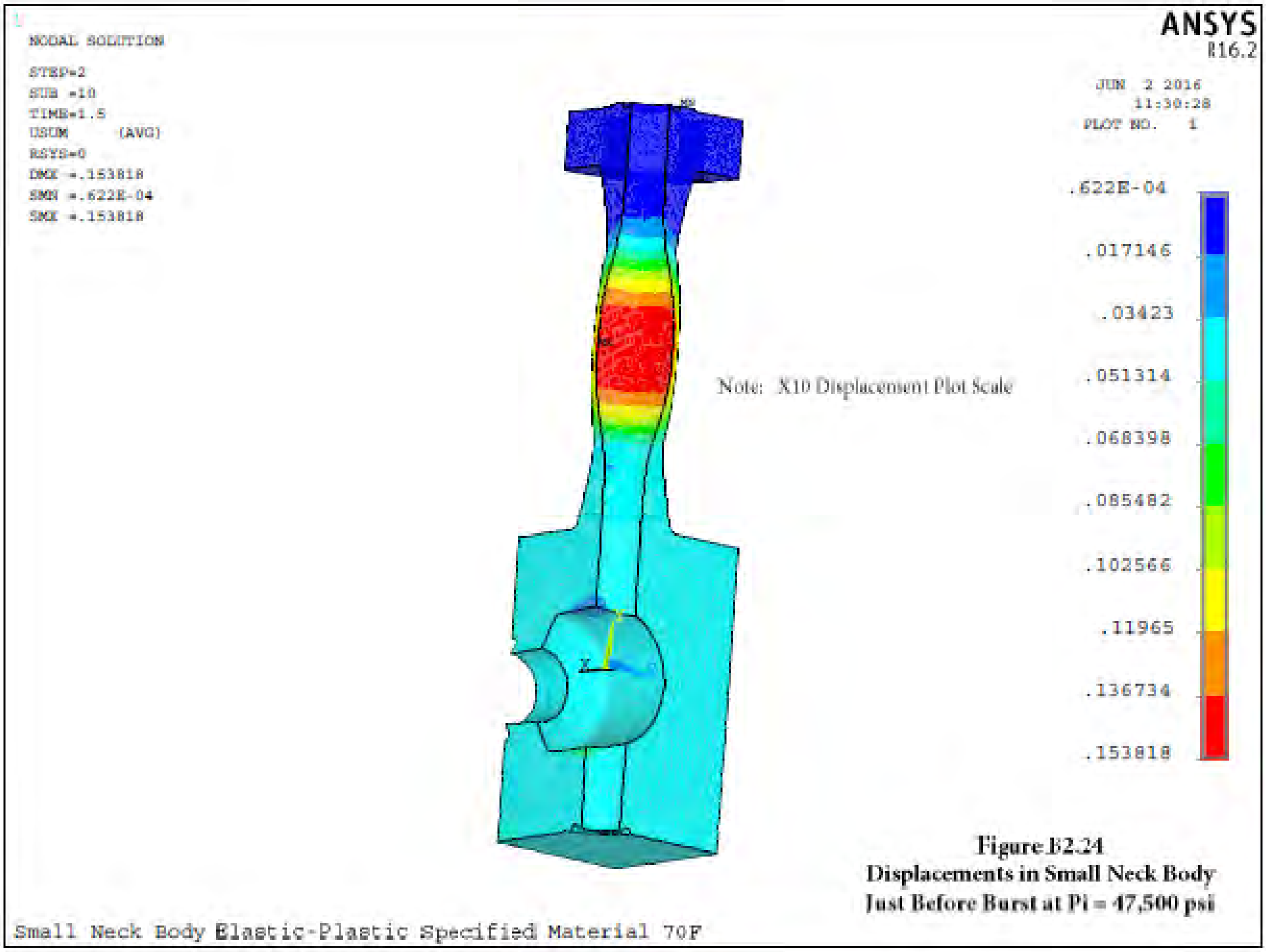


Figure B2.24
Displacements in Small Neck Body
Just Before Burst at Pi = 47,500 psi

Note: X10 Displacement Plot Scale

Appendix B3
FEA of API 13-5/8 x 20k Flange

The geometry and dimensions of the FEA model of the API 13-5/8 x 20k flange were taken from Table B.41 in API 6A. The geometry of the FEA model is shown in Figure B3.1. As the figure shows, neither the bolts nor the seal ring were included in the model because they are not critical components for this study and their presence will not affect the accuracy of the critical stress or the collapse pressure calculations. Numerous FEA of API flanges reported in literature have demonstrated that bolts and seal rings can be neglected without significantly affecting the critical results required for pressure rating of API flanges.

The model was axisymmetric and comprised of 17,135 elements and 52,344 nodes. All elements were quadrilateral, ANSYS Plane 183 elements. Figure B3.2 shows an enlarged view of the FEA mesh in the critical regions.

The model was solved with linear-elastic material properties and with elastic-plastic material properties. Results of the linear elastic solution were used to calculate pressure ratings based on API 6A and Division 2 linear-elastic procedures.

Linear-Elastic FEA

The model was solved with linear-elastic material properties at rated internal pressure of 20,000 psi. The following Figures at the end of this appendix describe the important features of the FEA model, loads and boundary conditions; and, the important results of the solution with linear-elastic material properties:

Figure B3.1...... Features of 13-5/8 x 20k API Flange Model for Linear-Elastic FEA
Figure B3.2...... Mesh Details for 13-5/8 x 20k Model for Linear Elastic FEA
Figure B3.3...... Pressures on 13-5/8 x 20k Flange Model with Linear-Elastic Material
Figure B3.4...... Radial Displacements of Flange with 20 ksi Internal Pressure
Figure B3.5...... Axial Displacements of Flange with 20 ksi Internal Pressure
Figure B3.6...... von Mises Stresses in Flange with 20 ksi Internal Pressure
Figure B3.7...... Linearized Stresses in 13-5/8 x 20k Flange with 20 ksi Internal Pressure
Figure B3.8...... Pressure Rating Calculations

Figure B3.3 shows the pressure load and boundary conditions for the linear-elastic solution. As shown in the figure, internal pressure was applied to the OD of the seal groove. The pressure end load was applied as a pressure on the simulated area of the bolts. The center line of the simulated bolt area was the bolt centerline. The width of the simulated bolt area was the bolt diameter. This method is commonly used to simulate bolt loads on axisymmetric models of flanges. The nodes on the bottom (pipe end) of the model were fixed in the axial direction.

Figure B3.6 is a plot of the von Mises stresses in the flange with the location of the critical path shown. The critical path was found by linearizing stresses across numerous sections and finding the section where primary and primary membrane plus bending stresses are largest. Figure B3.7 shows the linearized stresses across the critical path. The stresses underlined in red are the ones that must be compared with the allowable stresses.

Notice that the membrane stress intensity and the membrane von Mises stresses are both underlined. This is because API 6A requires that stress intensities be compared with the allowable stresses whereas Division 2 requires that the von Mises stresses be compared with the allowable stresses.

The linear-elastic stresses in Figure B3.7 were used to calculate the pressure rating based on the API 6A which requires the use of the ASME Division 2 linear-elastic analysis method. Calculations for pressure ratings based on the linearized stresses are Figure B3.8: They are listed below:

Pressure ratings for the 13-5/8 x 20k API Flange by linear-elastic FEA
25,497 psi .... Pressure rating by API 6A
29,098 psi .... Pressure rating by ASME Division 2

Elastic-Plastic FEA

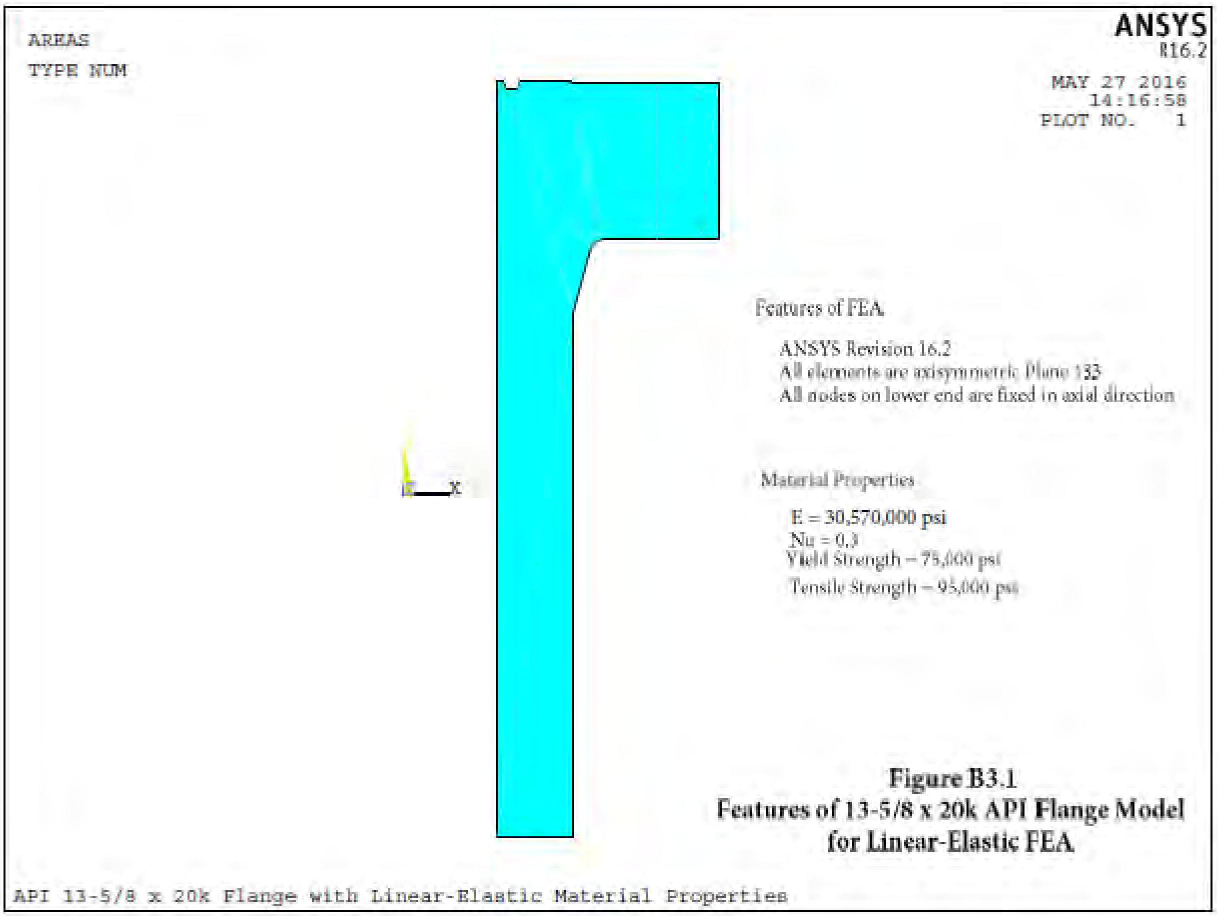
The FEA model was also solved with elastic-plastic material properties. The elastic-plastic solution used the material properties of the low alloy steel with a 75,000 psi yield strength. The following figures at the end of this appendix show the important features of the elastic-plastic model, solutions and important results:

Figure B3.9...... Features of 13-5/8 x 20k API Flange Model for Elastic-Plastic FEA
Figure B3.10.... Mesh Details for 13-5/8 x 20k Model for Elastic-Plastic FEA
Figure B3.11.... Pressures on 13-5/8 x 20k Flange Model after 300 Iterations
Figure B3.12.... Radial Displacements in Flange at Burst Pressure of 60 ksi
Figure B3.13.... Axial Displacements in Flange at Burst Pressure of 60 ksi
Figure B3.14.... von Mises Stresses in Flange at Burst Pressure of 60 ksi
Figure B3.15.... Total Strain in Flange at Burst Pressure of 60 ksi

The elastic-plastic solution was solved by incrementally increasing the internal pressures until the solution failed to converge. Figure B3.11 shows the model with an internal pressure of 75,000 psi after 300 equal iterations. The model failed to converge before all 300 iterations were completed. The last converged solution was at iteration 240. Hence, the pressure at the last converged solution was 60,000 psi.

The following pressure ratings where calculated by dividing the collapse pressure by the design factors:

Pressure ratings for 13-5/8 x 20k API Flange by Elastic-plastic FEA
25,000 psi .... Pressure rating by Division 2 elastic-plastic
33,333 psi .... Pressure rating by Division 3 elastic-plastic



Features of FEA

ANSYS Revision 16.2
All elements are axisymmetric Plane 183
All nodes on lower end are fixed in axial direction

Material Properties

E = 30,570,000 psi
Nu = 0.3
Yield Strength – 75,000 psi
Tensile Strength – 95,000 psi

Figure B3.1
Features of 13-5/8 x 20k API Flange Model for Linear-Elastic FEA

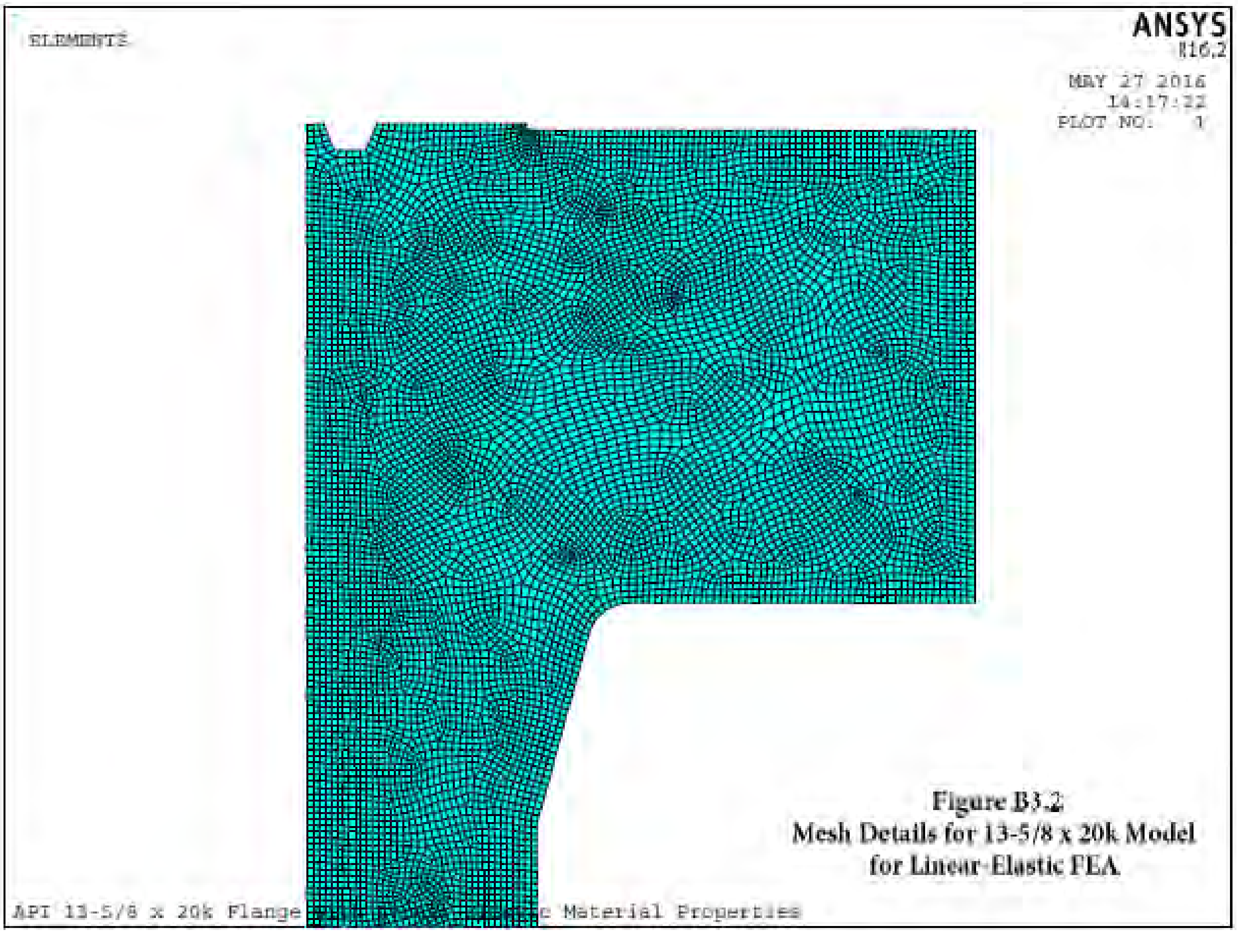


Figure B3.2
Mesh Details for 13-5/8 x 20k Model for Linear-Elastic FEA

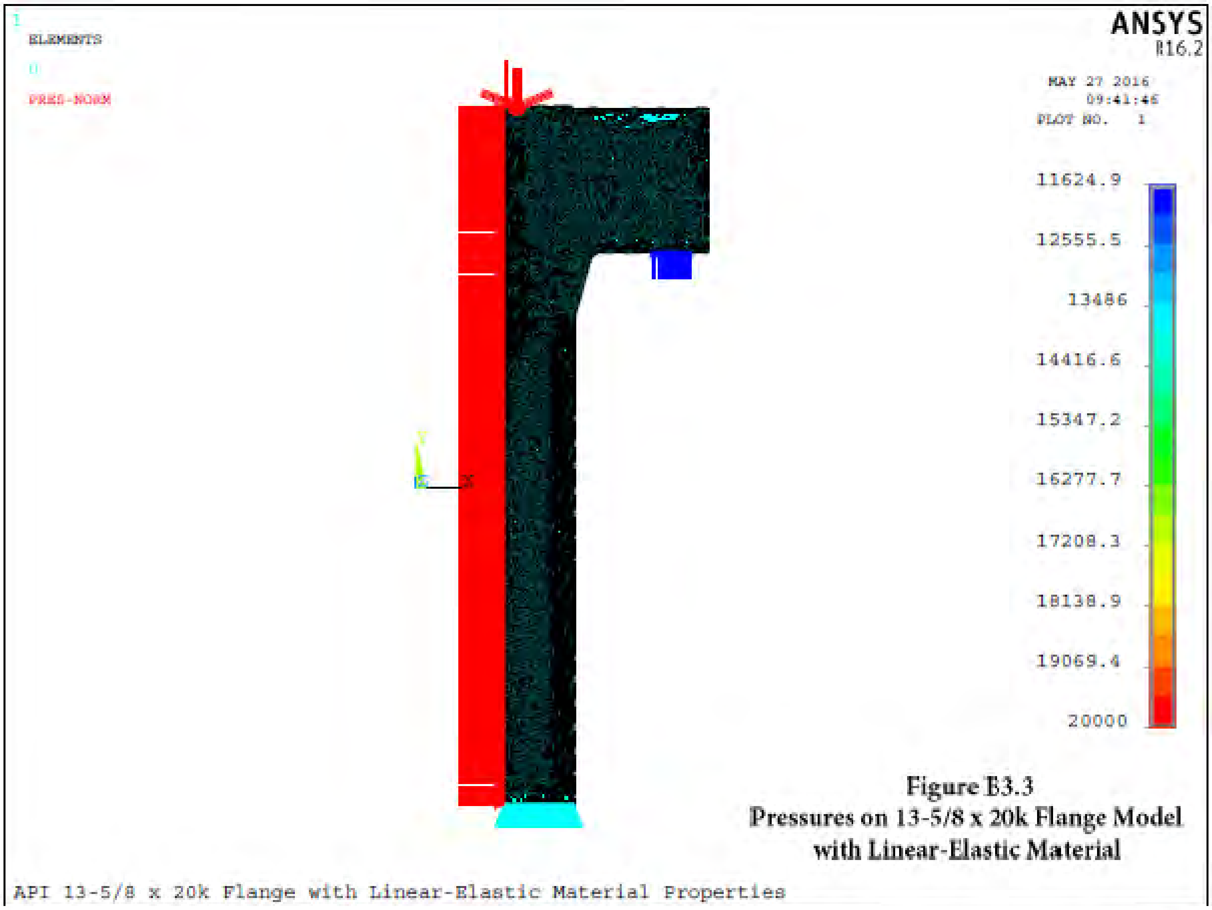


Figure B3.3
Pressures on 13-5/8 x 20k Flange Model
with Linear-Elastic Material

Figure B3.4
Radial Displacements of Flange
with 20,000 Internal Pressure

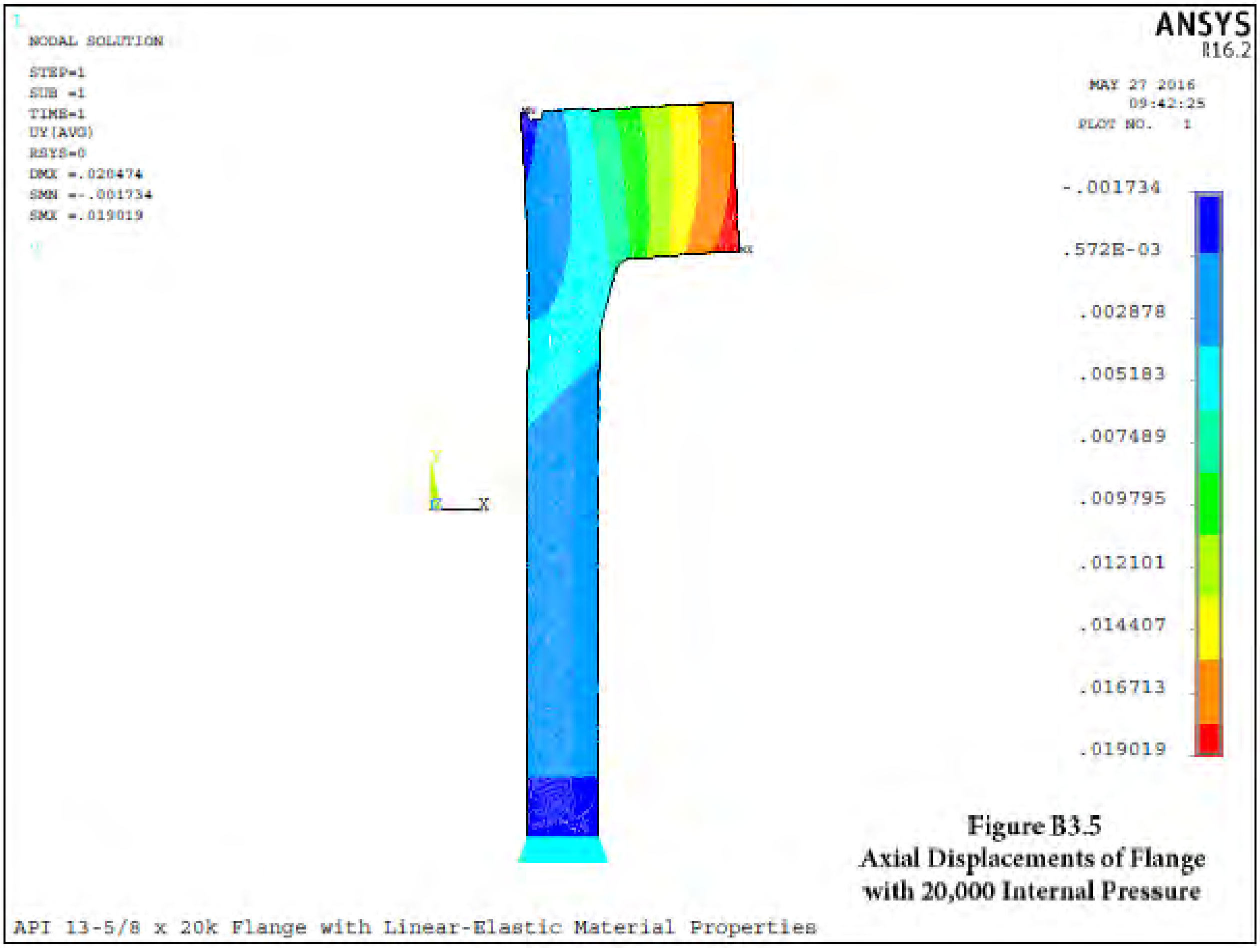


Figure B3.5
Axial Displacements of Flange
with 20,000 Internal Pressure

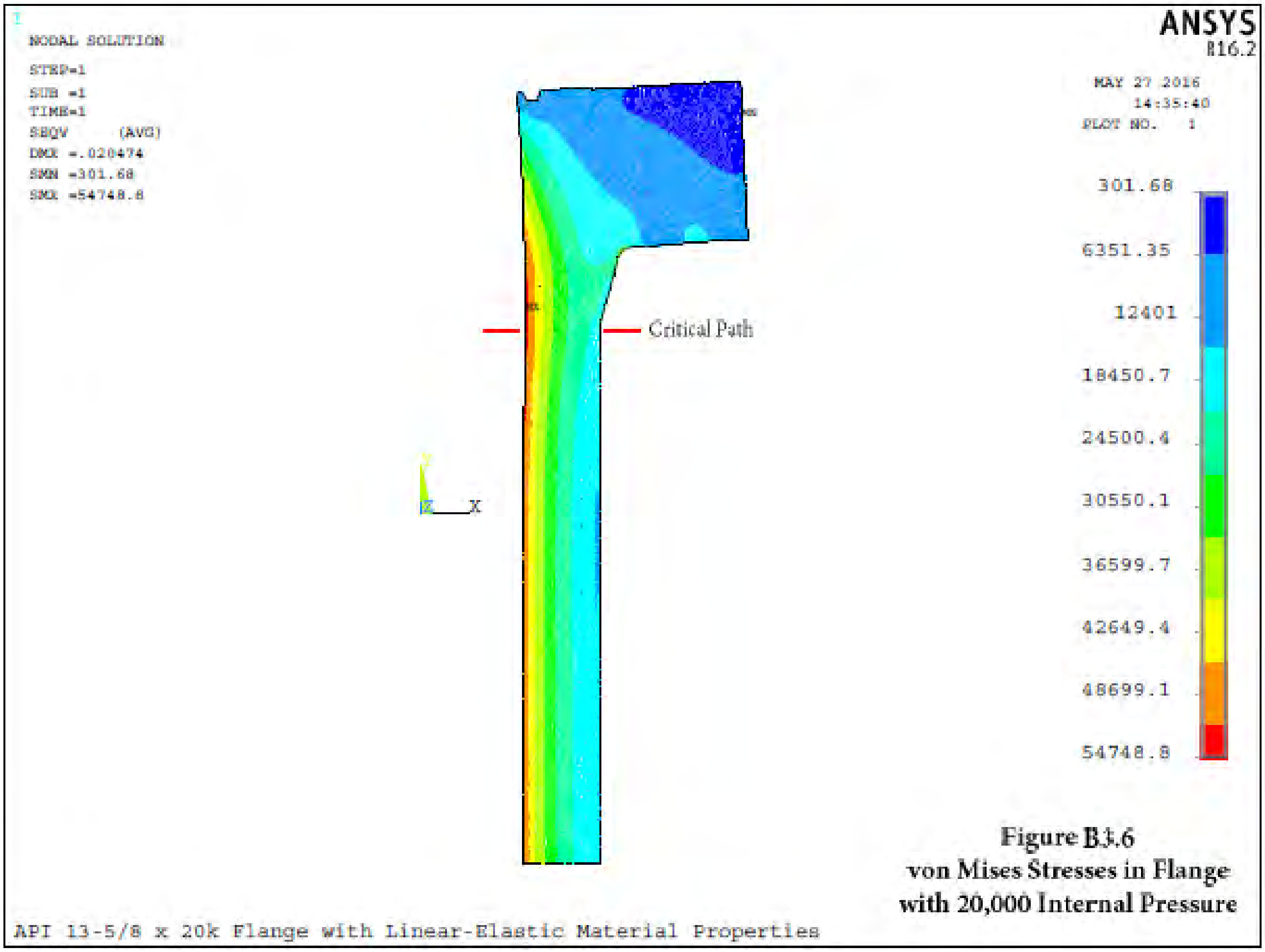


Figure B3.6
von Mises Stresses in Flange
with 20,000 Internal Pressure

```
                                       PathG

PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= PATHG      DSYS=  0

  RADIUS OF CURVATURE =   9.6030

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =   1885     OUTSIDE NODE =    803

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   9.6030
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX         SY          SZ         SXY         SYZ         SXZ
 -6304.       8785.      0.3044E+05   2132.       0.000       0.000
     S1         S2          S3         SINT        SEQV
 0.3044E+05   9081.      -6600.      0.3704E+05  0.3221E+05

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX         SY          SZ         SXY         SYZ         SXZ
I   6195.       6305.      -9924.       0.000       0.000       0.000
C  -3745.      -671.4      -871.3       0.000       0.000       0.000
O -0.1368E+05  -7648.       8181.       0.000       0.000       0.000
     S1         S2          S3         SINT        SEQV
I   6305.       6195.      -9924.      0.1623E+05  0.1617E+05
C  -671.4      -871.3      -3745.       3073.       2979.
O   8181.      -7648.     -0.1368E+05  0.2187E+05  0.1956E+05

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX         SY          SZ         SXY         SYZ         SXZ
I  -109.3      0.1509E+05  0.2052E+05   2132.       0.000       0.000
C -0.1005E+05   8114.       0.2957E+05   2132.       0.000       0.000
O -0.1999E+05   1137.       0.3862E+05   2132.       0.000       0.000
     S1         S2          S3         SINT        SEQV
I  0.2052E+05  0.1538E+05  -402.7      0.2092E+05  0.1889E+05
C  0.2957E+05   8361.     -0.1030E+05  0.3987E+05  0.3455E+05
O  0.3862E+05   1350.     -0.2020E+05  0.5883E+05  0.5155E+05

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX         SY          SZ         SXY         SYZ         SXZ
I -0.9379E-12   2088.       2950.      -2298.       0.000       0.000
C   5270.      -559.2      -1470.        571.3       0.000       0.000
O   0.000       1103.       3587.      -2405.       0.000       0.000
     S1         S2          S3         SINT        SEQV
I   3569.       2950.      -1480.       5049.       4770.
C   5325.      -614.7      -1470.       6795.       6411.
O   3587.       3019.      -1917.       5503.       5243.

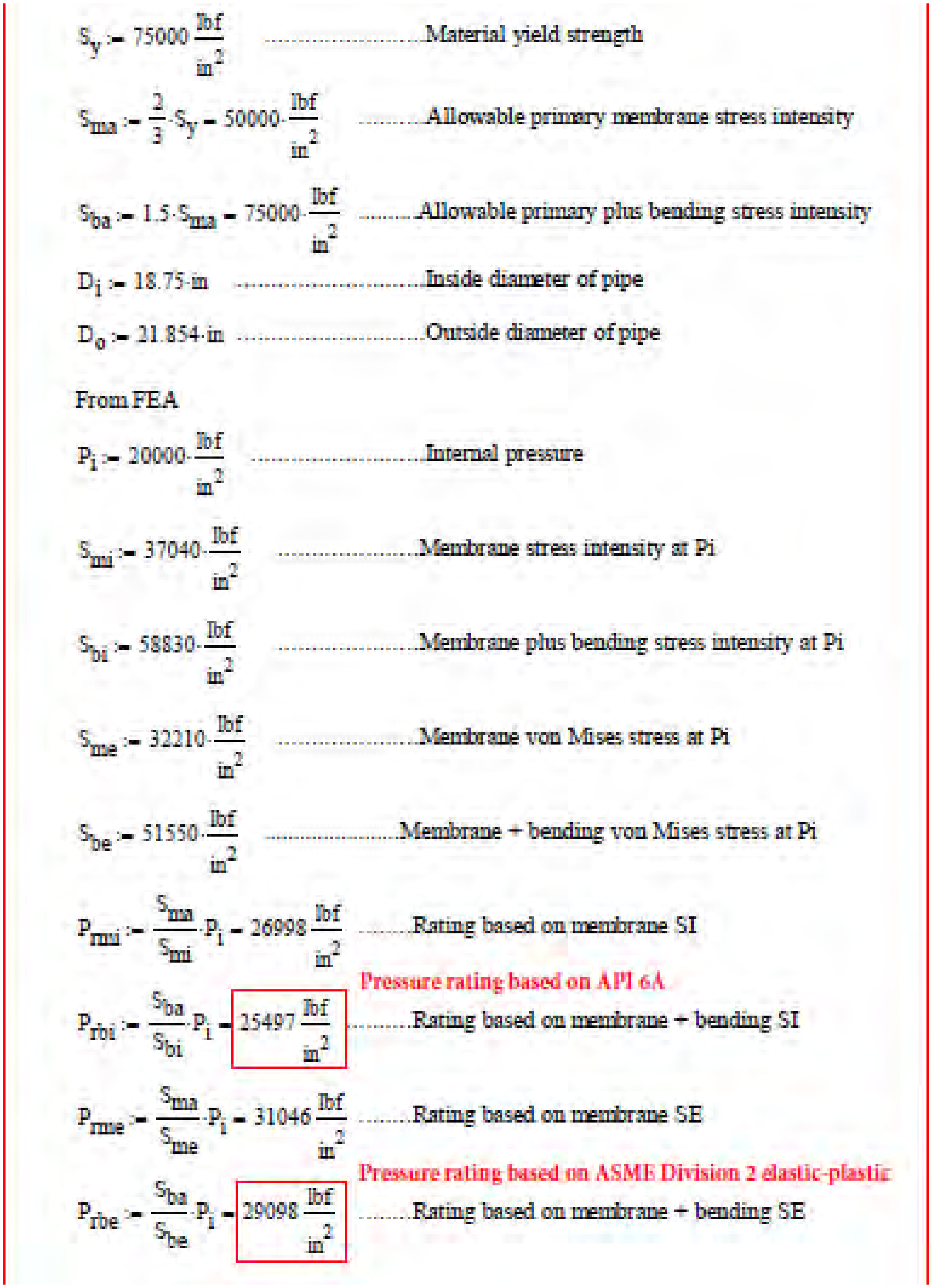
             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX         SY          SZ         SXY         SYZ         SXZ
I  -109.3      0.1718E+05  0.2347E+05  -166.2       0.000       0.000
C  -4780.       7554.       0.2810E+05   2704.       0.000       0.000
O -0.1999E+05   2240.       0.4221E+05  -273.2       0.000       0.000
     S1         S2          S3         SINT        SEQV        TEMP
I  0.2347E+05  0.1718E+05  -110.9      0.2358E+05  0.2115E+05   0.000
C  0.2810E+05   8121.      -5346.      0.3345E+05  0.2915E+05
O  0.4221E+05   2243.     -0.1999E+05  0.6220E+05  0.5459E+05   0.000
```

Figure B3.7

Linearized Stresses in 13-5/8 x 20k Flange with 20,000 psi Internal Pressure

Pressure Ratings of Flange with Elastic Material

Note: Stresses were calculated with an ANSYS 2D FEA Model.



$S_y := 75000 \cdot \frac{lbf}{in^2}$ ....Material yield strength

$S_{ma} := \frac{2}{3} \cdot S_y = 50000 \cdot \frac{lbf}{in^2}$ ....Allowable primary membrane stress intensity

$S_{ba} := 1.5 \cdot S_{ma} = 75000 \cdot \frac{lbf}{in^2}$ ....Allowable primary plus bending stress intensity

$D_i := 18.75 \cdot in$ ....Inside diameter of pipe

$D_o := 21.854 \cdot in$ ....Outside diameter of pipe

From FEA

$P_i := 20000 \cdot \frac{lbf}{in^2}$ ....Internal pressure

$S_{mi} := 37040 \cdot \frac{lbf}{in^2}$ ....Membrane stress intensity at Pi

$S_{bi} := 58830 \cdot \frac{lbf}{in^2}$ ....Membrane plus bending stress intensity at Pi

$S_{me} := 32210 \cdot \frac{lbf}{in^2}$ ....Membrane von Mises stress at Pi

$S_{be} := 51550 \cdot \frac{lbf}{in^2}$ ....Membrane + bending von Mises stress at Pi

$P_{rmi} := \frac{S_{ma}}{S_{mi}} \cdot P_i = 26998 \frac{lbf}{in^2}$ ....Rating based on membrane SI

Pressure rating based on API 6A

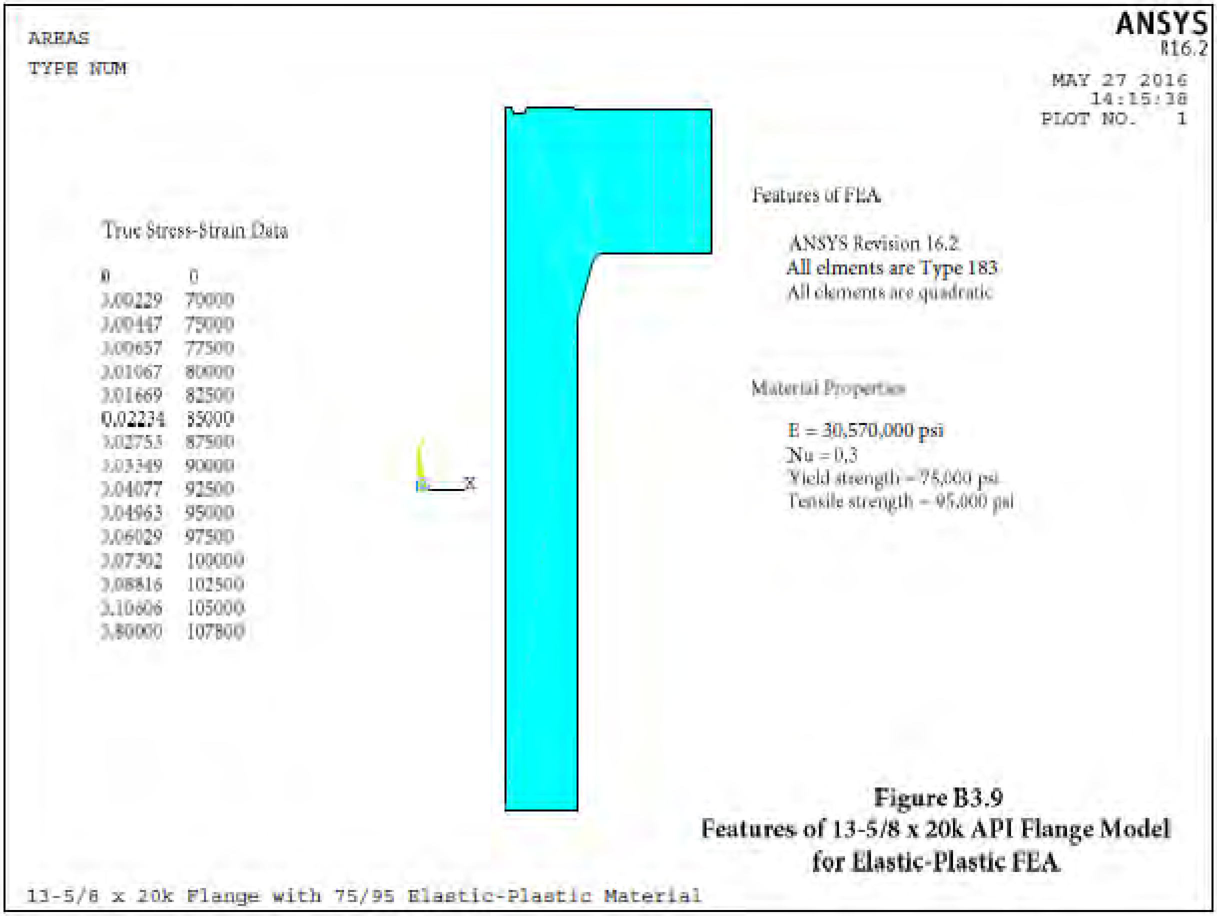
$P_{rbi} := \frac{S_{ba}}{S_{bi}} \cdot P_i = \boxed{25497 \frac{lbf}{in^2}}$ ....Rating based on membrane + bending SI

$P_{rme} := \frac{S_{ma}}{S_{me}} \cdot P_i = 31046 \frac{lbf}{in^2}$ ....Rating based on membrane SE

Pressure rating based on ASME Division 2 elastic-plastic

$P_{rbe} := \frac{S_{ba}}{S_{be}} \cdot P_i = \boxed{29098 \frac{lbf}{in^2}}$ ....Rating based on membrane + bending SE

Figure B3.8
Pressure Rating Calculations



True Stress-Strain Data

0	0
0.00229	70000
0.00447	75000
0.00657	77500
0.01067	80000
0.01669	82500
0.02234	85000
0.02753	87500
0.03349	90000
0.04077	92500
0.04963	95000
0.06029	97500
0.07302	100000
0.08816	102500
0.10606	105000
0.80000	107800

Features of FEA

ANSYS Revision 16.2
All elments are Type 183
All elements are quadratic

Material Properties

E = 30,570,000 psi
Nu = 0.3
Yield strength = 75,000 psi
Tensile strength = 95,000 psi

Figure B3.9
Features of 13-5/8 x 20k API Flange Model
for Elastic-Plastic FEA

13-5/8 x 20k Flange with 75/95 Elastic-Plastic Material

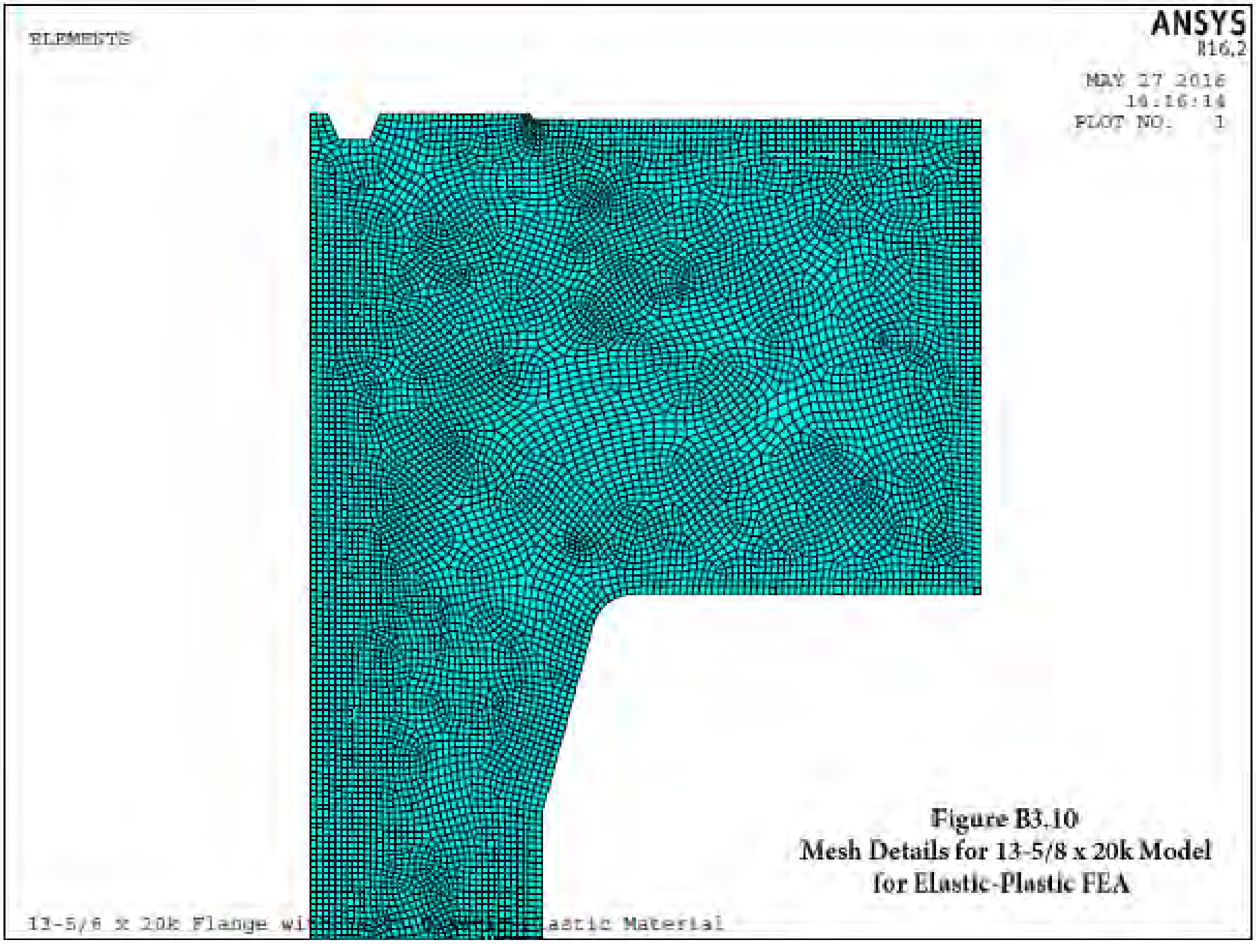
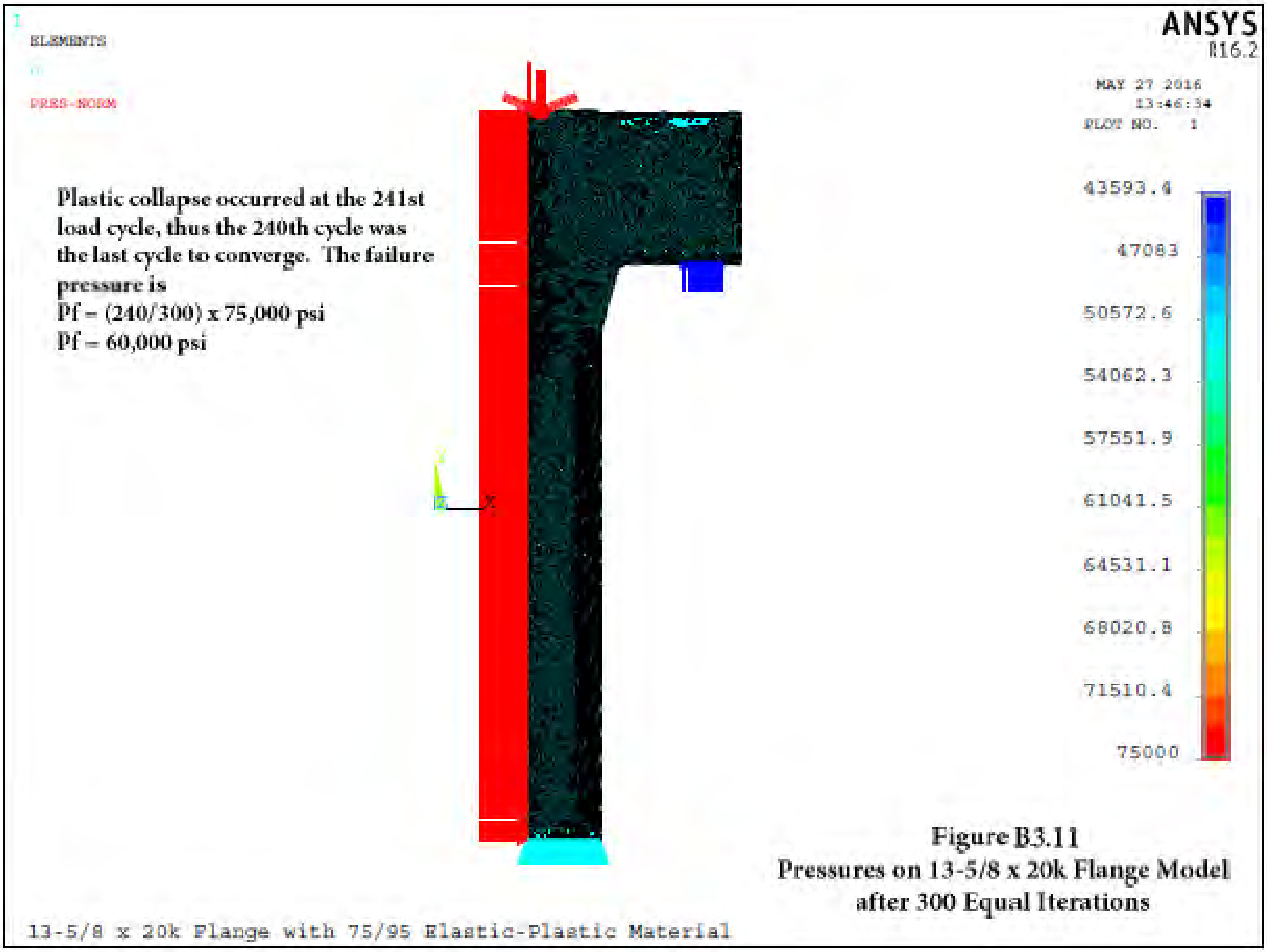


Figure B3.10
Mesh Details for 13-5/8 x 20k Model
for Elastic-Plastic FEA

13-5/8 x 20k Flange wi astic Material



Plastic collapse occurred at the 241st load cycle, thus the 240th cycle was the last cycle to converge. The failure pressure is

Pf = (240/300) x 75,000 psi

Pf = 60,000 psi

Figure B3.11
Pressures on 13-5/8 x 20k Flange Model
after 300 Equal Iterations

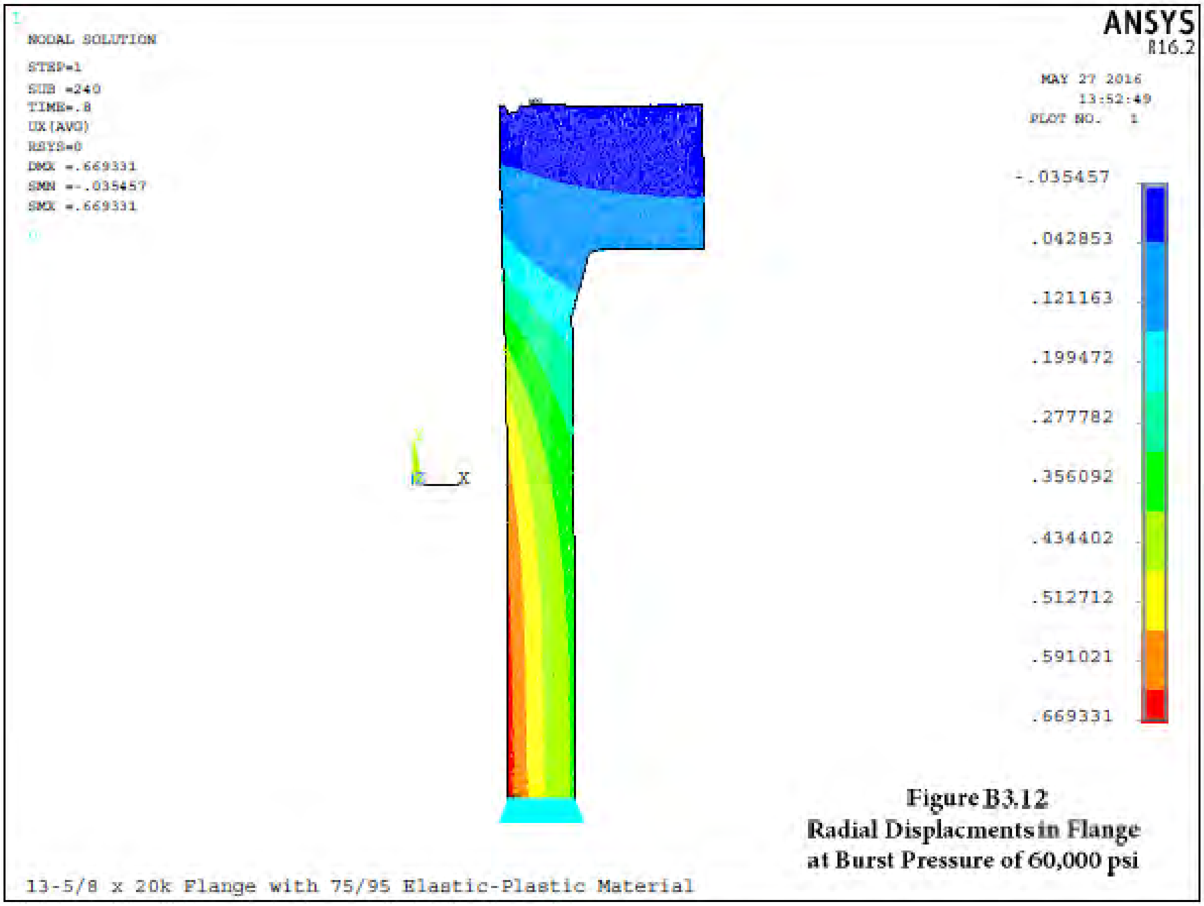


Figure B3.12
Radial Displacments in Flange
at Burst Pressure of 60,000 psi

Figure B3.13
Axial Displacments in Flange
at Burst Pressure of 60,000 psi

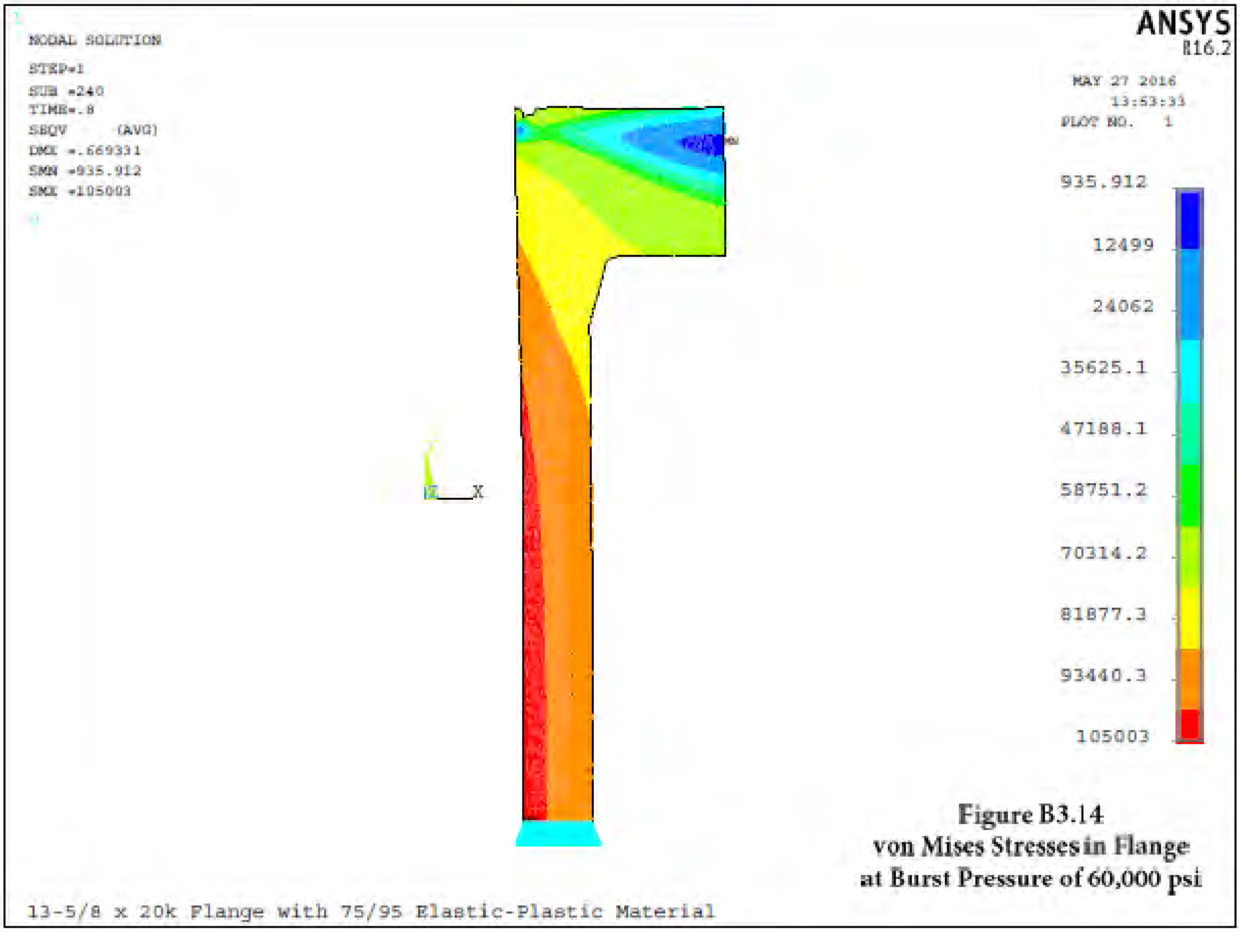


Figure B3.14
von Mises Stresses in Flange
at Burst Pressure of 60,000 psi

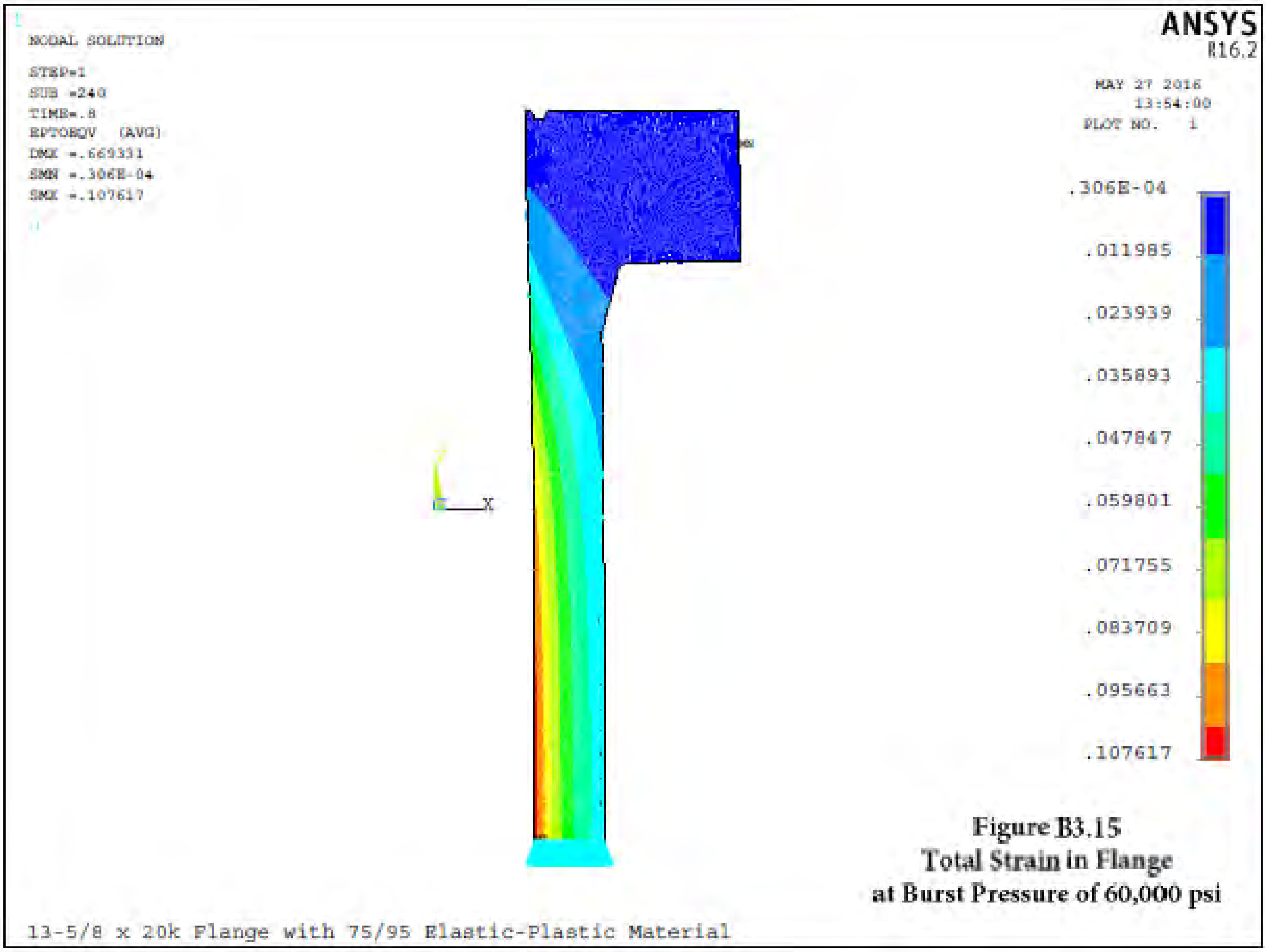


Figure B3.15
Total Strain in Flange
at Burst Pressure of 60,000 psi

Appendix B4
FEA of API 16-3/4 x 10k Flange

The geometry and dimensions of the FEA model of the API 16-3/4 x 10k flange were taken from Table B.40 in API 6A. The geometry of the FEA model is shown in Figure B4.1. As the figure shows, neither the bolts nor the seal ring were included in the model because they are not critical components for this study and their presence will not affect the accuracy of the critical stress or the collapse pressure calculations. Numerous FEA of API flanges reported in literature have demonstrated that bolts and seal rings can be neglected without significantly affecting the critical results required for pressure rating of API flanges.

The model was axisymmetric and comprised 13,102 elements and 40,071 nodes. All elements were quadrilateral, ANSYS Plane 183 elements. Figure B4.2 shows an enlarged view of the FEA mesh in the critical regions.

The model was solved with linear-elastic material properties and with elastic-plastic material properties. Results of the linear elastic solution were used to calculate pressure ratings based on API 6A and Division 2 linear-elastic procedures.

Linear-Elastic FEA

The model was solved with linear-elastic material properties at rated internal pressure of 10,000 psi. The following Figures at the end of this appendix describe the important features of the FEA model, loads and boundary conditions; and, the important results of the solution with linear-elastic material properties:

Figure B4.1...... Features of 16-3/4 x 10k API Flange Model for Linear-Elastic FEA
Figure B4.2...... Mesh Details for16-3/4 x 10k Model for Linear Elastic FEA
Figure B4.3...... Pressures on 16-3/4 x 10k Flange Model with Linear-Elastic Material
Figure B4.4...... Radial Displacements of Flange with 10 ksi Internal Pressure
Figure B4.5...... Axial Displacements of Flange with 10 ksi Internal Pressure
Figure B4.6...... von Mises Stresses in Flange with 10 ksi Internal Pressure
Figure B4.7...... Linearized Stresses in 16-3/4 x 10k Flange with 10 ksi Internal Pressure
Figure B4.8...... Pressure Rating Calculations

Figure B4.3 shows the pressure load and boundary conditions for the linear-elastic solution. As shown in the figure, internal pressure was applied to the OD of the seal groove. The pressure end load was applied as a pressure on the simulated area of the bolts. The center line of the simulated bolt area was the bolt centerline. The width of the simulated bolt area was the bolt diameter. This method is commonly used to simulate bolt loads on axisymmetric models of flanges. The nodes on the bottom (pipe end) of the model were fixed in the axial direction.

Figure B4.6 is a plot of the von Mises stresses in the flange with the location of the critical path shown. The critical path was found by linearizing stresses across numerous sections and finding the section where primary and primary membrane plus bending stresses are largest. Figure B4.7 shows the linearized stresses across the critical path. The stresses underlined in red are the ones that must be compared with the allowable stresses.

Notice that the membrane stress intensity and the membrane von Mises stresses are both underlined. This is because API 6A requires that stress intensities be compared with the allowable stresses whereas Division 2 requires that the von Mises stresses be compared with the allowable stresses.

The linear-elastic stresses in Figure B4.7 were used to calculate the pressure rating based on the API 6A which requires the use of the ASME Division 2 linear-elastic analysis method. Calculations for pressure ratings based on the linearized stresses are Figure B3.8: They are listed below:

Pressure ratings for 16-3/4 x 10k API Flange by linear-elastic FEA
14,310 psi .... Pressure rating by API 6A
16,453 psi .... Pressure rating by ASME Division 2

Elastic-Plastic FEA

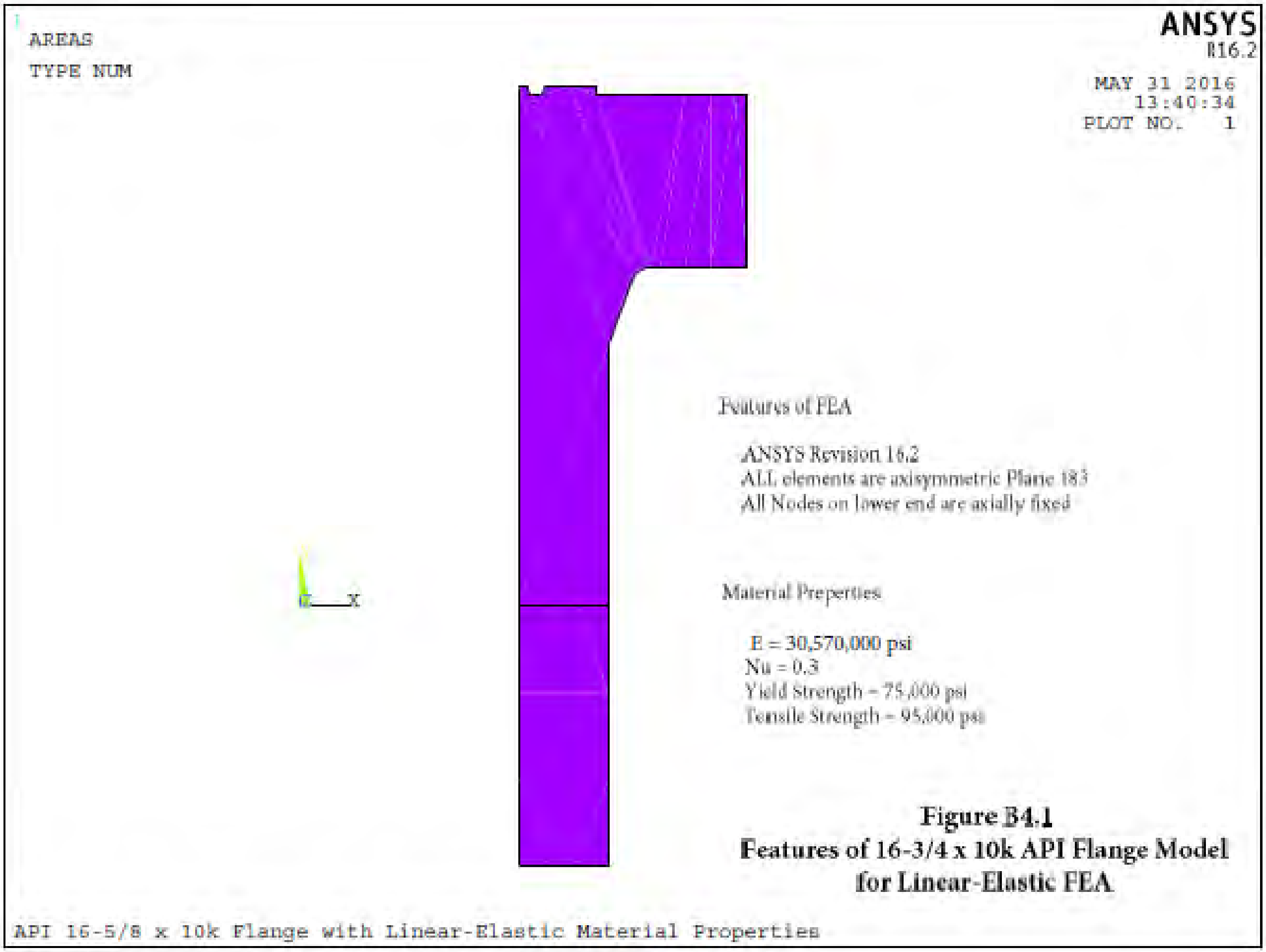
The FEA model was also solved with elastic-plastic material properties. The elastic-plastic solution used the material properties of the low alloy steel with a 75,000 psi yield strength. The following figures at the end of this appendix show the important features of the elastic-plastic model, solutions and important results:

Figure B4.9...... Features of 16-3/4 x 10k API Flange Model for Elastic-Plastic FEA
Figure B4.10.... Mesh Details for 16-3/4 x 10k Model for Elastic-Plastic FEA
Figure B4.11.... Pressures on 16-3/4 x 10k Flange Model after 160 Iterations
Figure B4.12.... Axial Displacements in Flange at Burst Pressure of 34.75 ksi
Figure B4.13.... Radial Displacements in Flange at Burst Pressure of 34.75 ksi
Figure B4.14.... von Mises Stresses in Flange at Burst Pressure of 34.75 ksi
Figure B4.15.... Total Strain in Flange at Burst Pressure of 34.75 ksi

The elastic-plastic solution was solved by incrementally increasing the internal pressures until the solution failed to converge. Figure B4.11 shows the model with an internal pressure of 40,000 psi after 160 equal iterations. The model failed to converge before all 160 iterations were completed. The last converged solution was at iteration 139. Hence, the pressure at the last converged solution was 34,750 psi.

The following pressure ratings where calculated by dividing the collapse pressure by the design factors:

Pressure ratings for 16-3/4 x 10k API Flange by elastic-plastic FEA
14,479 psi .... Pressure rating by Division 2 elastic-plastic
19,306 psi .... Pressure rating by Division 3 elastic-plastic



Features of FEA

ANSYS Revision 16.2
ALL elements are axisymmetric Plane 183
All Nodes on lower end are axially fixed

Material Properties

E = 30,570,000 psi
Nu = 0.3
Yield Strength = 75,000 psi
Tensile Strength = 95,000 psi

Figure B4.1
Features of 16-3/4 x 10k API Flange Model for Linear-Elastic FEA

API 16-5/8 x 10k Flange with Linear-Elastic Material Properties

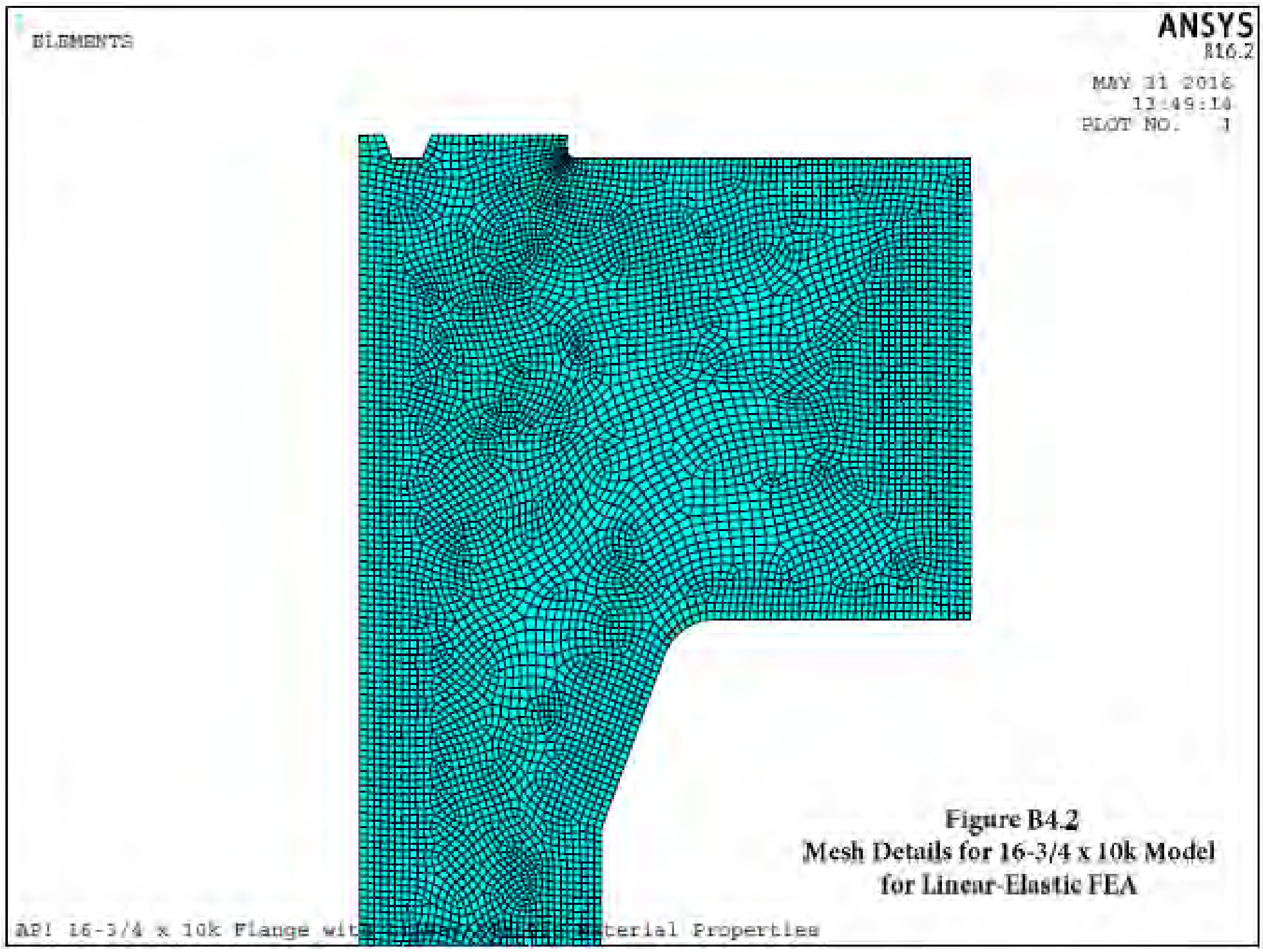


Figure B4.2
Mesh Details for 16-3/4 x 10k Model for Linear-Elastic FEA

API 16-3/4 x 10k Flange with Linear-Elastic Material Properties

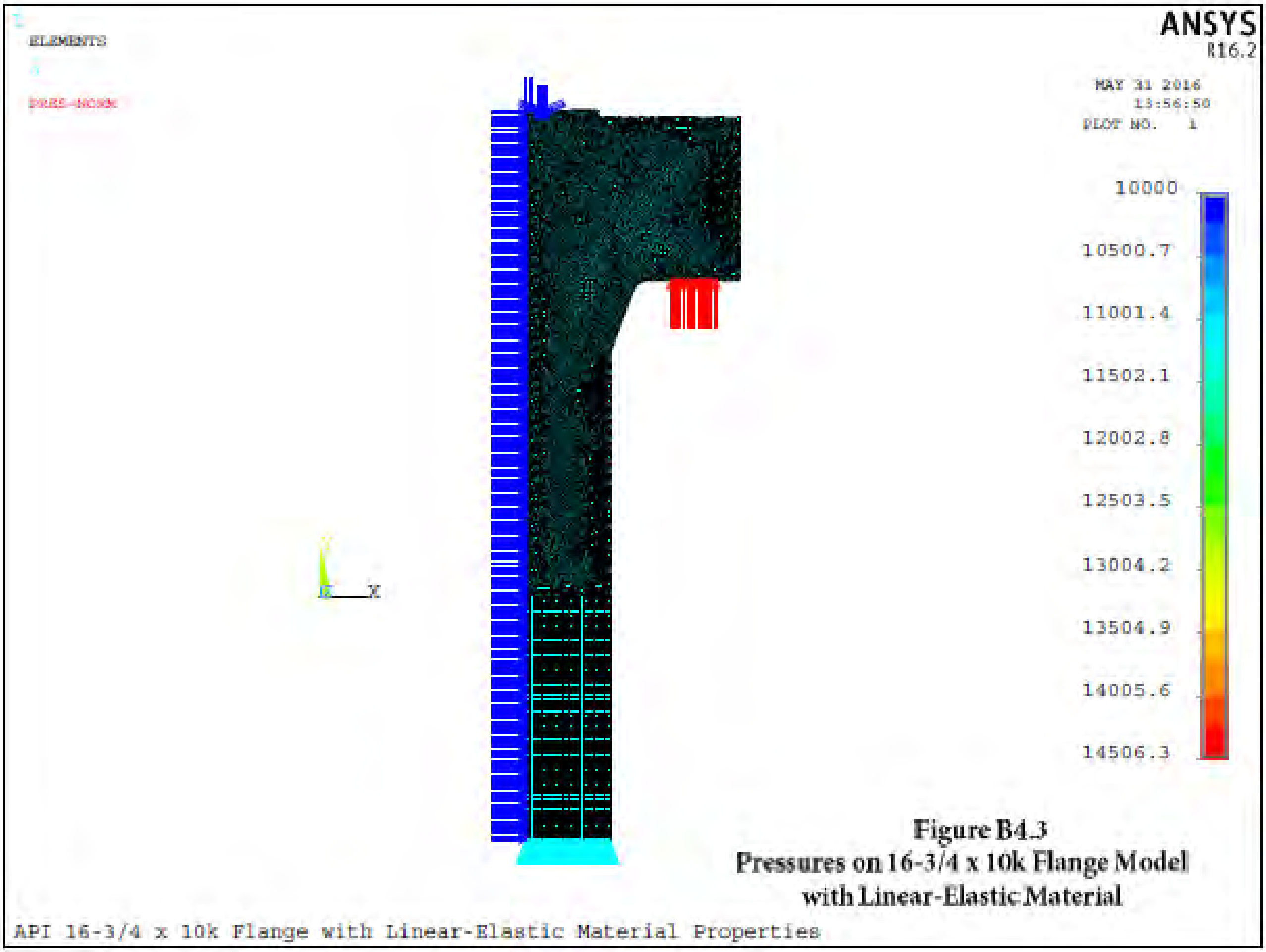


Figure B4.3
Pressures on 16-3/4 x 10k Flange Model
with Linear-Elastic Material

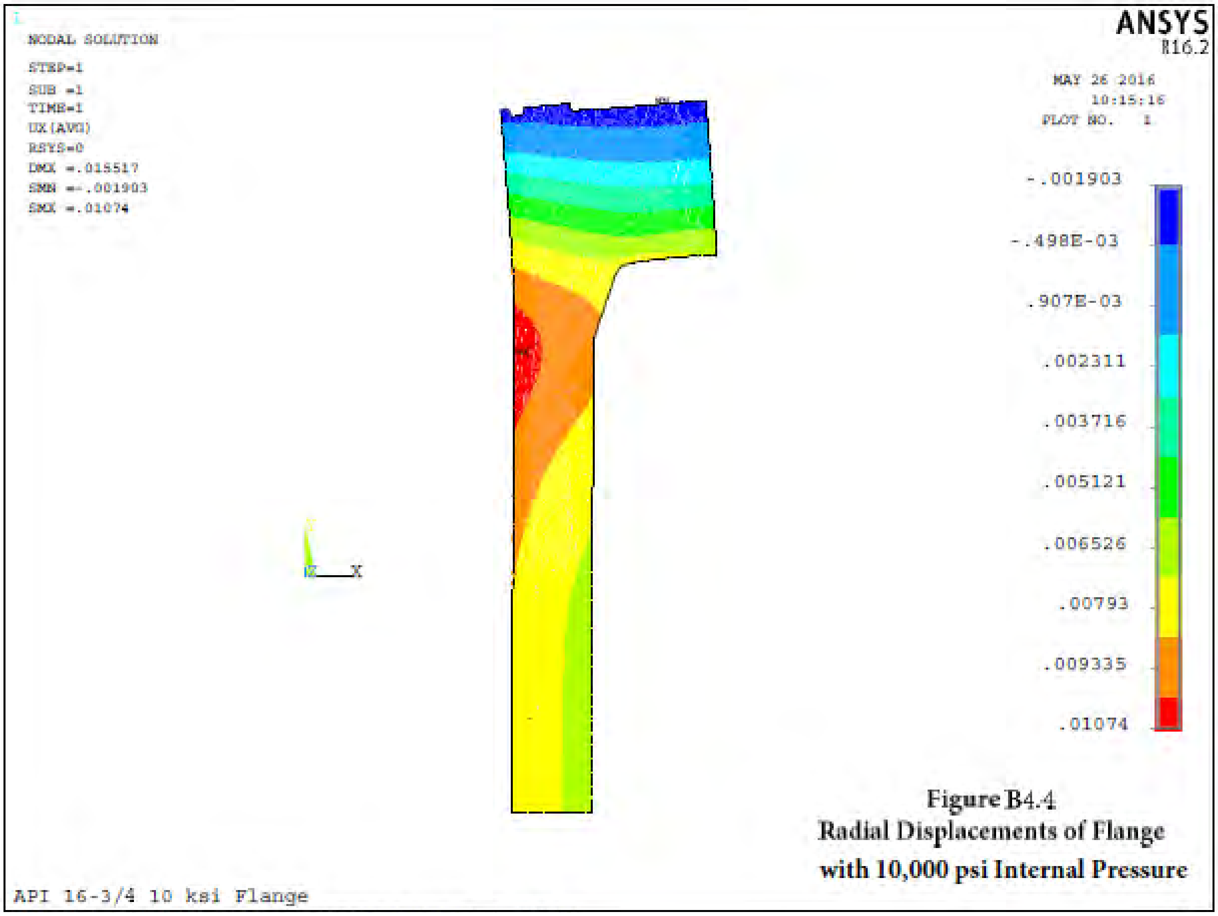


Figure B4.4
Radial Displacements of Flange
with 10,000 psi Internal Pressure

Figure B4.5
Axial Displacements of Flange
with 10,000 psi Internal Pressure

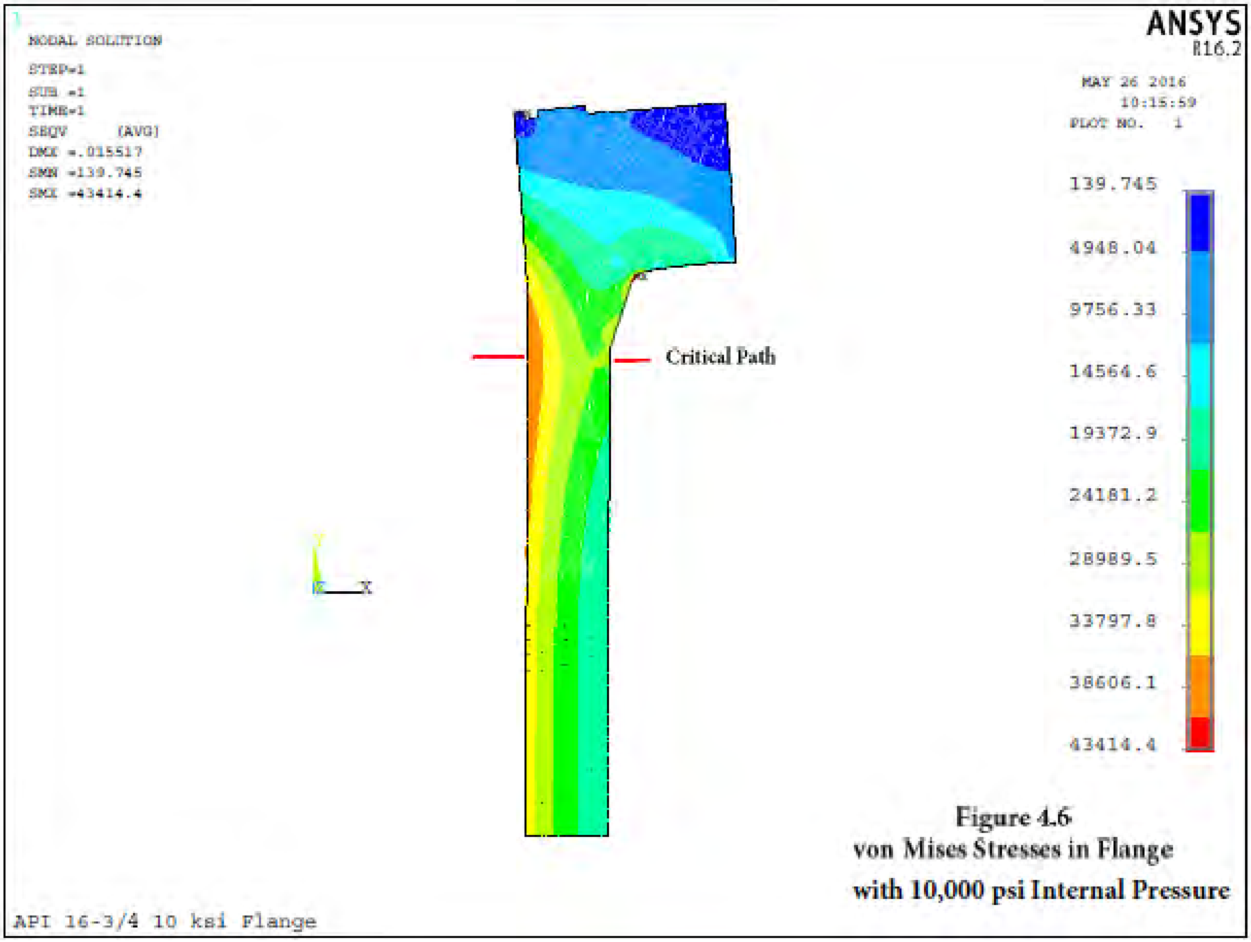


Figure 4.6
von Mises Stresses in Flange
with 10,000 psi Internal Pressure

```
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= PATHD      DSYS=  0

  RADIUS OF CURVATURE =   10.120

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =    302     OUTSIDE NODE =    969

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   10.120
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 -3625.      0.1007E+05  0.3082E+05   2668.       0.000       0.000
     S1          S2          S3          SINT        SEQV
 0.3082E+05  0.1057E+05  -4126.      0.3494E+05  0.3039E+05

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I   3621.      0.1125E+05  -2766.       0.000       0.000       0.000
C  -1376.      -680.0      -149.1       0.000       0.000       0.000
O  -6374.     -0.1261E+05   2468.       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.1125E+05   3621.      -2766.      0.1402E+05  0.1216E+05
C  -149.1      -680.0      -1376.       1227.       1066.
O   2468.      -6374.     -0.1261E+05  0.1508E+05  0.1313E+05

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -3.891      0.2132E+05  0.2805E+05   2668.       0.000       0.000
C  -5001.       9388.      0.3067E+05   2668.       0.000       0.000
O  -9999.      -2545.      0.3329E+05   2668.       0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.2805E+05  0.2165E+05  -332.7      0.2838E+05  0.2579E+05
C  0.3067E+05   9867.      -5480.      0.3615E+05  0.3142E+05
O  0.3329E+05  -1688.     -0.1086E+05  0.4414E+05  0.4035E+05

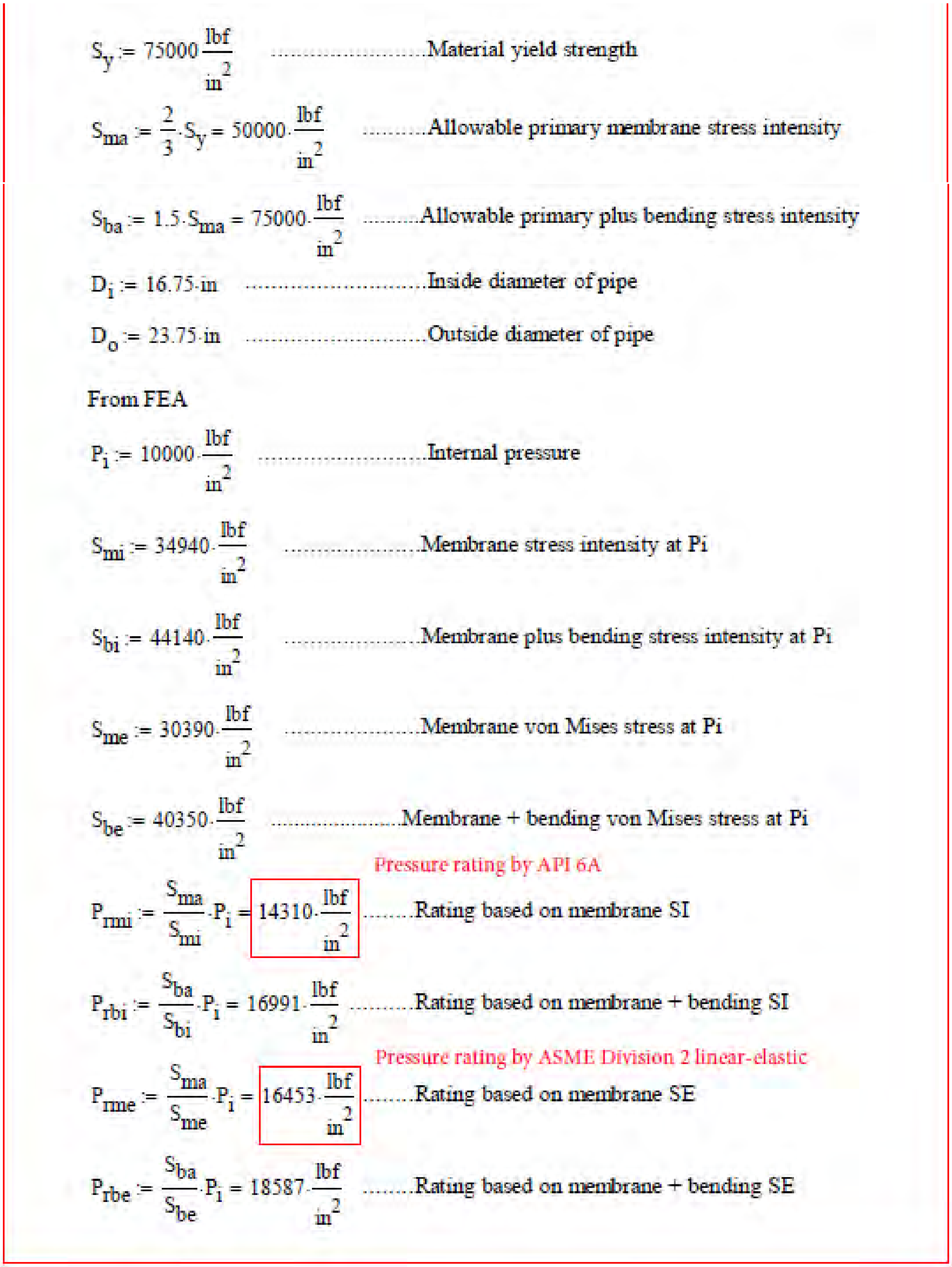
             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  0.4619E-13  -261.1       433.0      -2805.       0.000       0.000
C   2180.      -390.0      -370.6       1079.       0.000       0.000
O   0.000       421.0       827.4      -2716.       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   2677.       433.0      -2938.       5615.       4895.
C   2573.      -370.6      -783.2       3357.       3171.
O   2935.       827.4      -2514.       5449.       4759.

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -3.891      0.2106E+05  0.2848E+05  -136.3       0.000       0.000
C  -2821.       8998.      0.3030E+05   3748.       0.000       0.000
O  -9999.      -2124.      0.3411E+05  -48.14       0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
I  0.2848E+05  0.2106E+05  -4.773      0.2849E+05  0.2560E+05   0.000
C  0.3030E+05  0.1009E+05  -3909.      0.3421E+05  0.2979E+05
O  0.3411E+05  -2123.      -9999.      0.4411E+05  0.4075E+05   0.000
```

Figure B4.7
Linearized Stresses in 16-3/4 x 10 k Flange
with 10,000 psi Internal Pressure

Pressure Ratings of 16-3/4 x 10k API Flange

Note: Stresses were calculated with an ANSYS 2D FEA Model.



$S_y := 75000\,\frac{lbf}{in^2}$ ....Material yield strength

$S_{ma} := \frac{2}{3}\cdot S_y = 50000\cdot\frac{lbf}{in^2}$ ....Allowable primary membrane stress intensity

$S_{ba} := 1.5\cdot S_{ma} = 75000\cdot\frac{lbf}{in^2}$ ....Allowable primary plus bending stress intensity

$D_i := 16.75\cdot in$ ....Inside diameter of pipe

$D_o := 23.75\cdot in$ ....Outside diameter of pipe

From FEA

$P_i := 10000\cdot\frac{lbf}{in^2}$ ....Internal pressure

$S_{mi} := 34940\cdot\frac{lbf}{in^2}$ ....Membrane stress intensity at Pi

$S_{bi} := 44140\cdot\frac{lbf}{in^2}$ ....Membrane plus bending stress intensity at Pi

$S_{me} := 30390\cdot\frac{lbf}{in^2}$ ....Membrane von Mises stress at Pi

$S_{be} := 40350\cdot\frac{lbf}{in^2}$ ....Membrane + bending von Mises stress at Pi

Pressure rating by API 6A

$P_{rmi} := \frac{S_{ma}}{S_{mi}}\cdot P_i = \boxed{14310\cdot\frac{lbf}{in^2}}$ ....Rating based on membrane SI

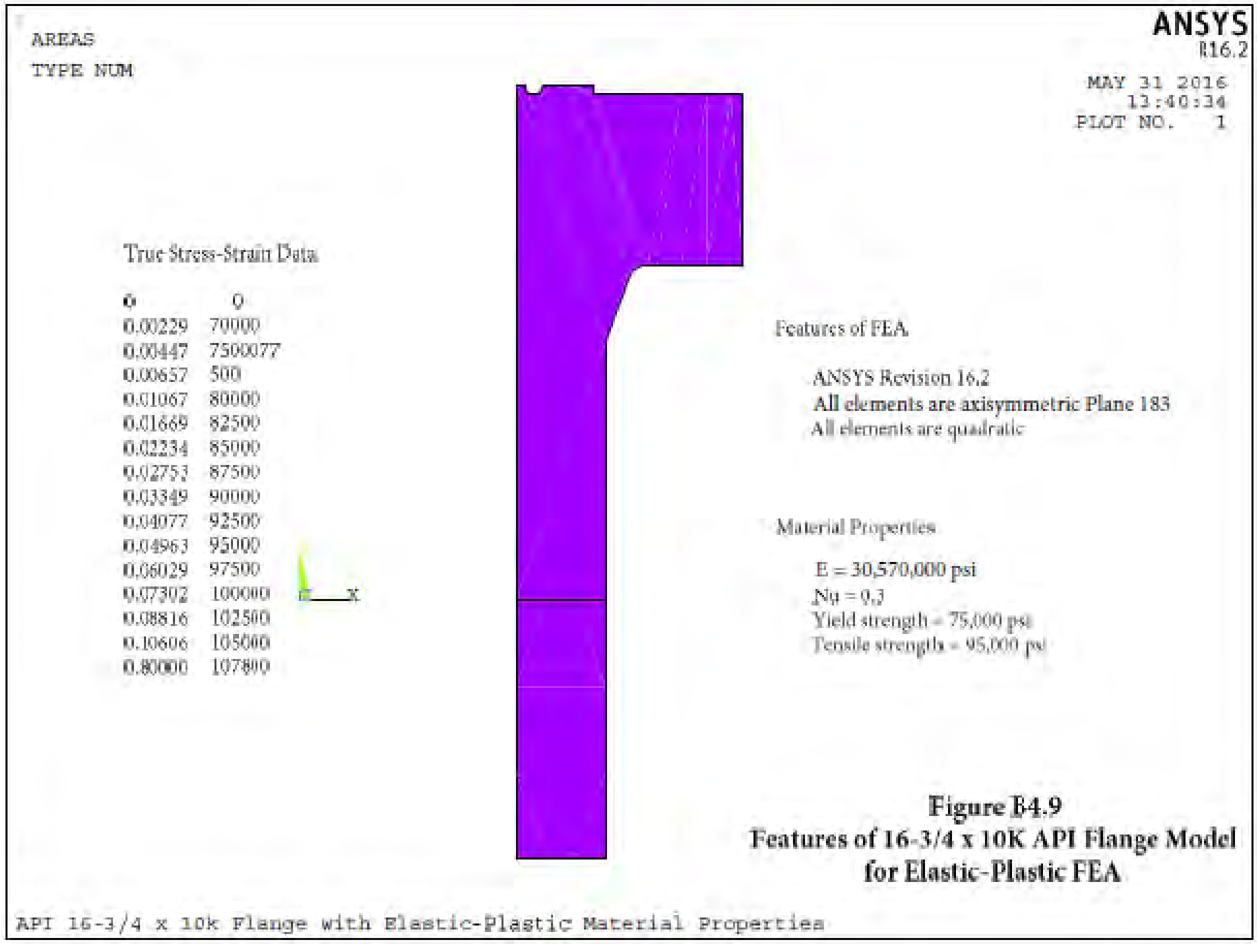
$P_{rbi} := \frac{S_{ba}}{S_{bi}}\cdot P_i = 16991\cdot\frac{lbf}{in^2}$ ....Rating based on membrane + bending SI

Pressure rating by ASME Division 2 linear-elastic

$P_{rme} := \frac{S_{ma}}{S_{me}}\cdot P_i = \boxed{16453\cdot\frac{lbf}{in^2}}$ ....Rating based on membrane SE

$P_{rbe} := \frac{S_{ba}}{S_{be}}\cdot P_i = 18587\cdot\frac{lbf}{in^2}$ ....Rating based on membrane + bending SE

Figure B4.8
Pressure Rating Calculations



True Stress-Strain Data

0	0
0.00229	70000
0.00447	7500077
0.00657	500
0.01067	80000
0.01669	82500
0.02234	85000
0.02753	87500
0.03349	90000
0.04077	92500
0.04963	95000
0.06029	97500
0.07302	100000
0.08816	102500
0.10606	105000
0.80000	107800

Features of FEA

ANSYS Revision 16.2
All elements are axisymmetric Plane 183
All elements are quadratic

Material Properties

E = 30,570,000 psi
Nu = 0.3
Yield strength = 75,000 psi
Tensile strength = 95,000 psi

Figure B4.9
Features of 16-3/4 x 10K API Flange Model for Elastic-Plastic FEA

API 16-3/4 x 10k Flange with Elastic-Plastic Material Properties

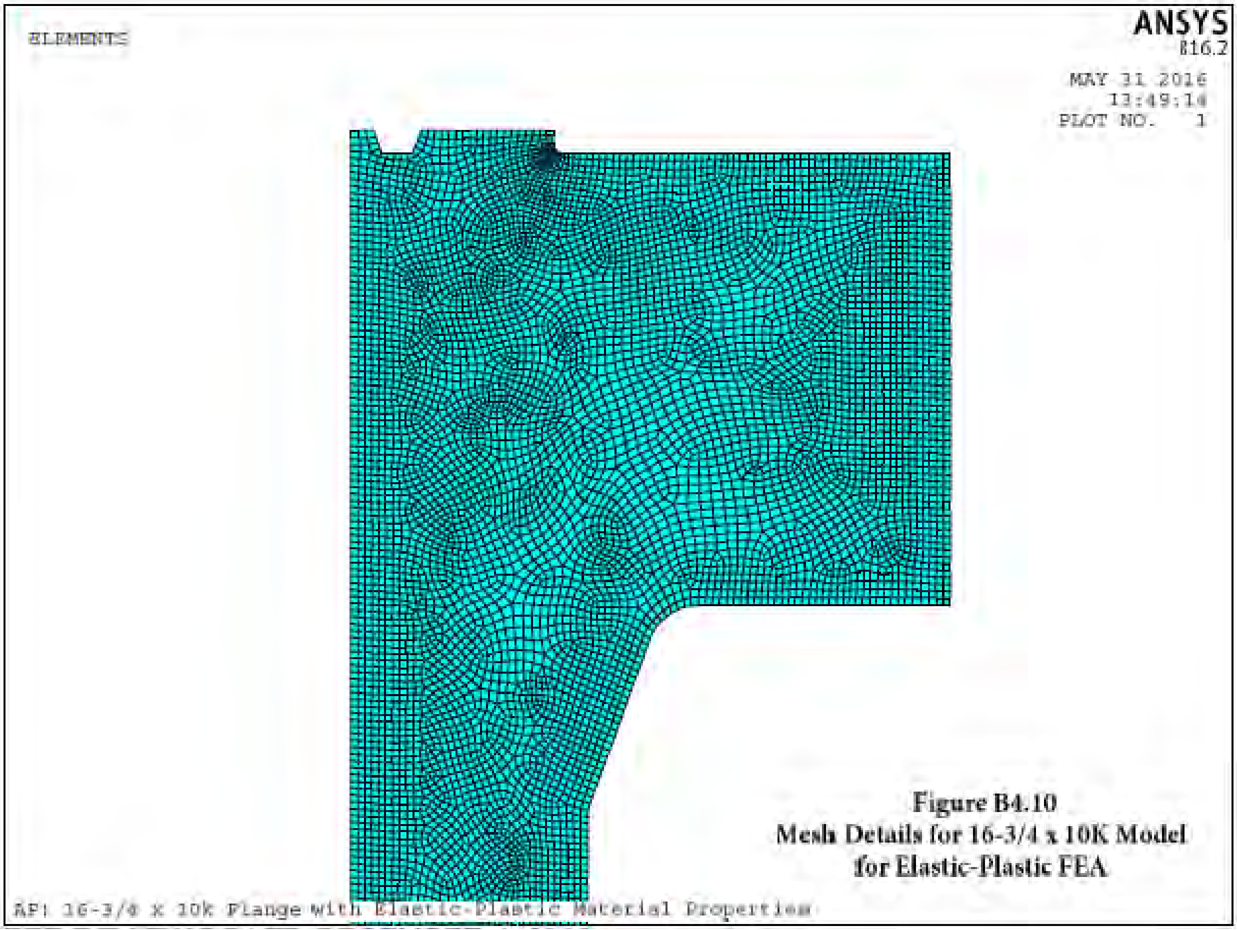
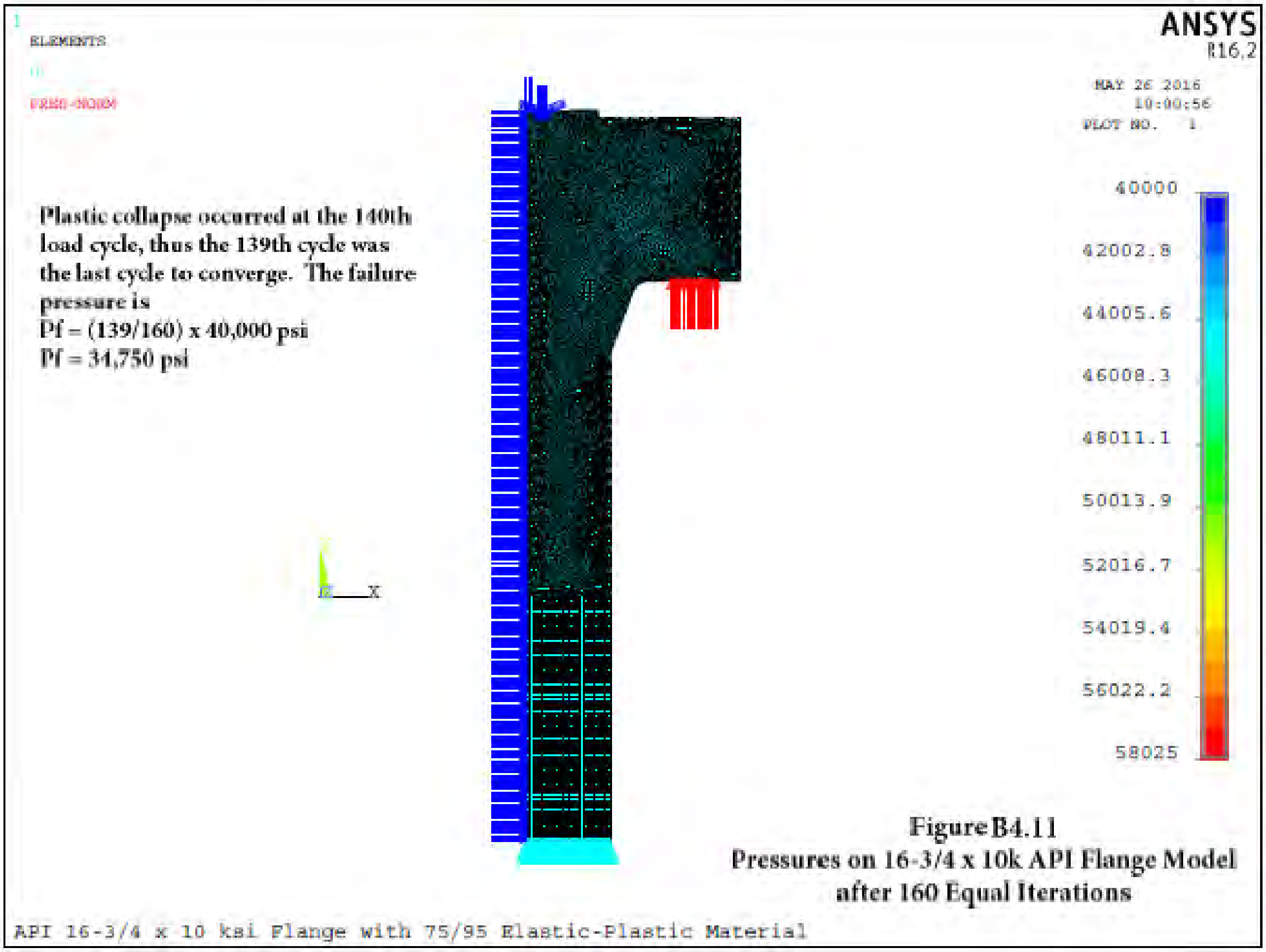


Figure B4.10
Mesh Details for 16-3/4 x 10K Model for Elastic-Plastic FEA

API 16-3/4 x 10k Flange with Elastic-Plastic Material Properties



Plastic collapse occurred at the 140th load cycle, thus the 139th cycle was the last cycle to converge. The failure pressure is

Pf = (139/160) x 40,000 psi

Pf = 34,750 psi

Figure B4.11
Pressures on 16-3/4 x 10k API Flange Model
after 160 Equal Iterations

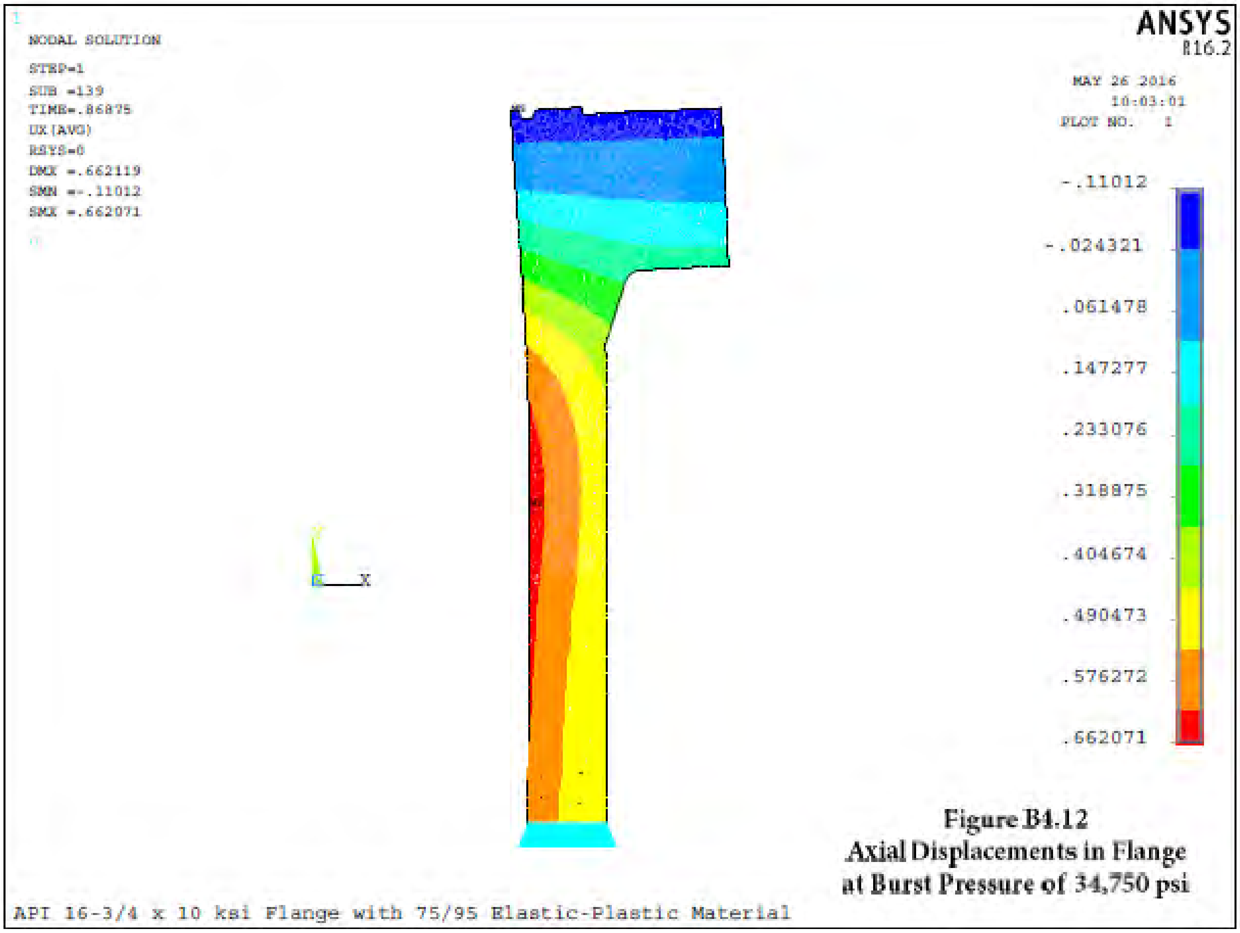


Figure B4.12
Axial Displacements in Flange
at Burst Pressure of 34,750 psi

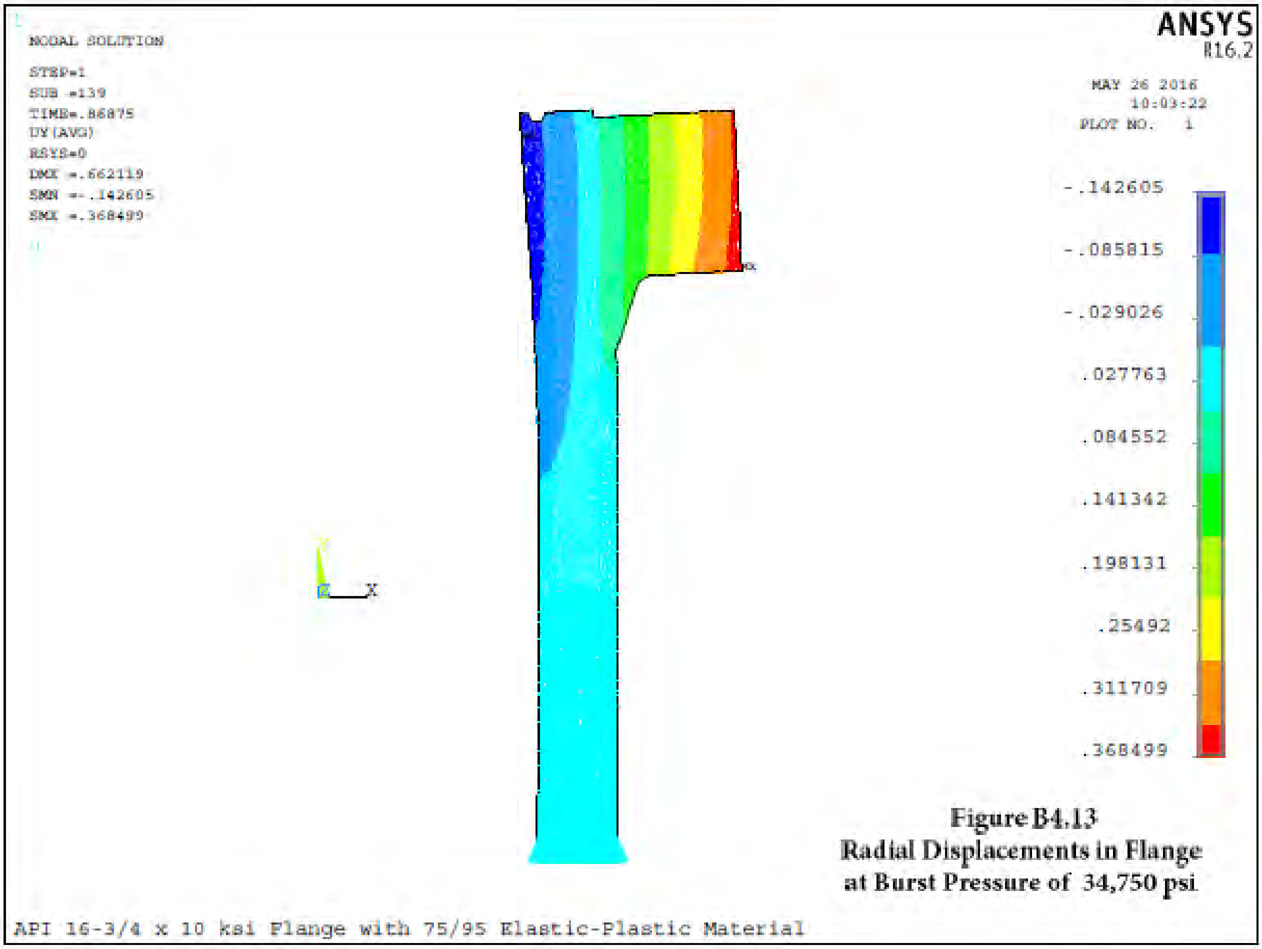


Figure B4.13
Radial Displacements in Flange
at Burst Pressure of 34,750 psi

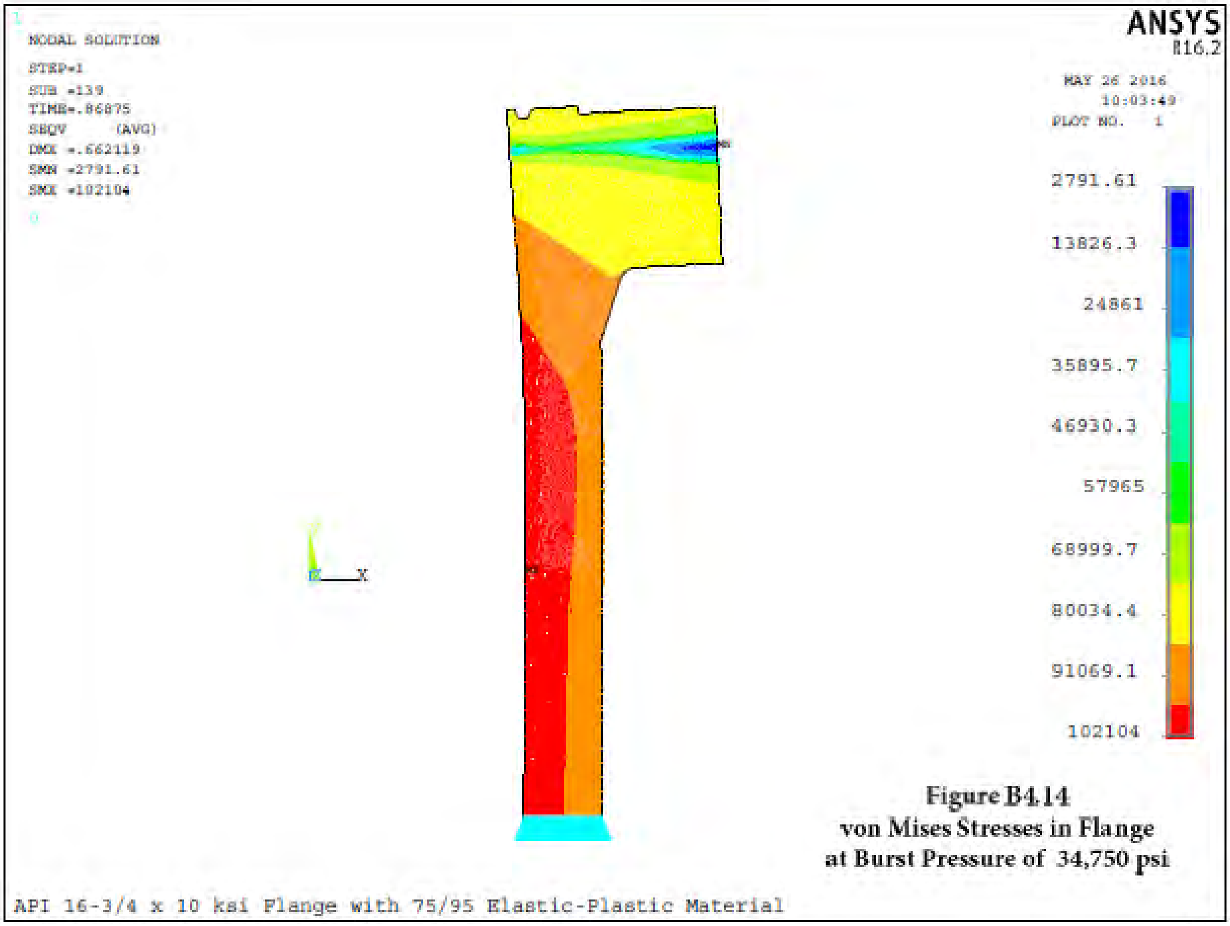


Figure B4.14
von Mises Stresses in Flange
at Burst Pressure of 34,750 psi

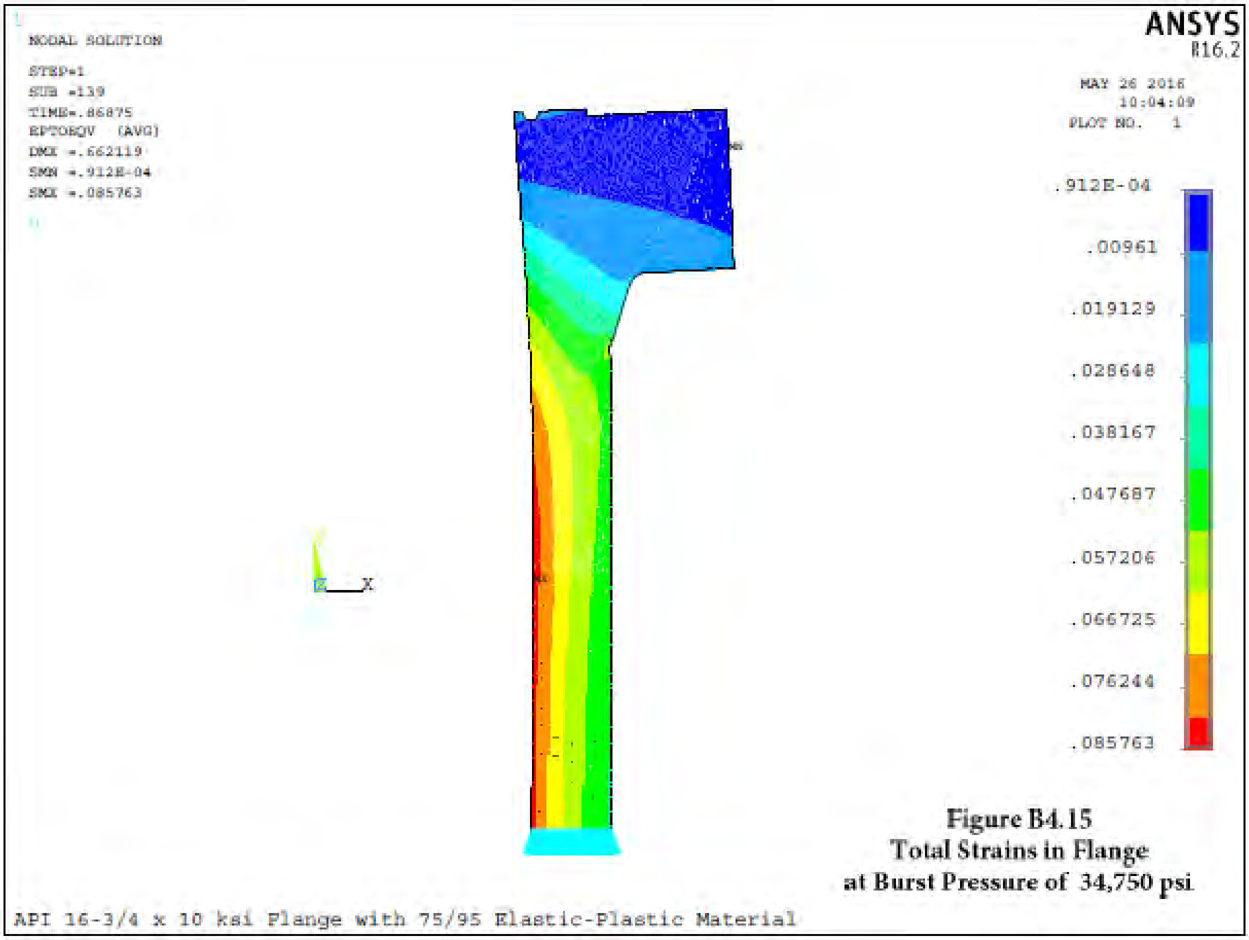


Figure B4.15
Total Strains in Flange
at Burst Pressure of 34,750 psi

APPENDIX C

HYDRO AND BURST TESTS OF BODIES

C1 Documents by Aiken Engineering

As stated in Section 5.1 prototypes of the large neck and small neck test bodies were manufactured and prepared for hydrotesting. Hydrotests were performed by Southwest Research Institute in San Antonio Texas.

Table C1 summarizes the hydrotest plan that was proposed by Aiken Engineering. SwRI for all practical intent followed this plan. As shown in the table, two types of hydrotests were performed on each body. In the first set of tests the test bodies were hydrotested inside a hyperbaric chamber with various combinations of internal and external pressure as listed in Table C1. For these tests strain gages were mounted at critical locations on the test bodies and strain readings were recorded throughout the test program. Figures III-1, III-2, and III-3 show the locations of strain gages on the test Bodies.

In the second set of tests, the test bodies were mounted inside blast containment structures. Then internal pressure was slowly applied until the test bodies ruptured and relieved pressure. An identical but separate containment structure was provided for each test body.

Figure IV-8 on page C-89 is a photograph of the large neck body after rupture and Figure IV-7 is a photograph of the small neck body after rupture. As the photographs show, as expected both ruptures occurred in the thin neck sections. The maximum internal pressures before rupture occurred were

Burst pressure of large neck body = 67,959 psi

Burst pressure of small neck body = 51,469 psi

Table C1 - Proposed Test Plan for 1st Test Body

Step	Description	Pressures (psi)			Notes
		Internal	External	Increment	
0	Zero Strain Gages	0	0	0	Mount, run lead wires and assemble w/o bolt torque; zero gages
1	Bolt Preload	0	0	0	Torque bolts to 80% of yield using stud tensioners
2	Hydrotest + Preload	30,000	0	5,000	Record strain gage readings after each pressure step
3	Bolt Preload	0	0	-30,000	Slowly return internal pressure to zero and record strain gage readings
4	MAWP at Surface + Preload	20,000	0	5,000	Record strain gage readings after each pressure step
5	Bolt Preload	0	0	-30,000	Slowly return internal pressure to zero and record strain gage readings
6	MAWP at 5,000 Ft + Preload	22,222	2,222	5,000	Set internal and external pressures to 2,222 psi and record gage readings
7	Bolt Preload	0	0	-22,222	Slowly return internal pressure to zero and record strain gage readings
8	MAWP at 10,000 Ft + Preload	24,444	4,444	5,000	Set internal and external pressures to 4,444 psi and record gage readings
9	Bolt Preload	0	0	-24,400	Slowly return internal pressure to zero and record strain gage readings
10	Failure Pressure + Preload	~72,000	0	5,000	Record strain gage readings after each pressure step

C2 Test Report by Southwest Research Institute

Following completion of the hydrotest program, Southwest Research Institute produced a comprehensive report that described the test equipment, procedures and important results. The SwRI report is included in this appendix with the strain gage data for hydrotest of the two test bodies. The stain gage data for the burst test and operating pressure tests have been removed because the data is not related to this report and the data includes more than 150 pages of plots.

VALVE BODY HYDROSTATIC AND BURST TESTING

FINAL REPORT

SwRI Project 18.21910
Aiken Engineering Purchase Order 2456-0127-2016

prepared by

VERONICA MCDONALD

prepared for

Aiken Engineering Company
9720 Cypresswood Drive, Suite 340
Houston, Texas 77070

May 12, 2016

VALVE BODY HYDROSTATIC AND BURST TESTING

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9720 Cypresswood Drive, Suite 340
Houston, Texas 77070

May 12, 2016

APPROVED:

Chris Storey

Chris Storey, Group Leader
Ocean Simulation Laboratory

TABLE OF CONTENTS

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1.0 INTRODUCTION

Southwest Research Institute® (SwRI®) was contracted by Aiken Engineering to perform testing on two valve bodies in accordance with Aiken Engineering's Request for Quotation. The report contains the recorded data of the various test parameters measured during the tests, and presents the test results.

The valve body testing was conducted at Southwest Research Institute in San Antonio, Texas from April 15 through April 26, 2016.

2.0 TEST SETUP

2.1 Strain Gaging

Prior to pressure testing, a total of 10 biaxial strain gages were installed on the sample at locations agreed upon by SwRI and Aiken. Micro-Measurements MMF003153, 350 Ω, ±5% gages were used, giving the ability to measure 50,000 microstrain in tension or compression. Figures of the strain gage locations are included in Appendix III. Each gage was installed such that one element (strain channel) was placed in the axial direction and one in the hoop, or circumferential, direction. Two uniaxial strain gages were installed on samples of F22 material to be compared to other strain results. All gage locations required light surface preparations to create a suitable surface to bond to the gage (light scrubbing with Scotch-Brite pad and use of degreaser/solvent). Each gage was adhered to the surface of the test article using Vishay M-Bond 600 adhesive. SwRI technicians applied the adhesive then used heated vacuum pads to apply the necessary hold down pressure and cure temperature. Each location was cured for 1.1 hours at 275°F then temperature was allowed to return to ambient while the vacuum pads were left on for an additional 20-30 minutes.

Following confirmation of adhesive cure, the Teflon coated wiring was soldered in place, and each gage was tested for functionality. Dow Corning 748 sealant was applied over the strain gage locations and wiring to protect against water ingress.

2.2 Test Facility

The hydrostatic portions of testing were conducted in SwRI's 50-inch, 6,000 psi pressure vessel. The burst test was conducted at a remote test site on SwRI's campus. All tests were conducted at ambient temperature.

2.3 Test Medium

The pressurization medium for the valve body for all internal and external testing was San Antonio city water.

2.4 High-Pressure Connections / Supply

For testing in the 50 inch chamber, high pressure (¼") stainless steel tubing was connected to the top and bottom flanges of the valve under test. The valve body was pressurized through the bottom flange connection. The valve body was depressurized through the top flange connection. For the burst test, ultra high pressure (¼") stainless steel tubing was connected to the bottom flanges of the valve body under test. All other ports on the valve body flanges were plugged. The valve body was pressurized through the bottom flange connection. For both tests, the bore pressure was generated with a Haskel pump mounted on a SwRI pressure control panel used for this type of testing. To ensure that the rate of pressure reduction was not too rapid, a metering valve (1/4" ultra high pressure) was added to the pressure control panel downstream of the relay-controlled dump valve.

2.5 Instrumentation

The valve internal and external (where applicable) pressures were monitored by a digital pressure controller/display. A thermocouple was placed in the interior of the pressure vessel to monitor the ambient temperature during testing in the vessel. These instruments were connected to a computer data acquisition (DAQ) system. The computer data acquisition system recorded:

A: Internal and External Pressure
B: Thermocouple Temperature Reading (when applicable)
C: Strain

Data was scanned and logged with National Instruments LabView software at preset intervals and electronically saved to the computer during each test sequence. Prior to testing, all pressure measuring instrumentation was calibrated on an SI Barnett or an Ashcroft deadweight calibrator which has calibrations traceable to the National Institute of Standards and Technology (NIST). The instruments used are listed in Tables 1 and 2 below. The calibration sheets for these instruments are included in Appendix II.

Table 1 – Instrumentation Used for Sections 3.0 and 5.0

Test Item Monitored	Make/Model	Serial Number
Sample Pressure	Honeywell / TJE	1467253
Chamber Pressure	Sensotec/A5/B489-02	559498
Thermocouple Calibrator	Fluke	1131008

Table 2 – Instrumentation Used for Sections 4.0 and 6.0

Test Item Monitored	Make/Model	Serial Number
Sample Pressure	Sensotec/HP/8810-02	889788

2.6 General Test Schematic

A general schematic for the test setup in the hyperbaric chamber is shown below in Figure 1. A general schematic for the test setup for the burst test is shown in Figure 2 below.

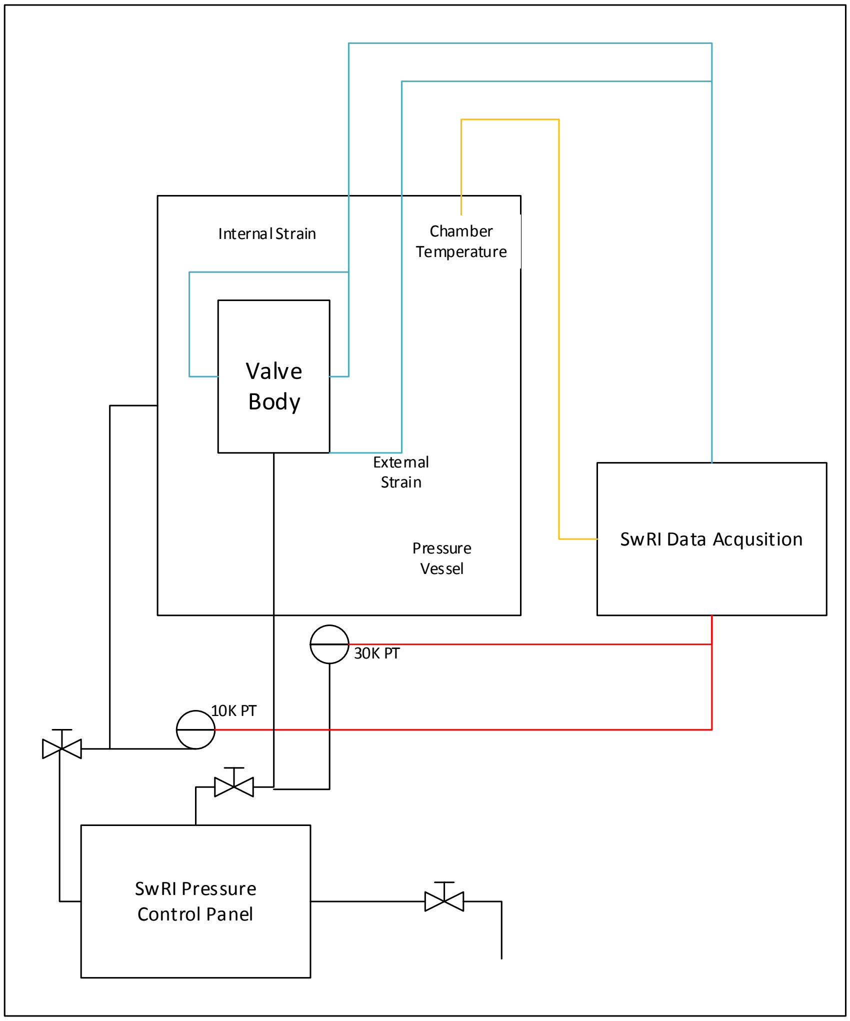


Figure 1: Simplified Hyperbaric Chamber Test Connection Schematic, Orange = Thermocouple Lines, Blue= Strain Gage Lines, Black = Piping or High-Pressure Tubing, Red = Instrumentation Lines.

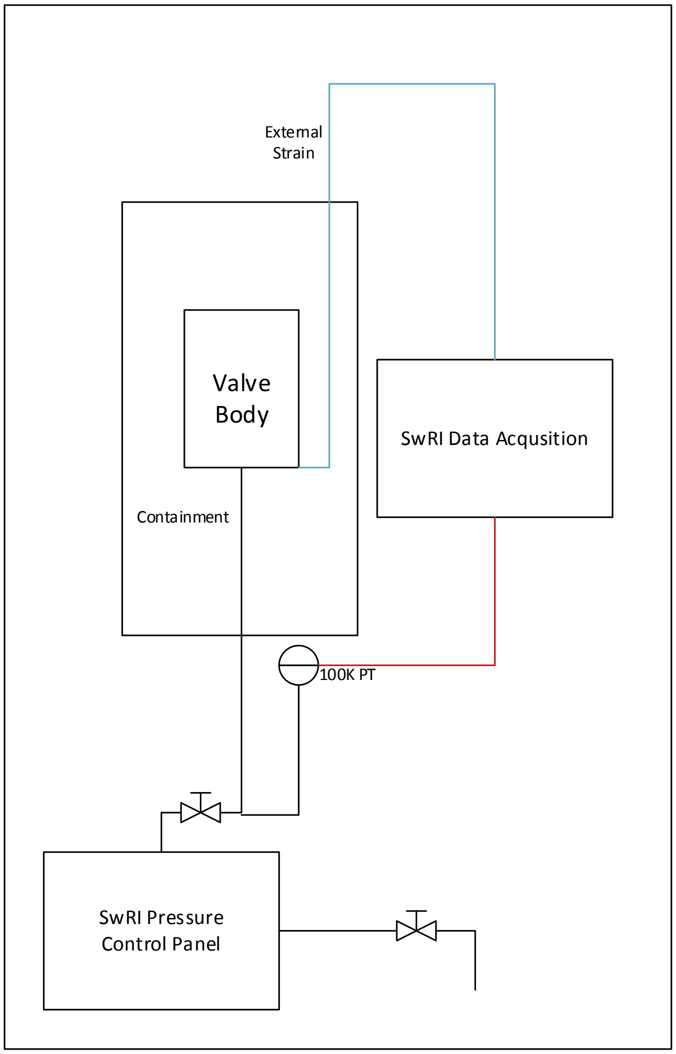


Figure 2: Simplified Burst Test Connection Schematic, **Blue= Strain Gage Lines, Black = Piping or High-Pressure Tubing, Red = Instrumentation Lines.**

3.0 HYDROSTATIC TESTING OF SMALL VALVE BODY

3.1 30,000 psig Hydrostatic Test

After the valve body was set up inside the 50-inch vessel, the body was pressurized in 5,000 psig increments. At each increment, pressure was maintained for two (2) minutes. When 30,000 psig was reached, pressure was maintained for two (2) minutes. Pressure was then vented slowly. No leaks in the valve body were observed during this test. The results of this test are shown in Appendix I.

3.2 Test at MAWP

Following the hydrostatic test, the valve body was tested at 20,000 psig with no external pressure. Pressure was applied in 5,000 psig increments. At each increment, pressure was maintained for two (2) minutes. When 20,000 psig was reached, pressure was maintained for two (2) minutes. Pressure was then vented. No leaks in the valve body were observed during this test. The results of this test are shown in Appendix I.

3.3 Test at MAWP at approximately 5,000 ft Simulated Depth

For this test, the hyperbaric chamber was sealed and filled with water. The chamber was pressurized to 2,222 psig. Pressure was maintained for two (2) minutes. The valve body was then pressurized in 5,000 psig increments. At each increment, pressure was maintained for two (2) minutes. When 22,222 psig was reached, 20,000 psig of differential pressure, pressure was maintained for two (2) minutes. The valve body pressure was then released to 2,222 psig. With both valve body and chamber pressures at 2,222 psig, valve body and chamber pressures were bled to ambient. No leaks in the valve body were observed during this test. The results of this test are shown in Appendix I.

3.4 Test at MAWP at approximately 10,000 ft Simulated Depth

Following the previous test, the chamber was pressurized to 4,444 psig. Pressure was maintained for two (2) minutes. The body was then pressurized in 5,000 psig increments. At each increment, pressure was maintained for two (2) minutes. When 24,444 psig was reached, 20,000 psig of differential pressure, pressure was maintained for two (2) minutes. The valve body pressure was then released to 4,444 psig. With both valve body and chamber pressures at 4,444 psig, body and chamber pressures were bled to ambient. No leaks in the valve body were observed during this test. The results of this test are shown in Appendix I.

4.0 BURST TEST OF SMALL VALVE BODY

4.1 Burst Test

For the burst test, the valve body was secured in an Aiken-provided containment and moved to a remote SwRI test site. Ultra high pressure (¼”) tubing was connected to the valve, as described in Section 2.4. The valve was pressurized continuously until failure. During this test, pressurization was paused periodically to guarantee that appropriate air pressure was being supplied to the high pressure pump. The maximum pressure reached during the test was 51,469 psig. As the material yielded, pressure decreased. The pressure at failure was 42,414 psig. The results of this test are shown in Appendix I.

5.0 HYDROSTATIC TEST OF LARGE VALVE BODY

5.1 Hydrostatic Tests

All tests outlined in Sections 3.1 through 3.4 were repeated for the large valve body. No leaks in the valve body were observed during testing. The results of these tests are shown in Appendix I.

6.0 BURST TEST OF LARGE VALVE BODY

6.1 Burst Test

For the burst test, the valve body was secured in an Aiken-provided containment and moved to a remote SwRI test site. Ultra high pressure (¼”) tubing was connected to the valve, as described in Section 2.4. The valve was pressurized continuously until failure. The maximum pressure reached during testing was 67,959 psig. As the material yielded, pressure decreased. The pressure at failure was 60,058 psig. The results of this test are shown in Appendix I.

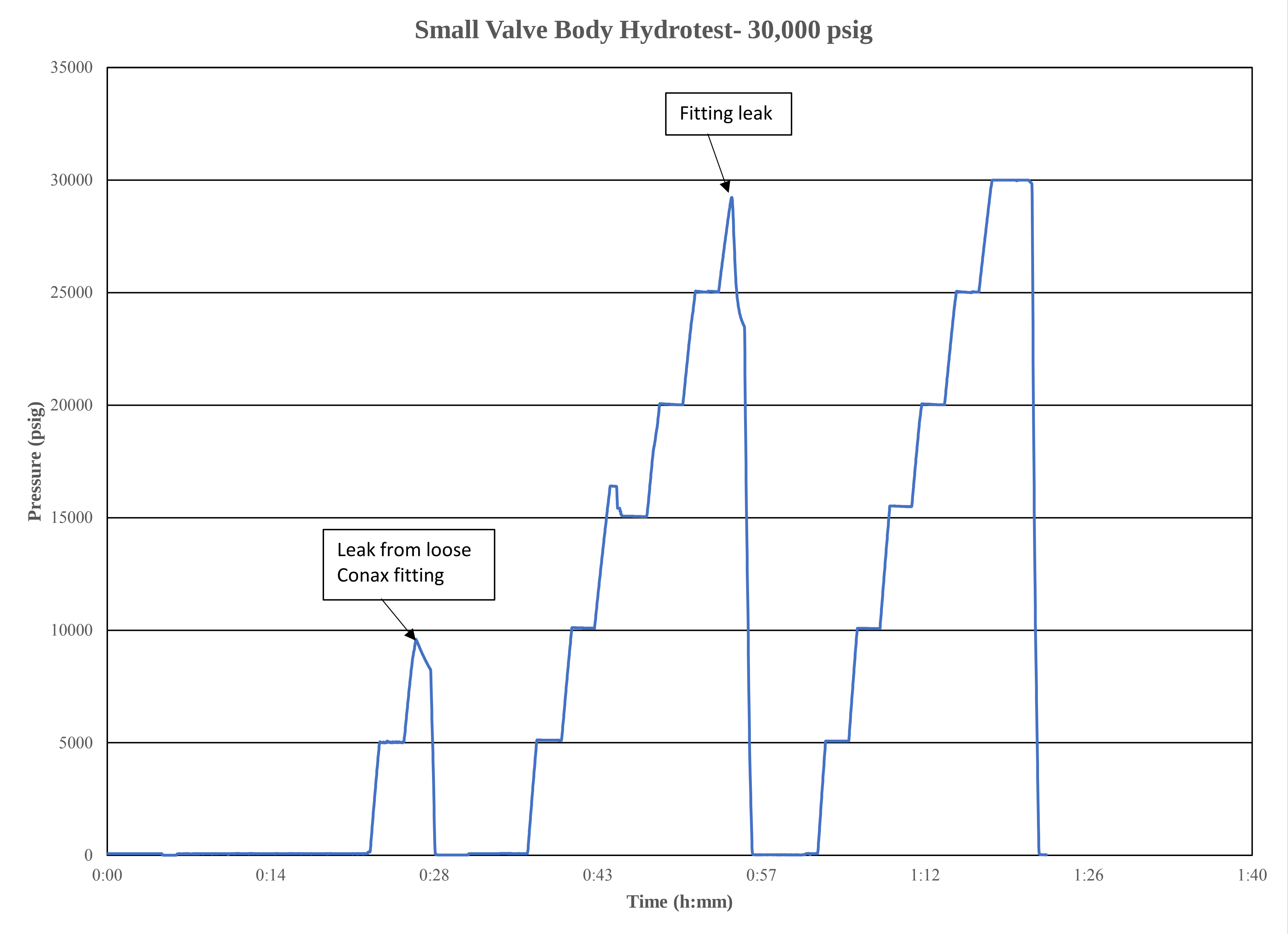
7.0 STRAIN GAGE RESULTS

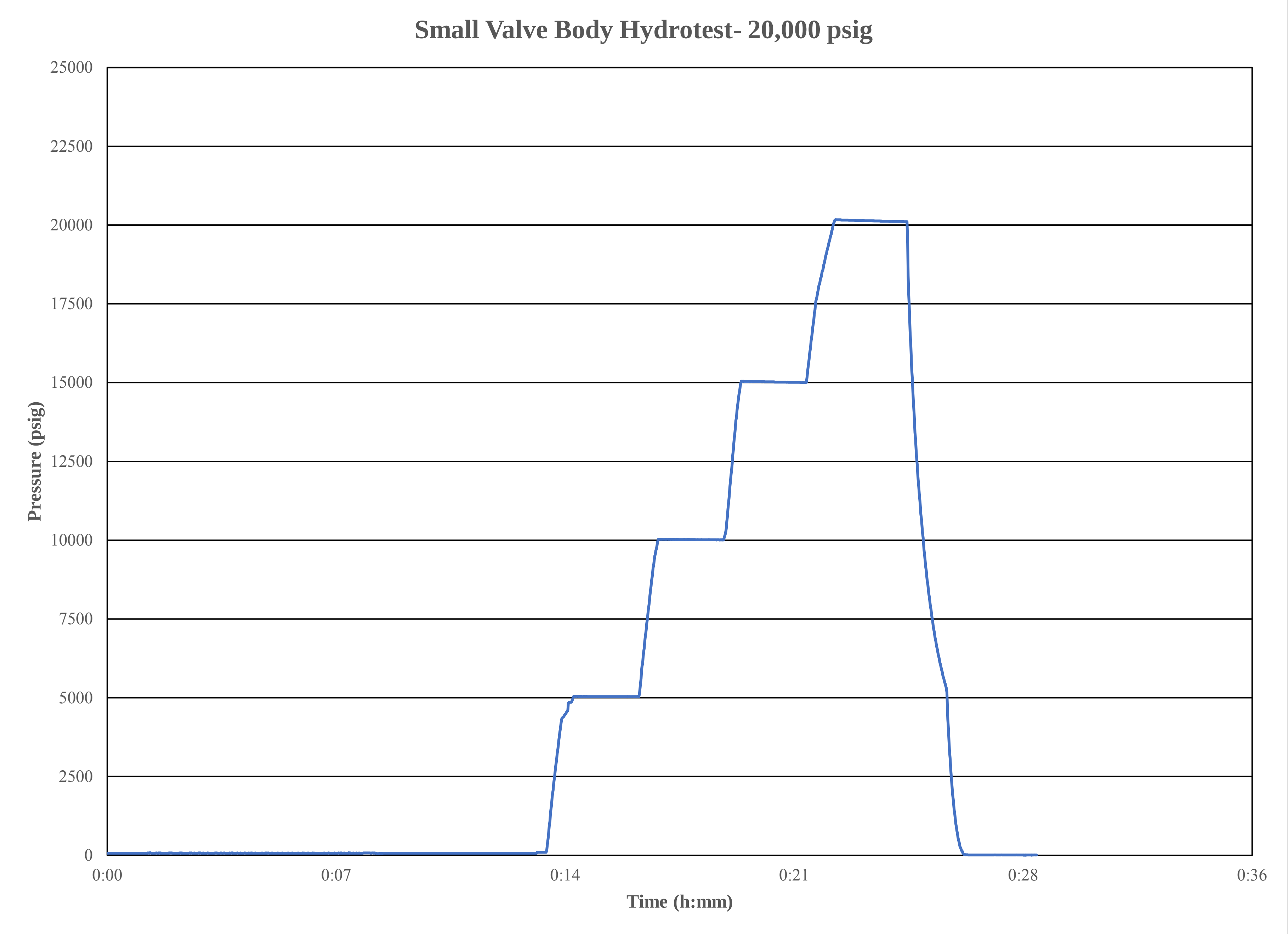
On the small valve body, two strain channels experienced signal loss during testing. The internal calibration block experienced signal loss during the 30,000 psig hydrostatic test. The gage at location 2B in the hoop direction was lost during the test at MAWP and a simulated depth of 5,000 ft. On the large valve body, the internal calibration block experienced signal loss during the test at MAWP and a simulated depth of 10,000 ft. All internal strain gages and calibration blocks were disconnected before the burst test. Plots showing the strain data for each element are included in Appendix I.

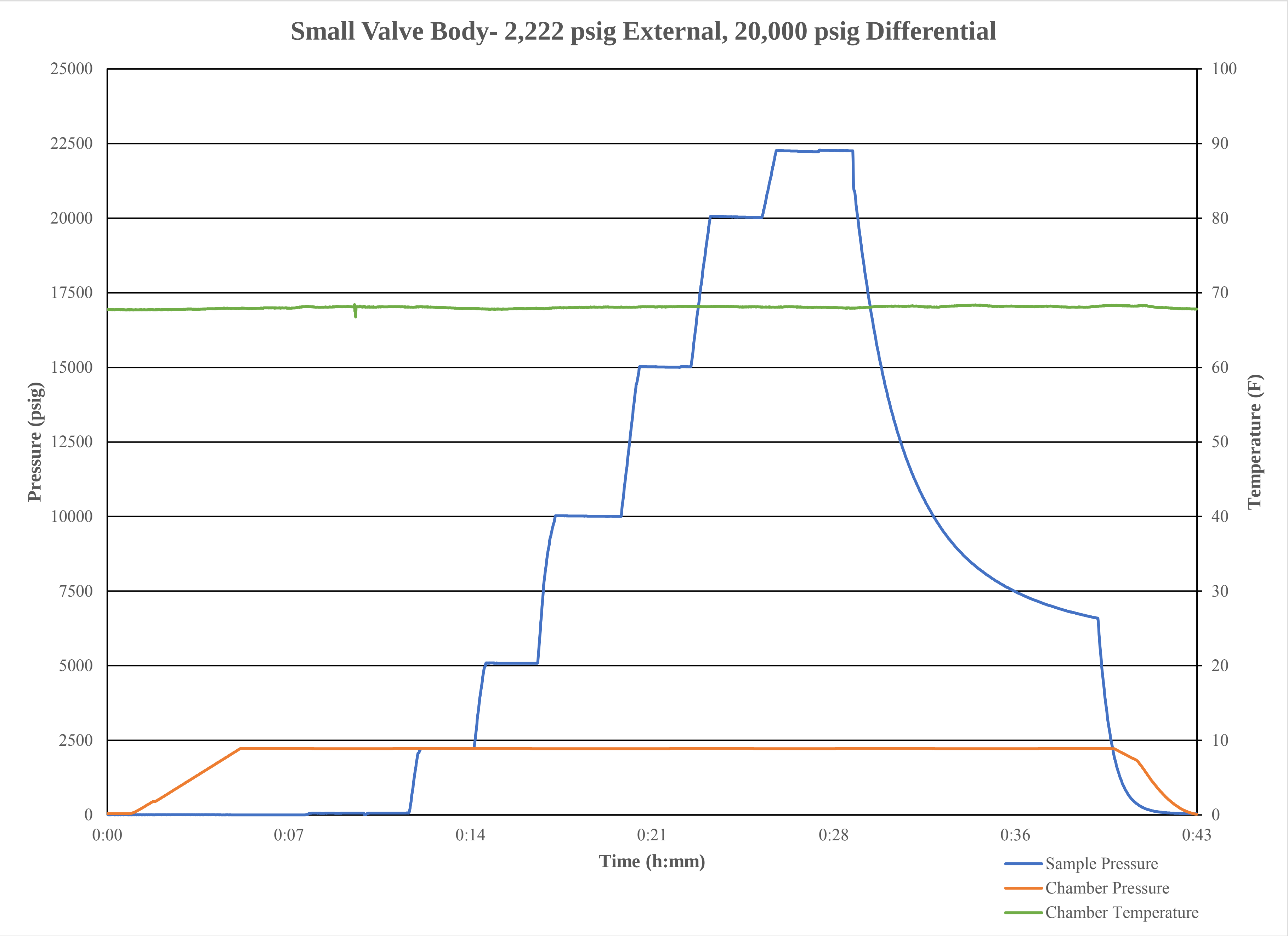
APPENDIX I

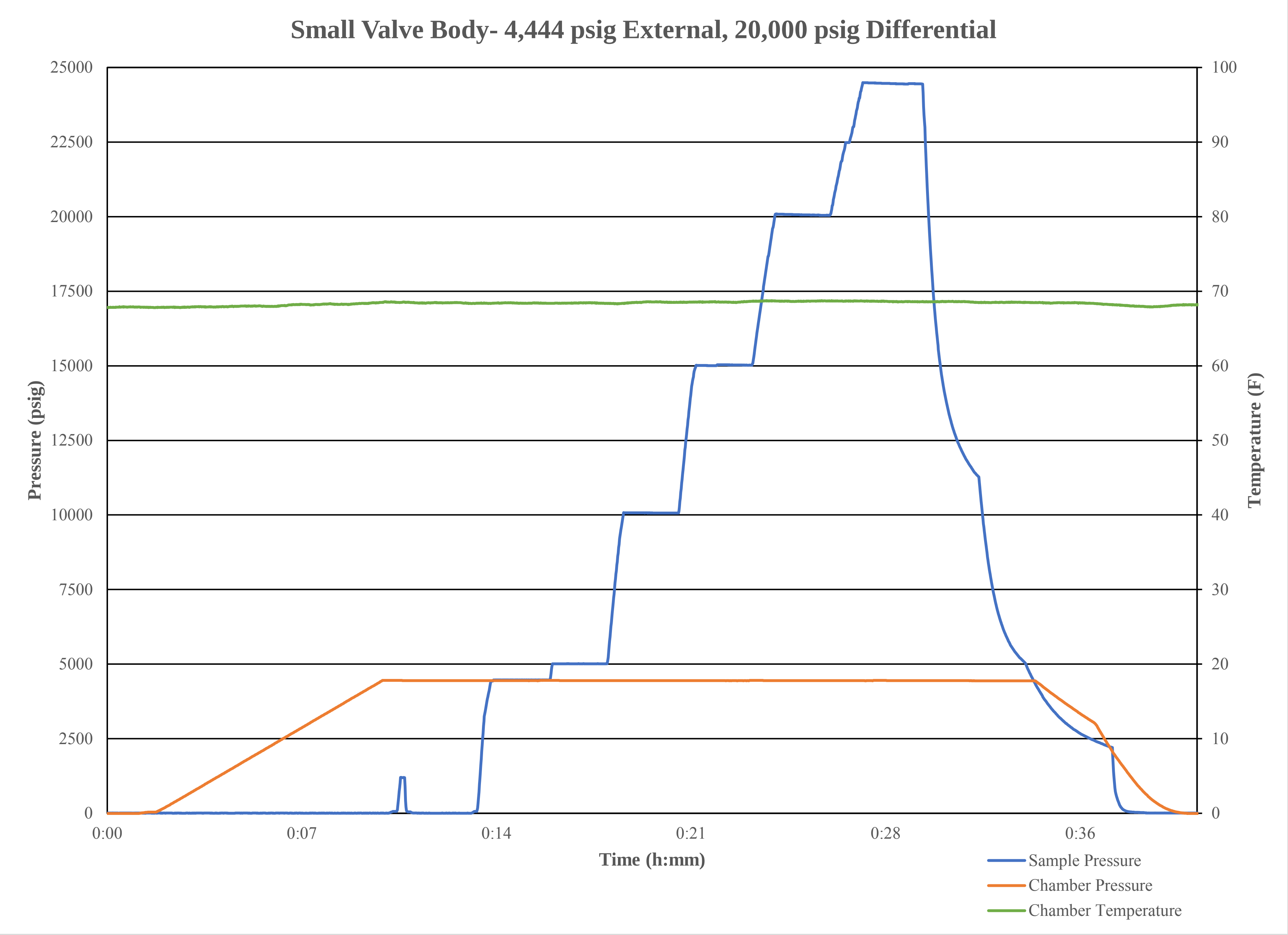
TEST DATA

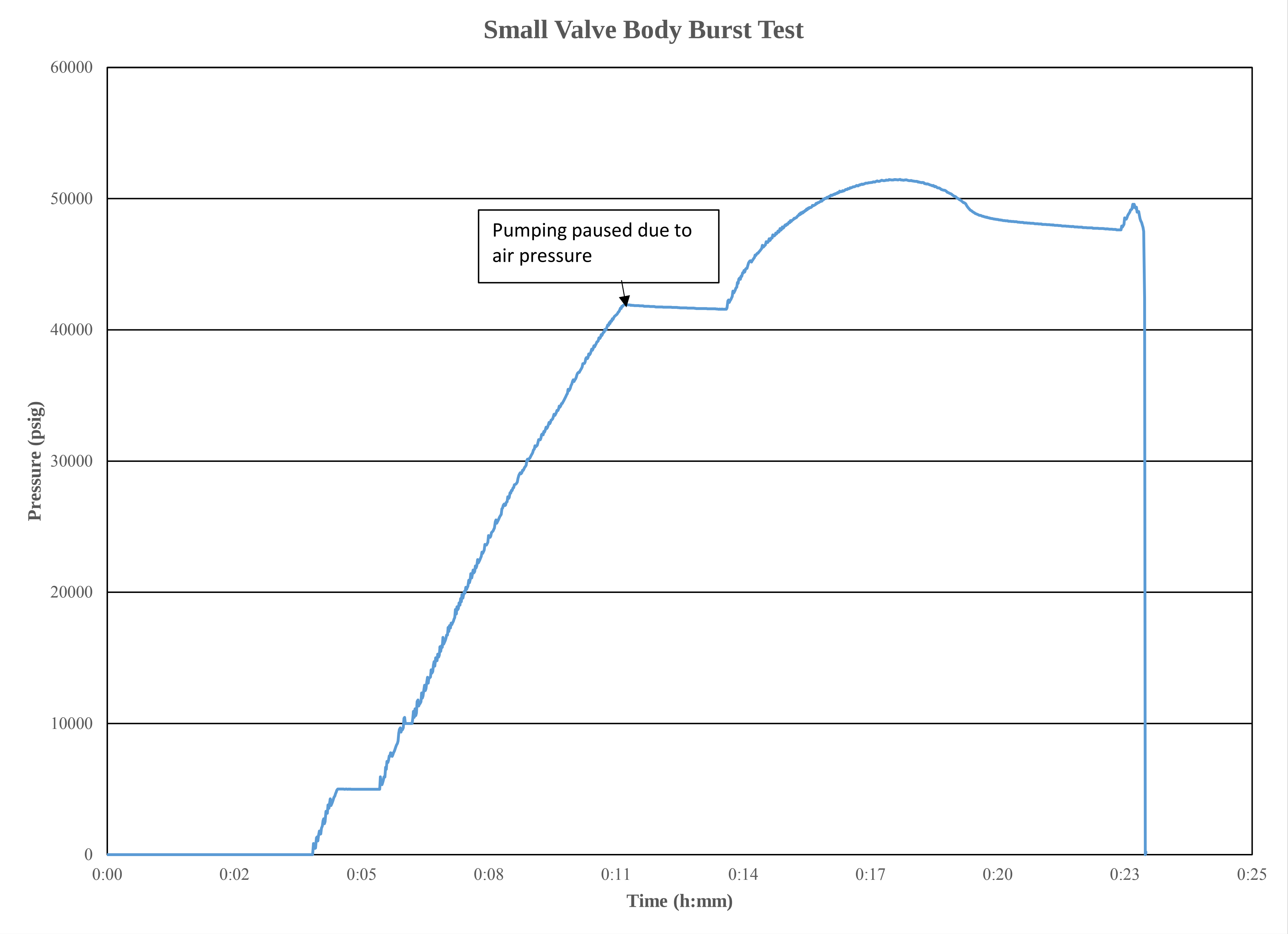
SMALL VALVE BODY
PRESSURE DATA


Small Valve Body Hydrotest- 30,000 psig
Fitting leak
Leak from loose Conax fitting
Pressure (psig)
35000
30000
25000
20000
15000
10000
5000
0
0:00
0:14
0:28
0:43
0:57
1:12
1:26
1:40
Time (h:mm)

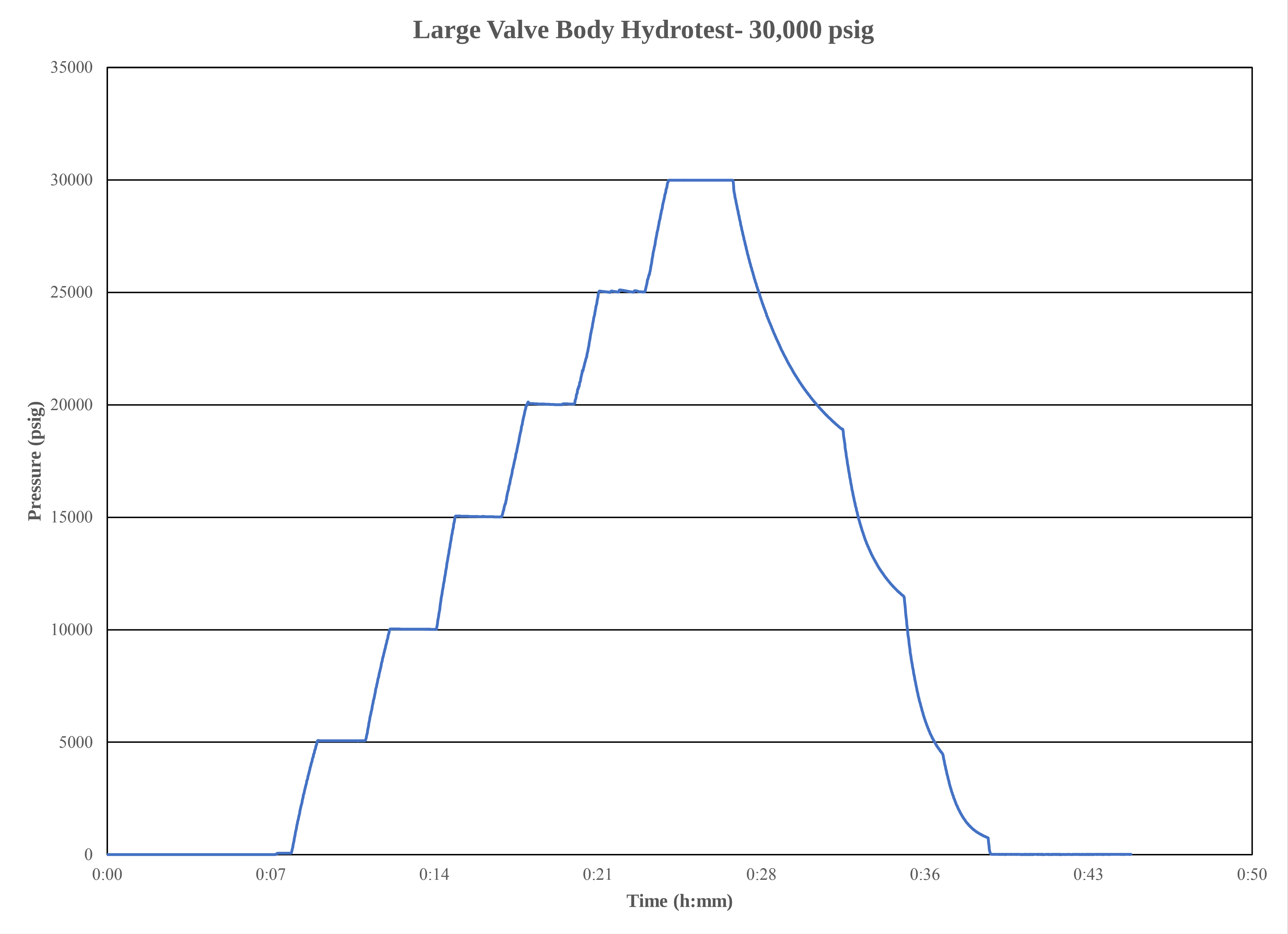

Small Valve Body Hydrotest- 20,000 psig
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Pressure (psig)
0:00
0:07
0:14
0:21
0:28
0:36
Time (h:mm)

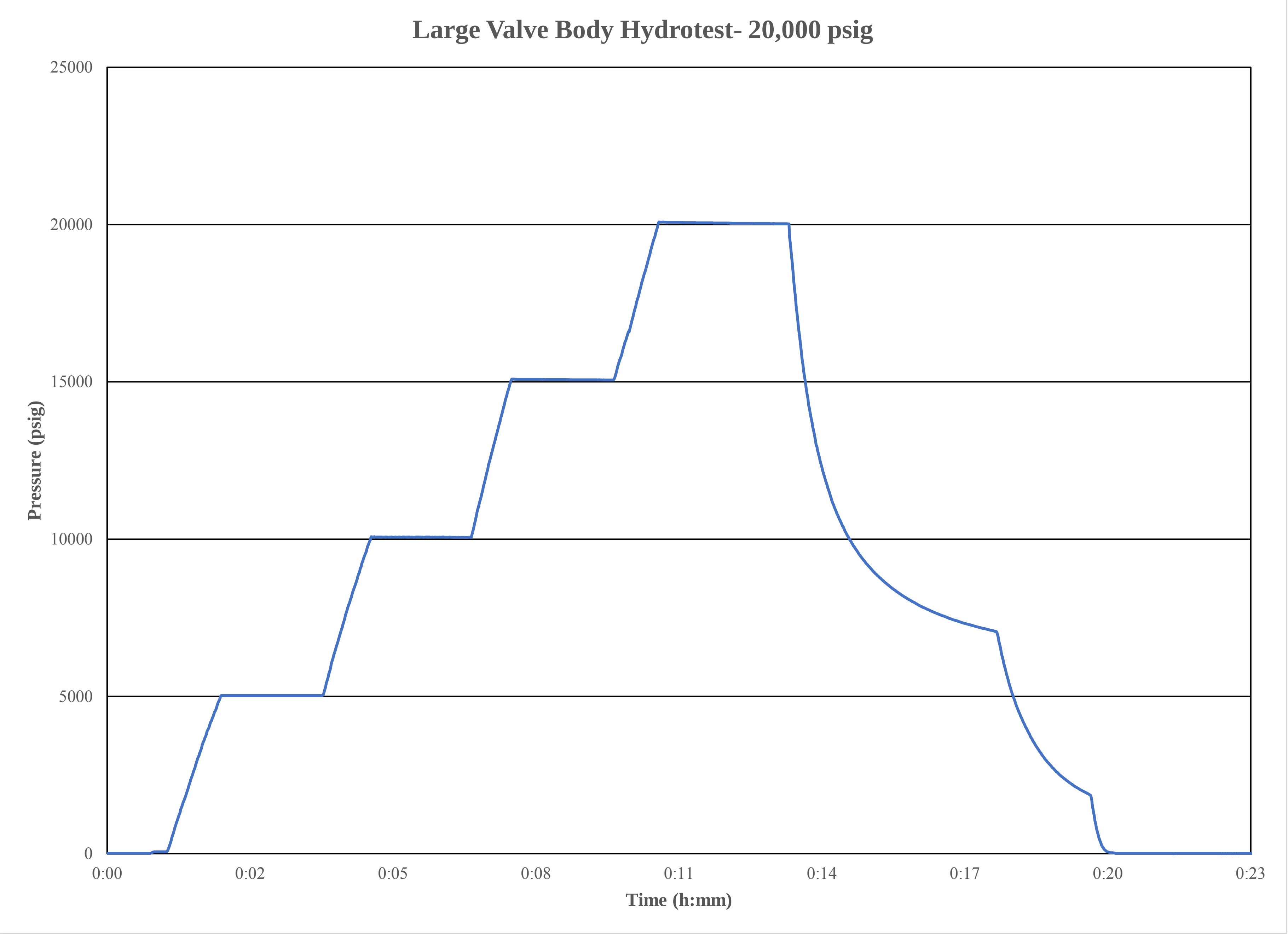

Small Valve Body- 2,222 psig External, 20,000 psig Differential
Pressure (psig)
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Temperature (F)
100
90
80
70
60
50
40
30
20
10
0
0:00
0:07
0:14
0:21
0:28
0:36
0:43
Time (h:mm)
Sample Pressure
Chamber Pressure
Chamber Temperature

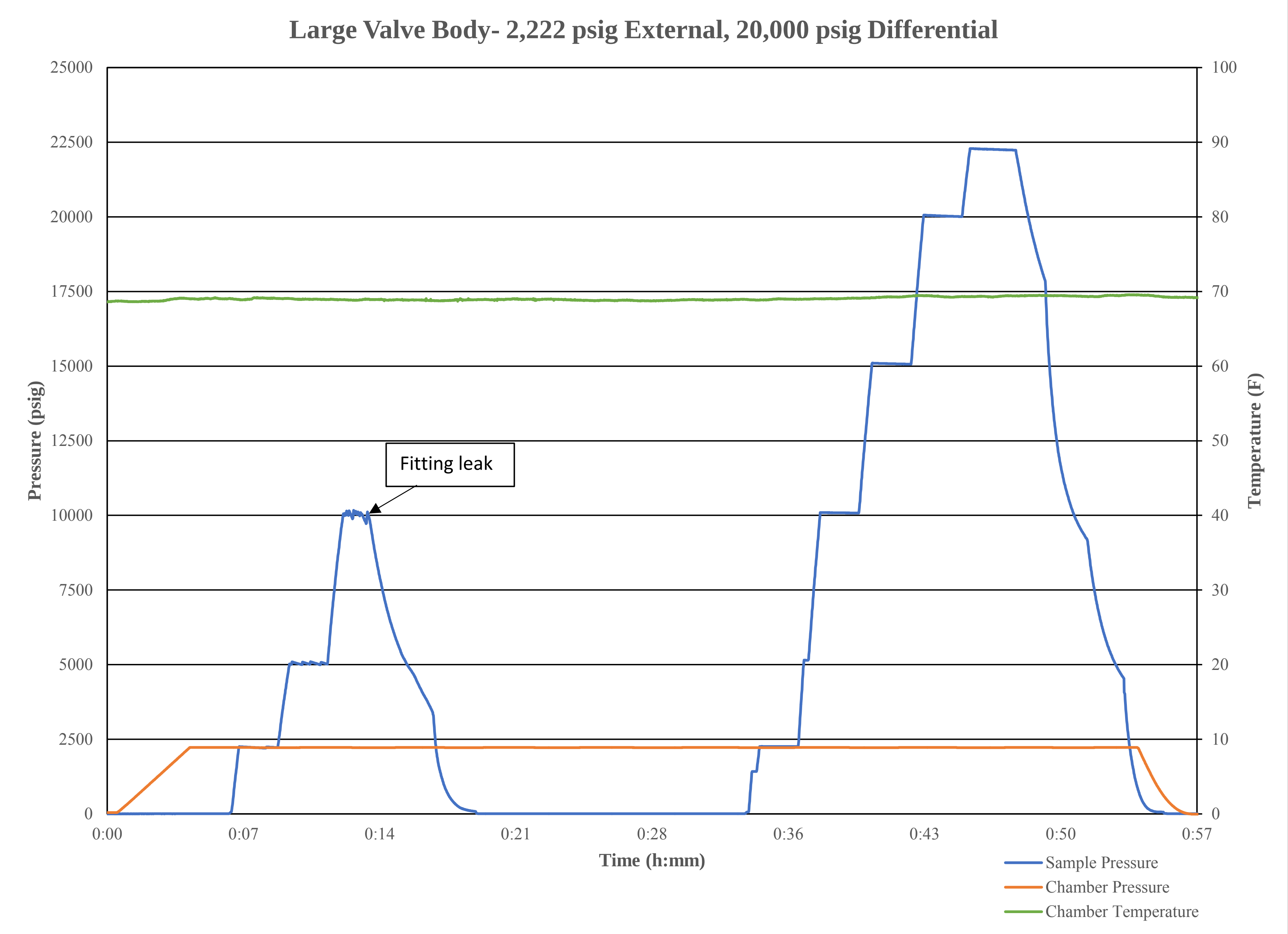

Small Valve Body- 4,444 psig External, 20,000 psig Differential
Pressure (psig)
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Temperature (F)
100
90
80
70
60
50
40
30
20
10
0
0:00
0:07
0:14
0:21
0:28
0:36
Time (h:mm)
Sample Pressure
Chamber Pressure
Chamber Temperature

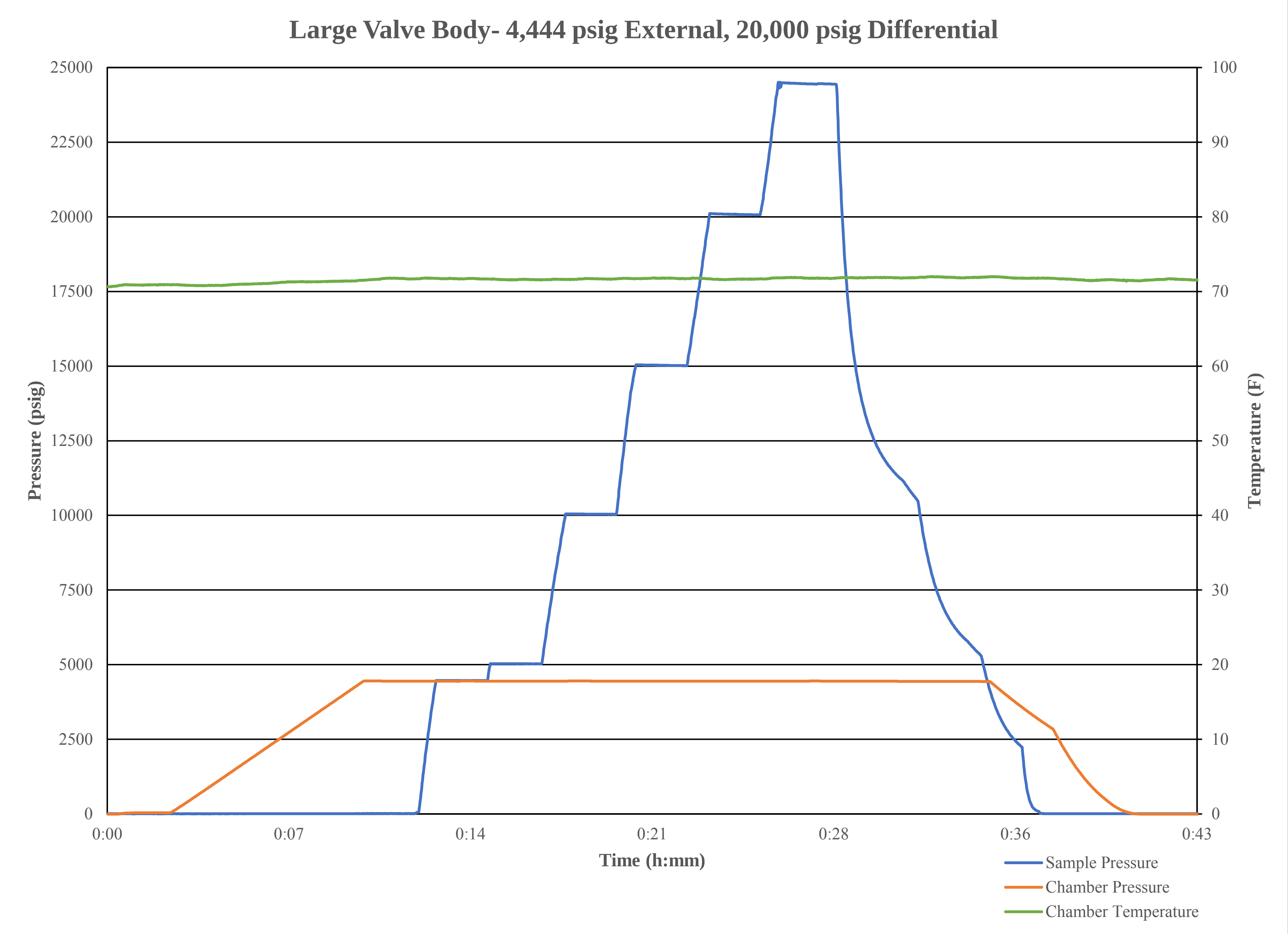

Small Valve Body Burst Test
Pumping paused due to air pressure
Pressure (psig)
60000
50000
40000
30000
20000
10000
0
0:00
0:02
0:05
0:08
0:11
0:14
0:17
0:20
0:23
0:25
Time (h:mm)

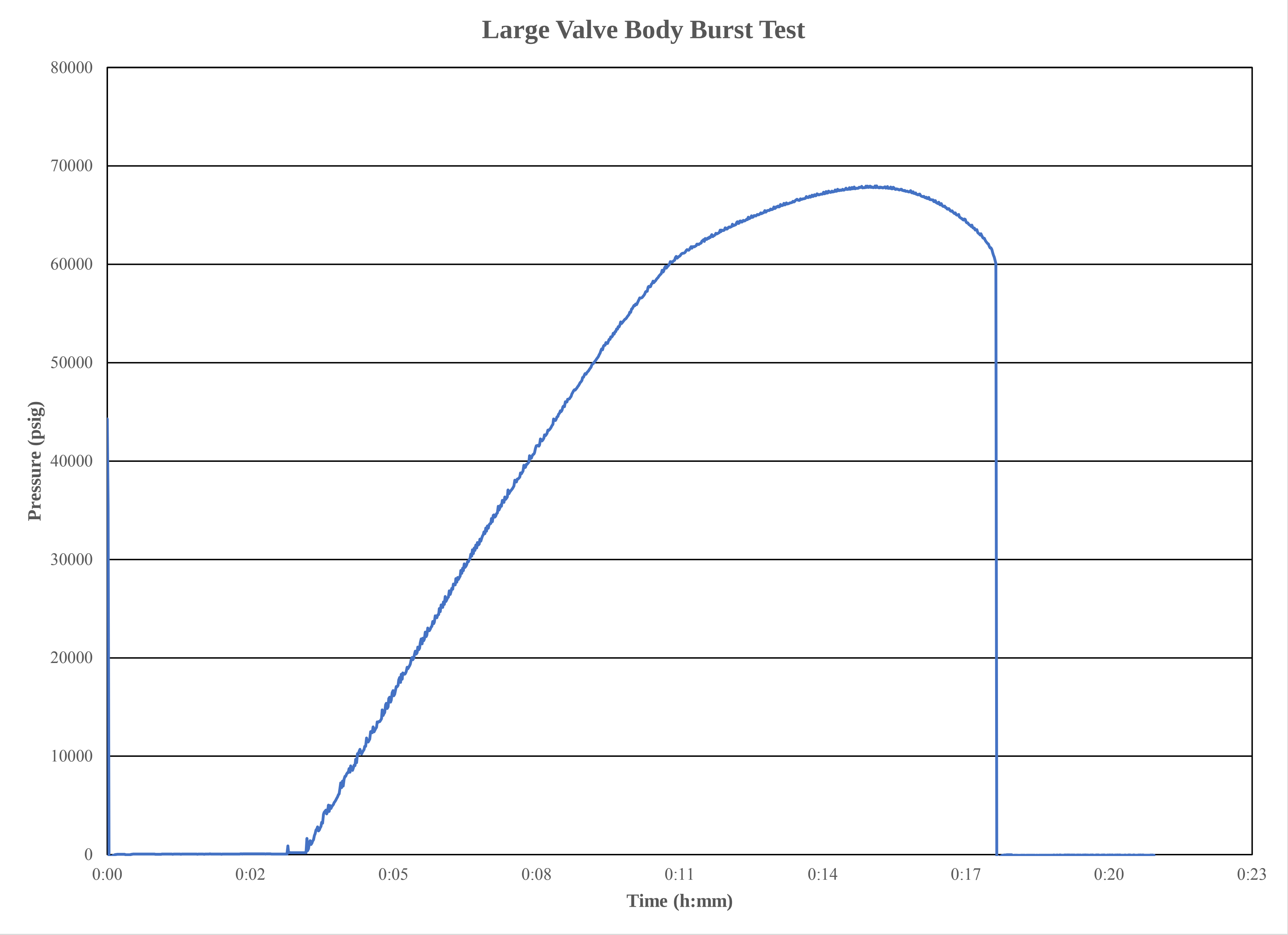
LARGE VALVE BODY
PRESSURE DATA


Large Valve Body Hydrotest- 30,000 psig
Pressure (psig)
35000
30000
25000
20000
15000
10000
5000
0
0:00
0:07
0:14
0:21
0:28
0:36
0:43
0:50
Time (h:mm)


Large Valve Body Hydrotest- 20,000 psig
25000
20000
15000
10000
5000
0
Pressure (psig)
0:00
0:02
0:05
0:08
0:11
0:14
0:17
0:20
0:23
Time (h:mm)

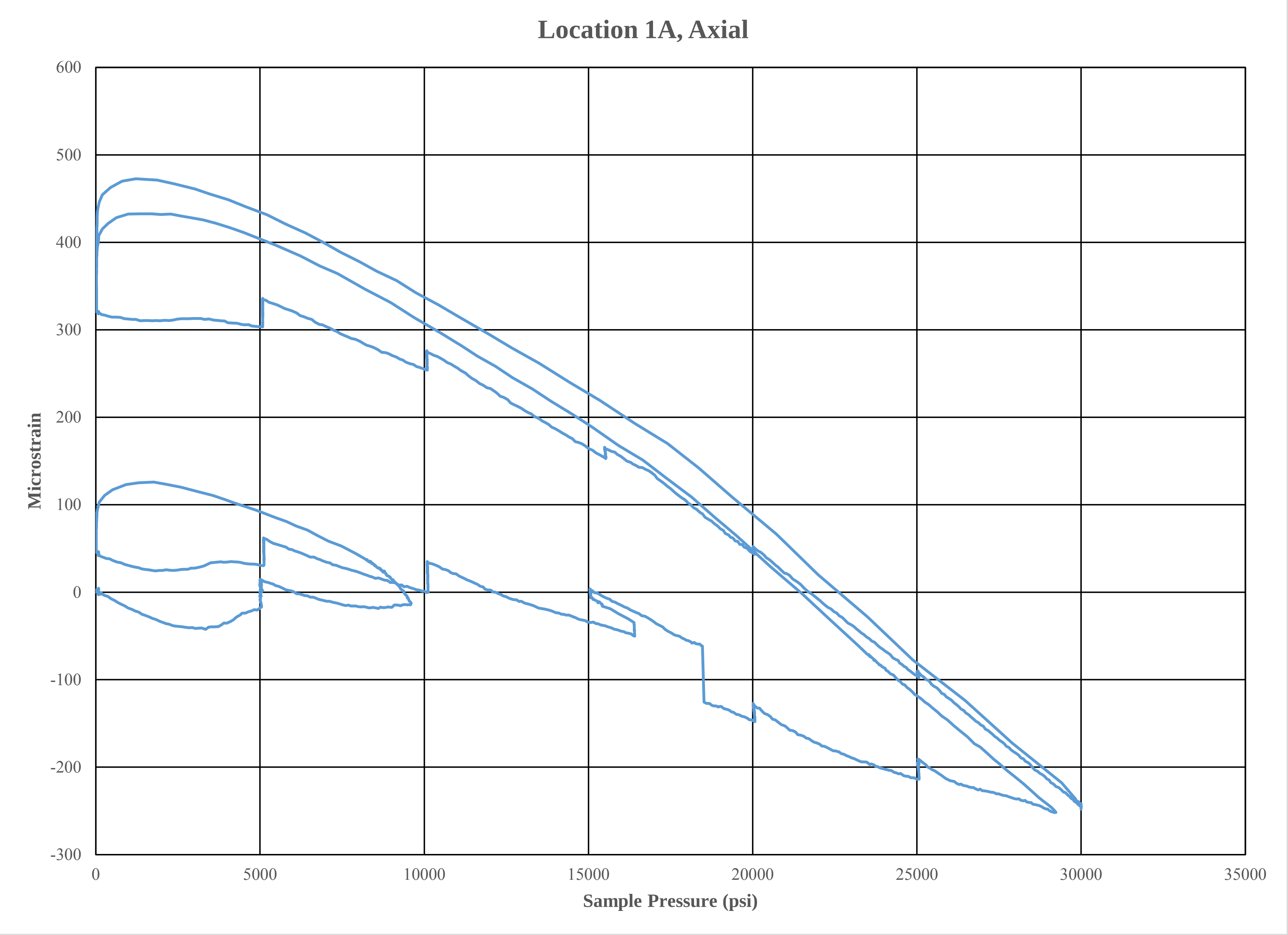

Large Valve Body- 2,222 psig External, 20,000 psig Differential
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Pressure (psig)
100
90
80
70
60
50
40
30
20
10
0
Temperature (F)
0:00
0:07
0:14
0:21
0:28
0:36
0:43
0:50
0:57
Time (h:mm)
Fitting leak
Sample Pressure
Chamber Pressure
Chamber Temperature


Large Valve Body- 4,444 psig External, 20,000 psig Differential
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Pressure (psig)
100
90
80
70
60
50
40
30
20
10
0
Temperature (F)
0:00
0:07
0:14
0:21
0:28
0:36
0:43
Time (h:mm)
Sample Pressure
Chamber Pressure
Chamber Temperature

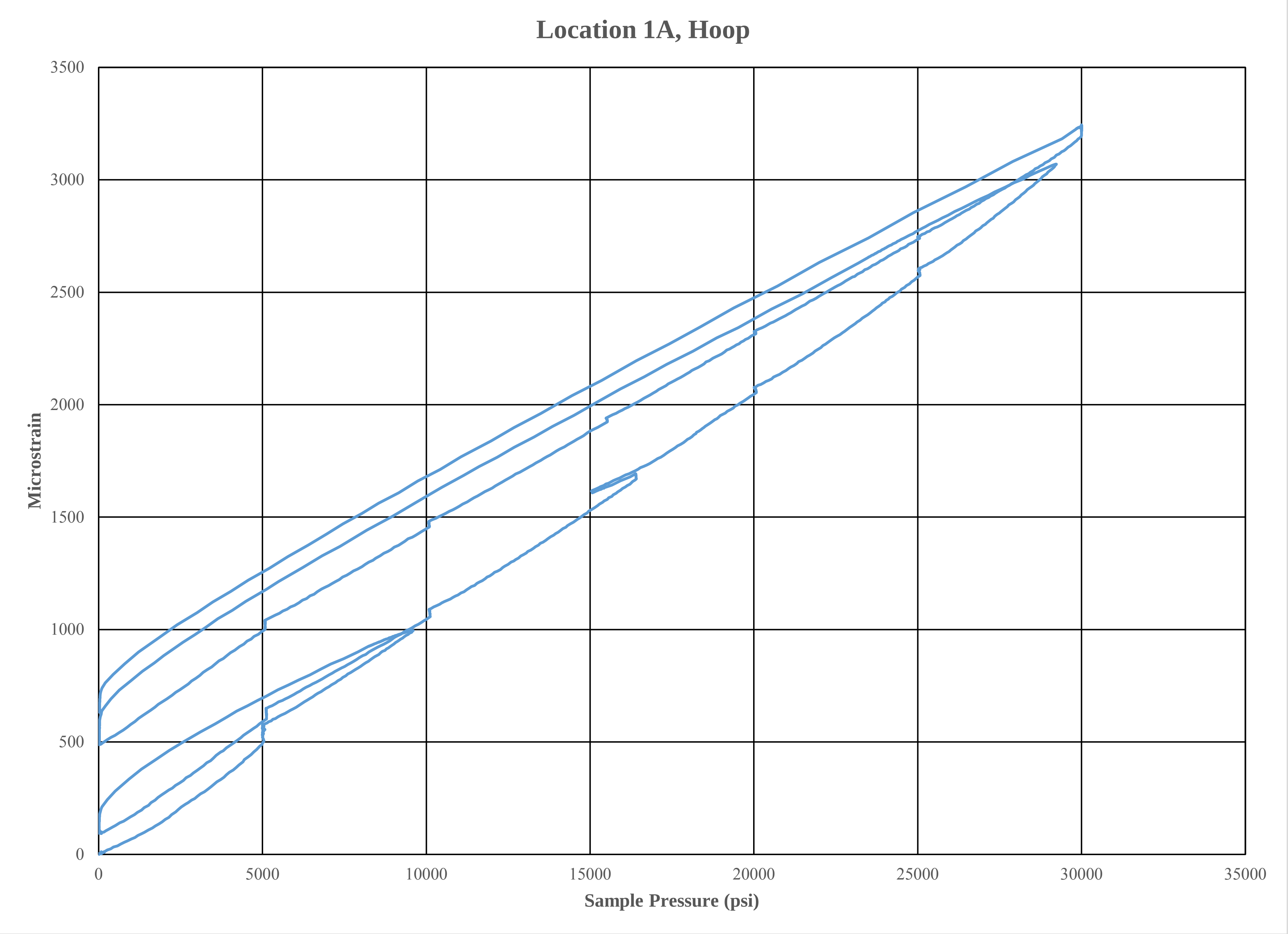

Large Valve Body Burst Test
Pressure (psig)
80000
70000
60000
50000
40000
30000
20000
10000
0
0:00
0:02
0:05
0:08
0:11
0:14
0:17
0:20
0:23
Time (h:mm)

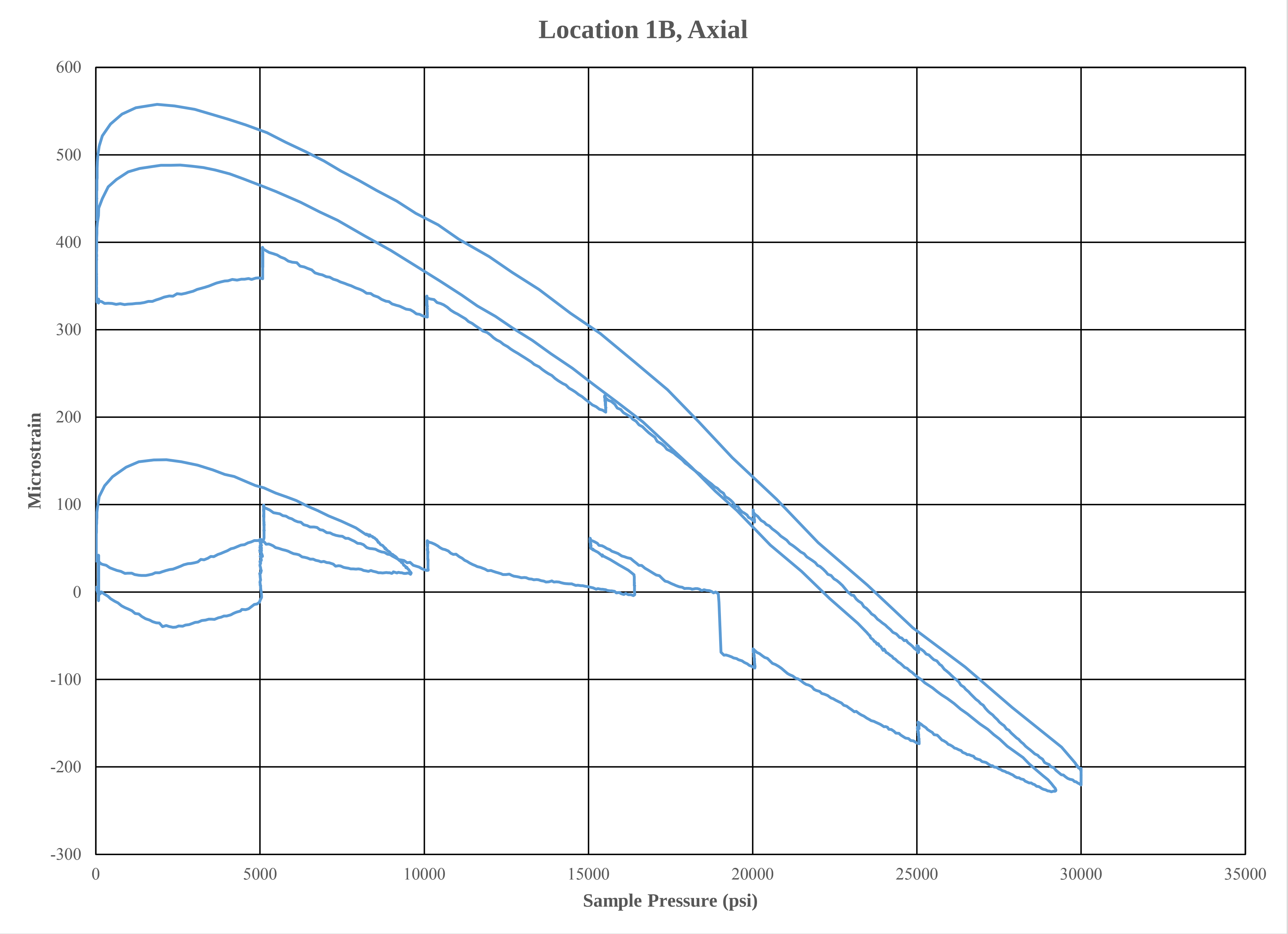
STRAIN DATA- SMALL VALVE BODY

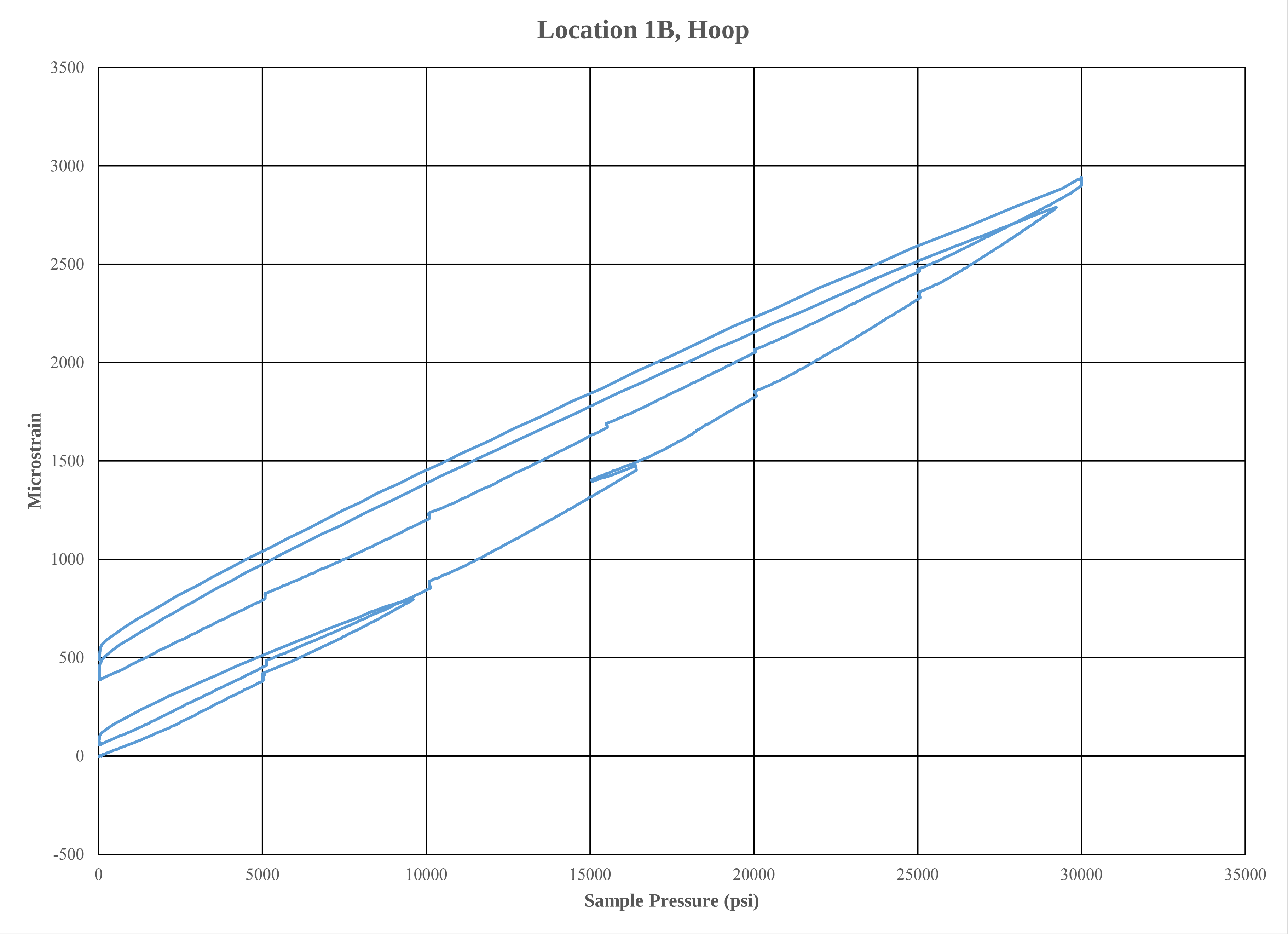
30,000 PSIG HYDROSTATIC TEST

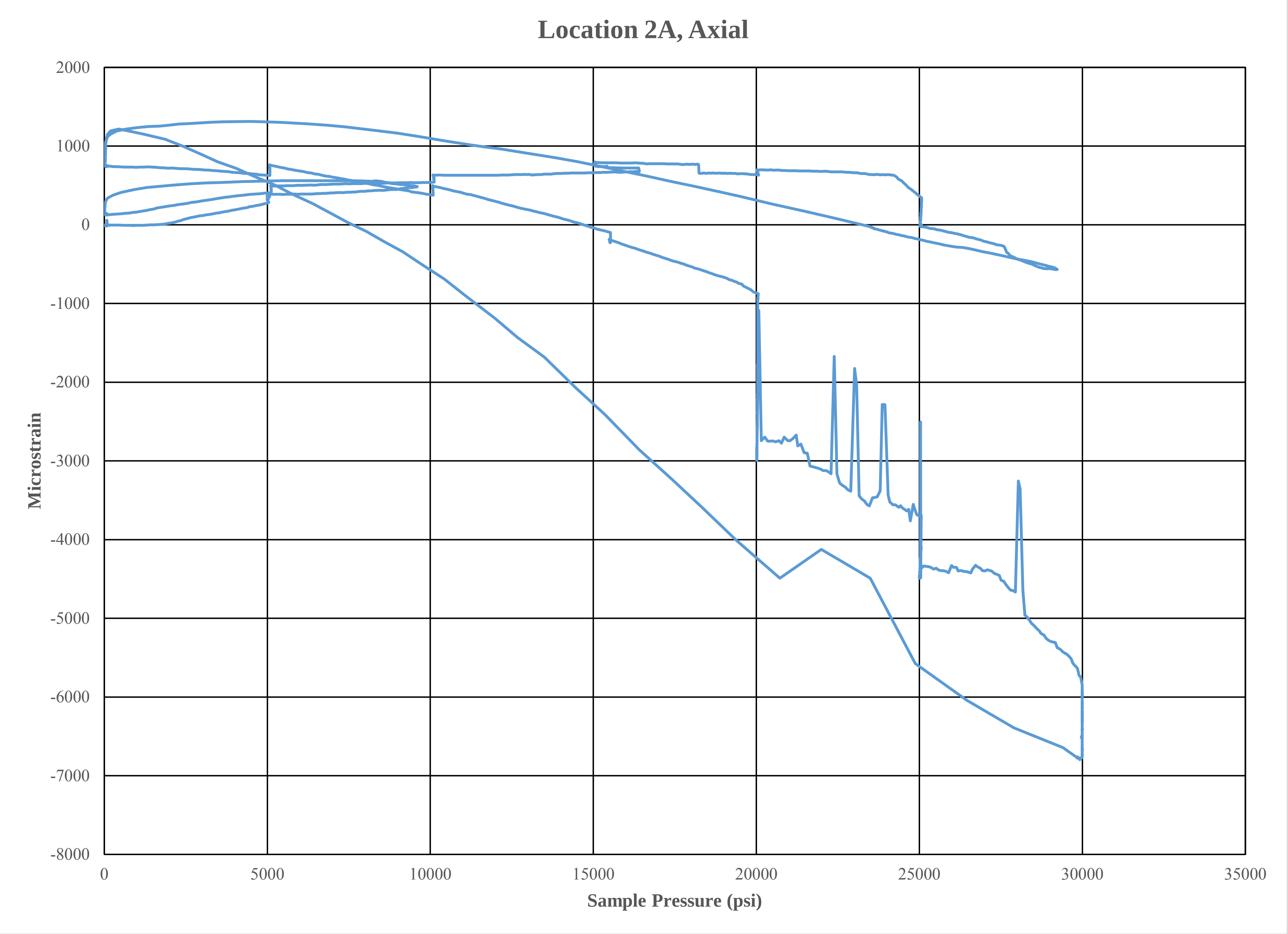


Location 1A, Axial
600
500
400
300
200
100
0
-100
-200
-300
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

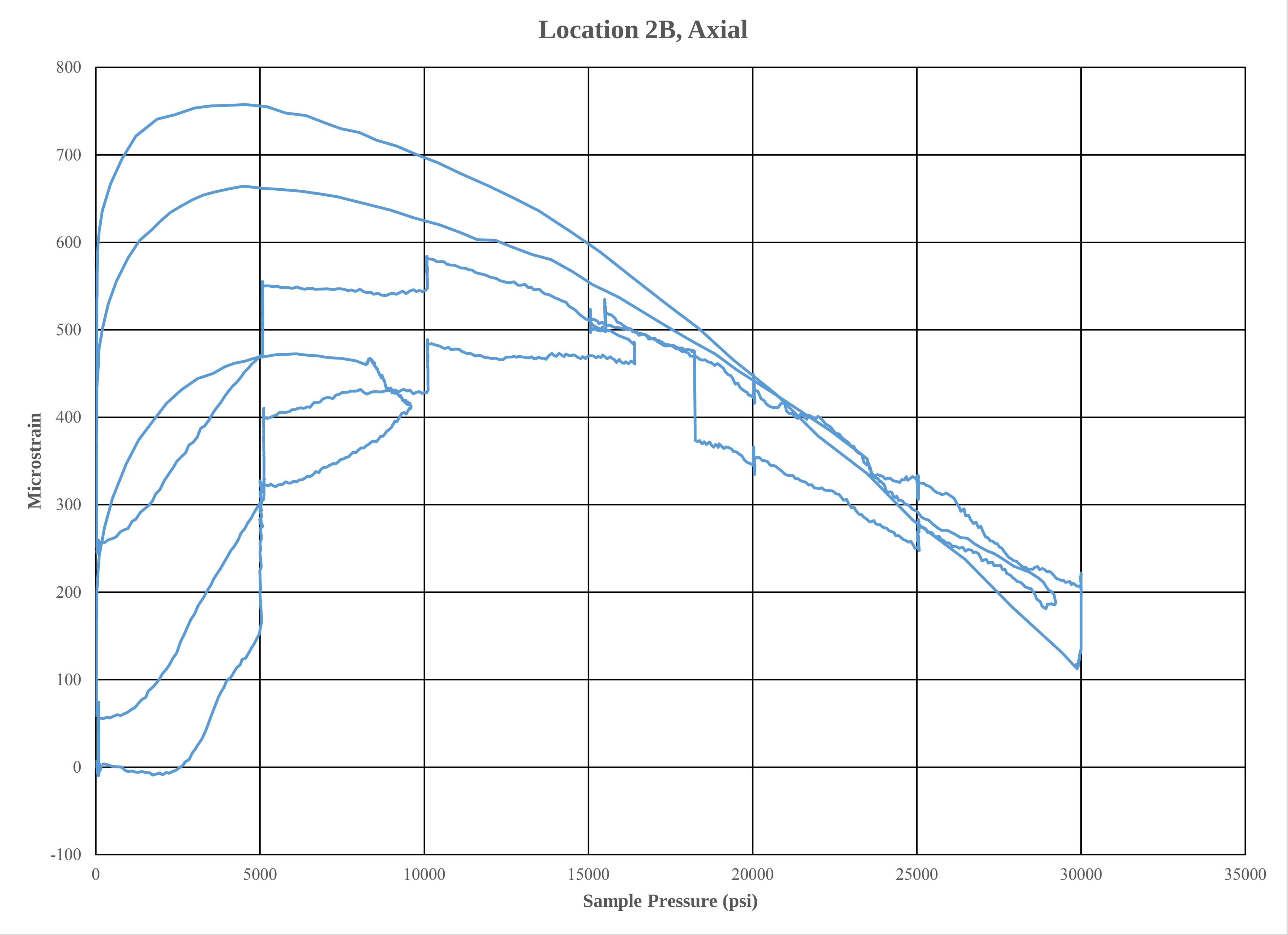

Location 1A, Hoop
Microstrain
0
500
1000
1500
2000
2500
3000
3500
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

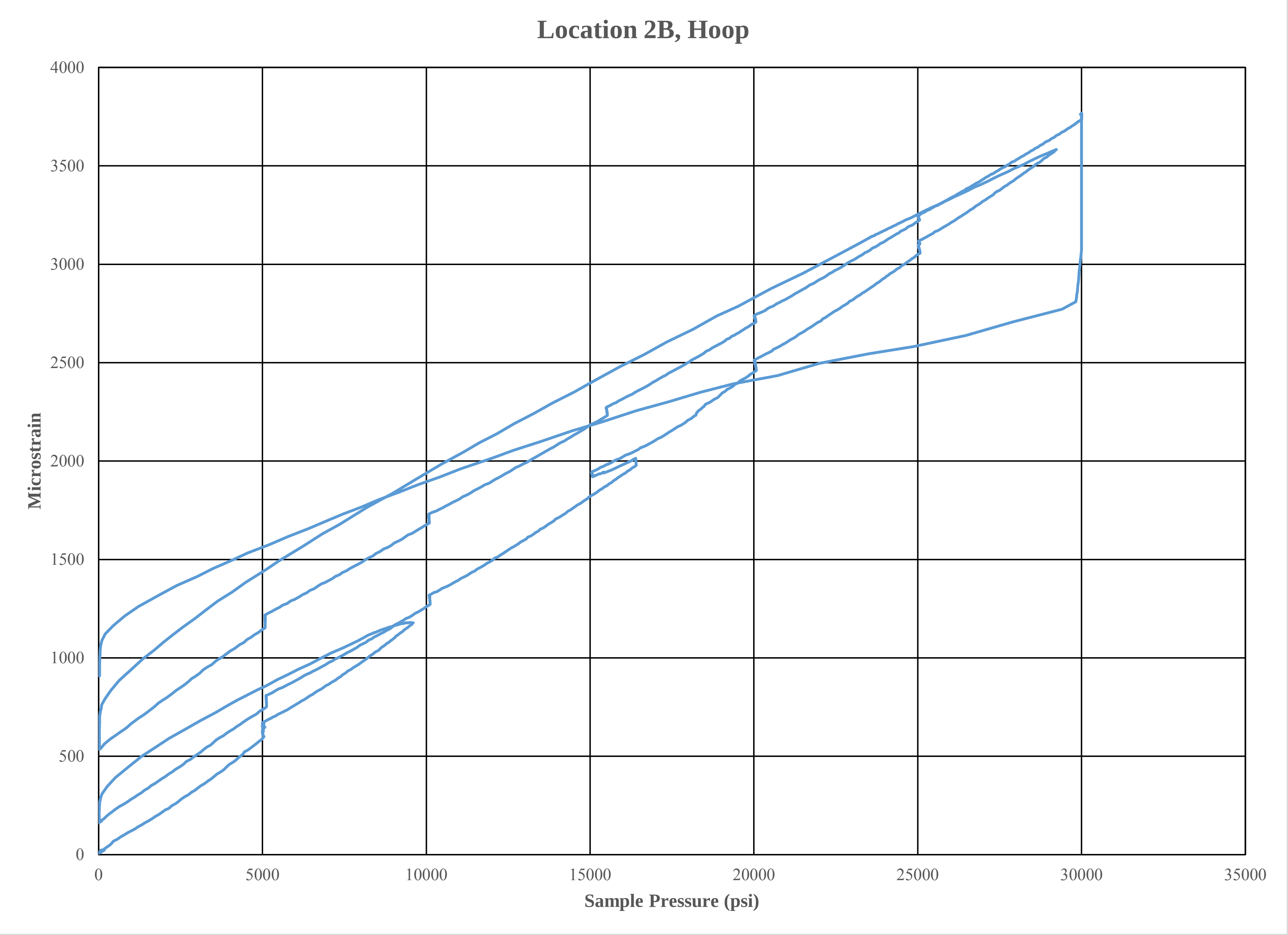

Location 1B, Axial
Microstrain
600
500
400
300
200
100
0
-100
-200
-300
Sample Pressure (psi)
0
5000
10000
15000
20000
25000
30000
35000


Location 1B, Hoop
Microstrain
3500
3000
2500
2000
1500
1000
500
0
-500
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

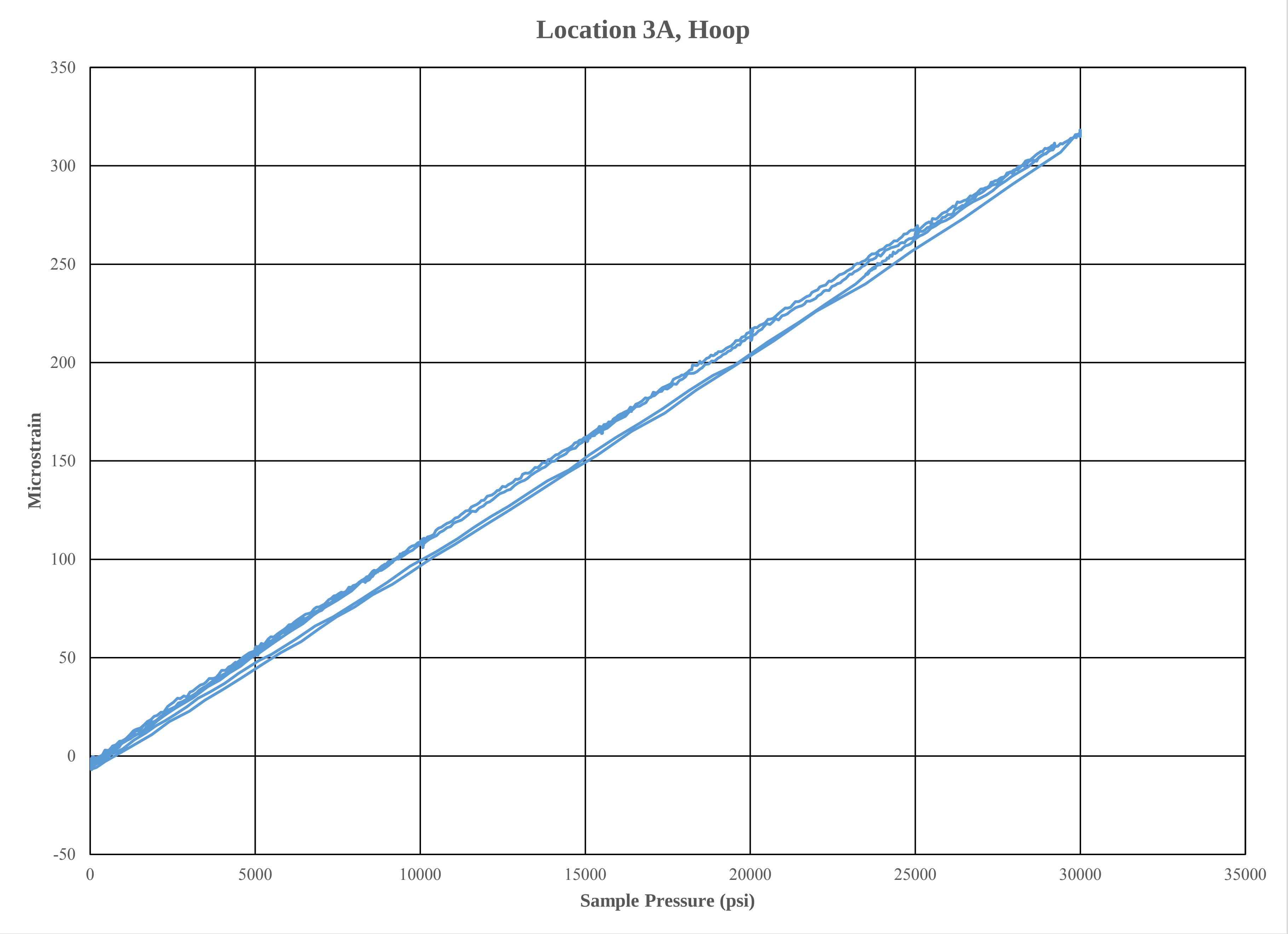

Location 2A, Axial
Microstrain
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

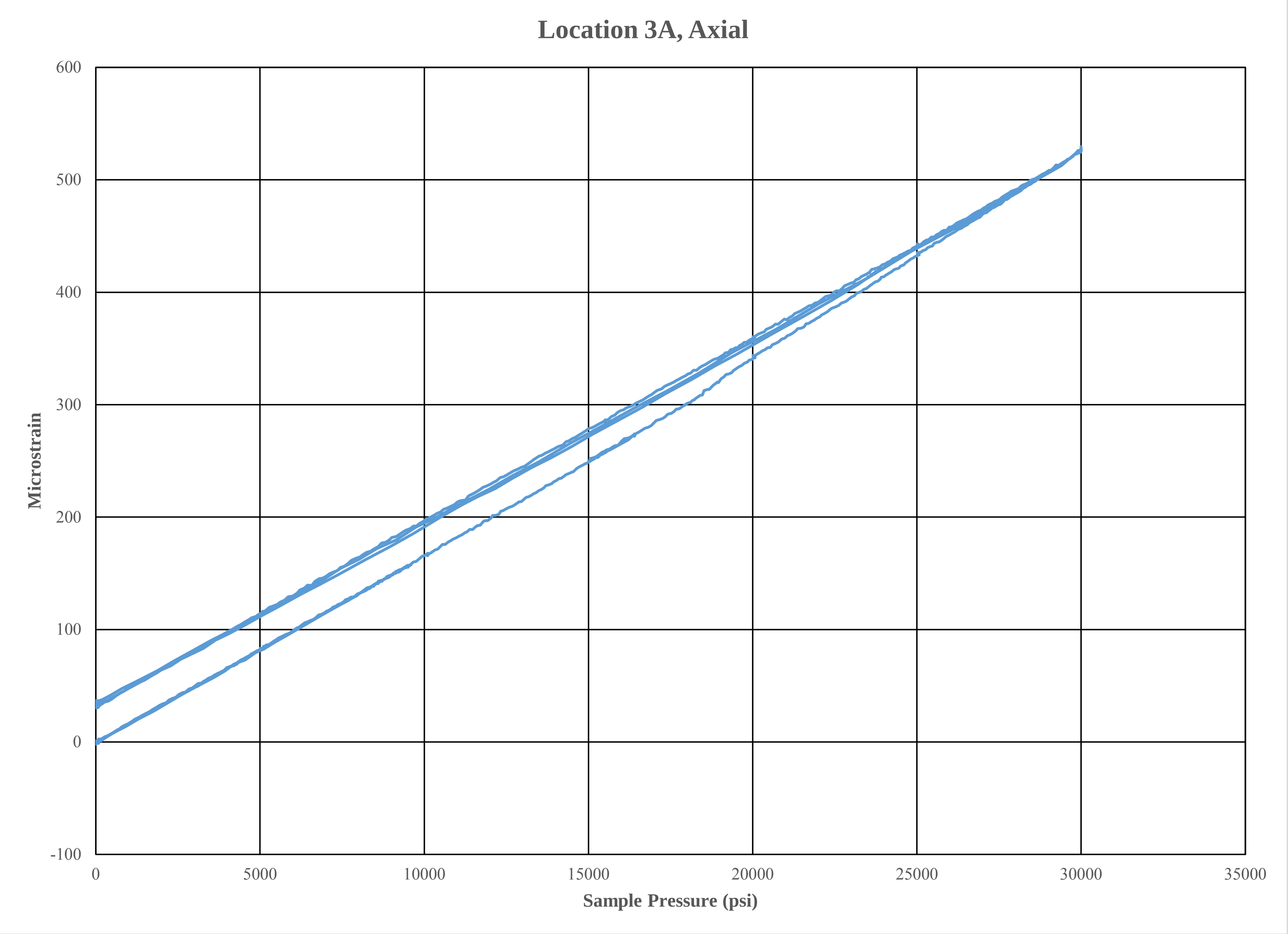

Location 2A, Hoop
Microstrain
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

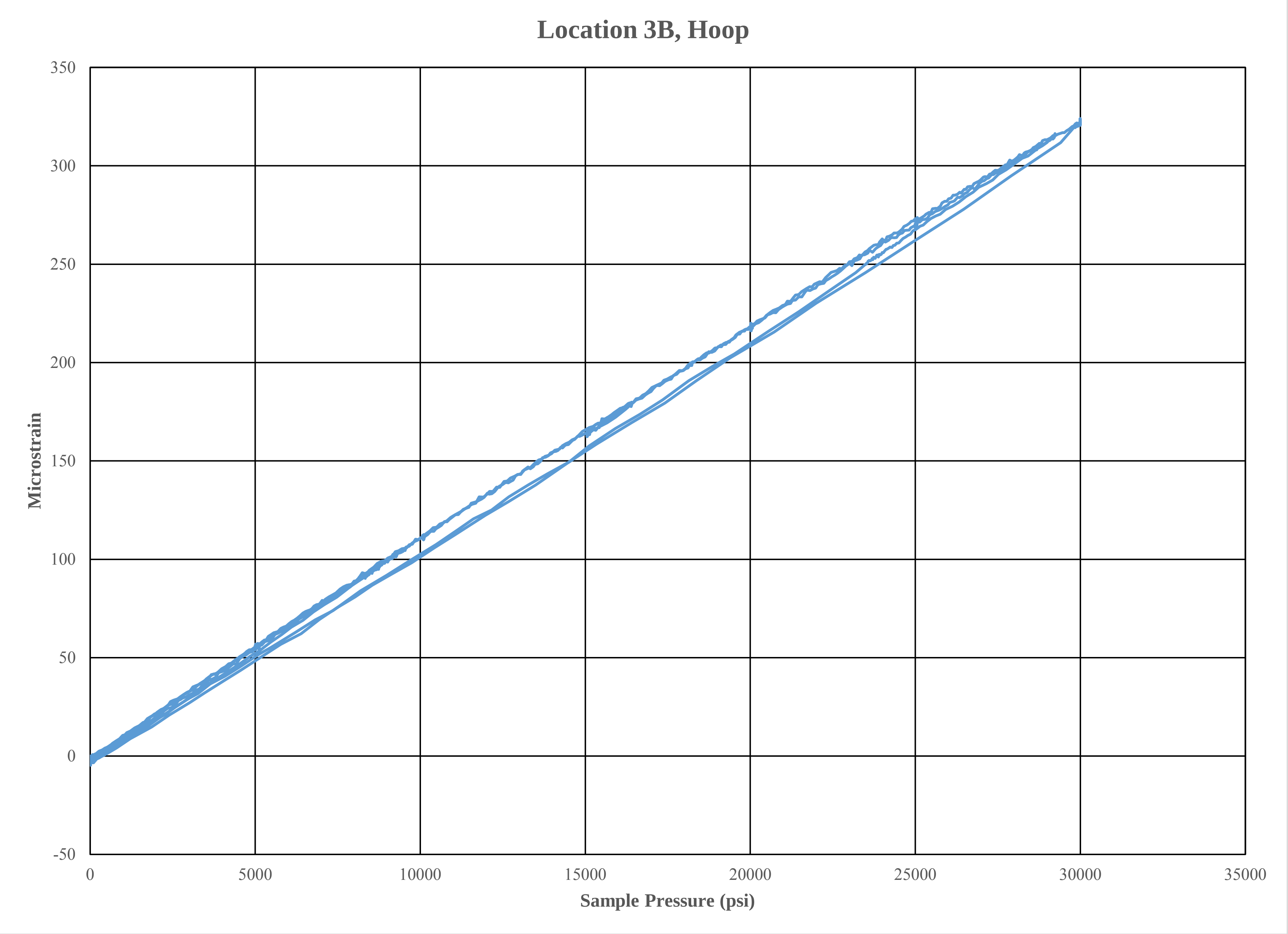

Location 2B, Axial
800
700
600
500
400
300
200
100
0
-100
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

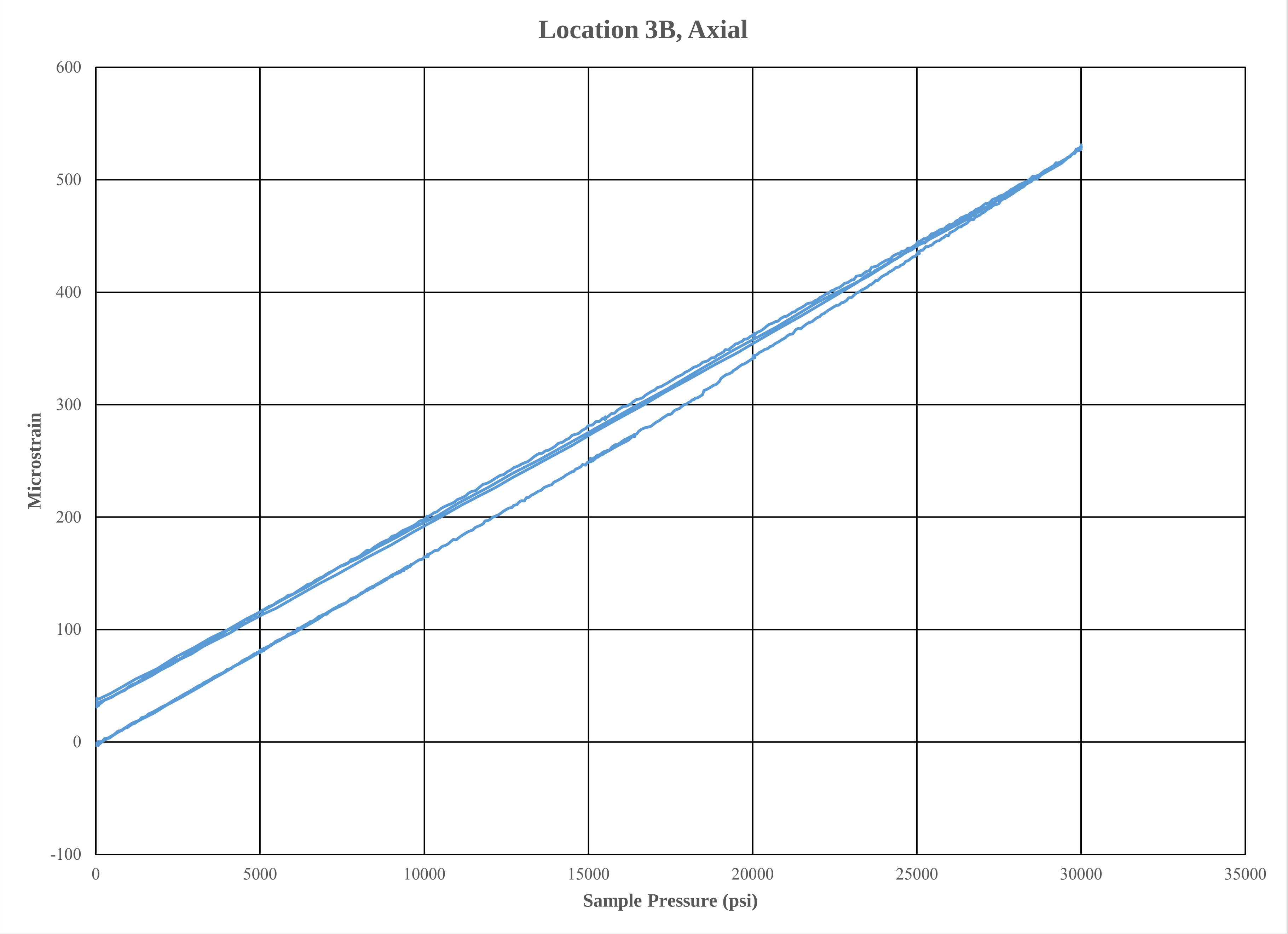


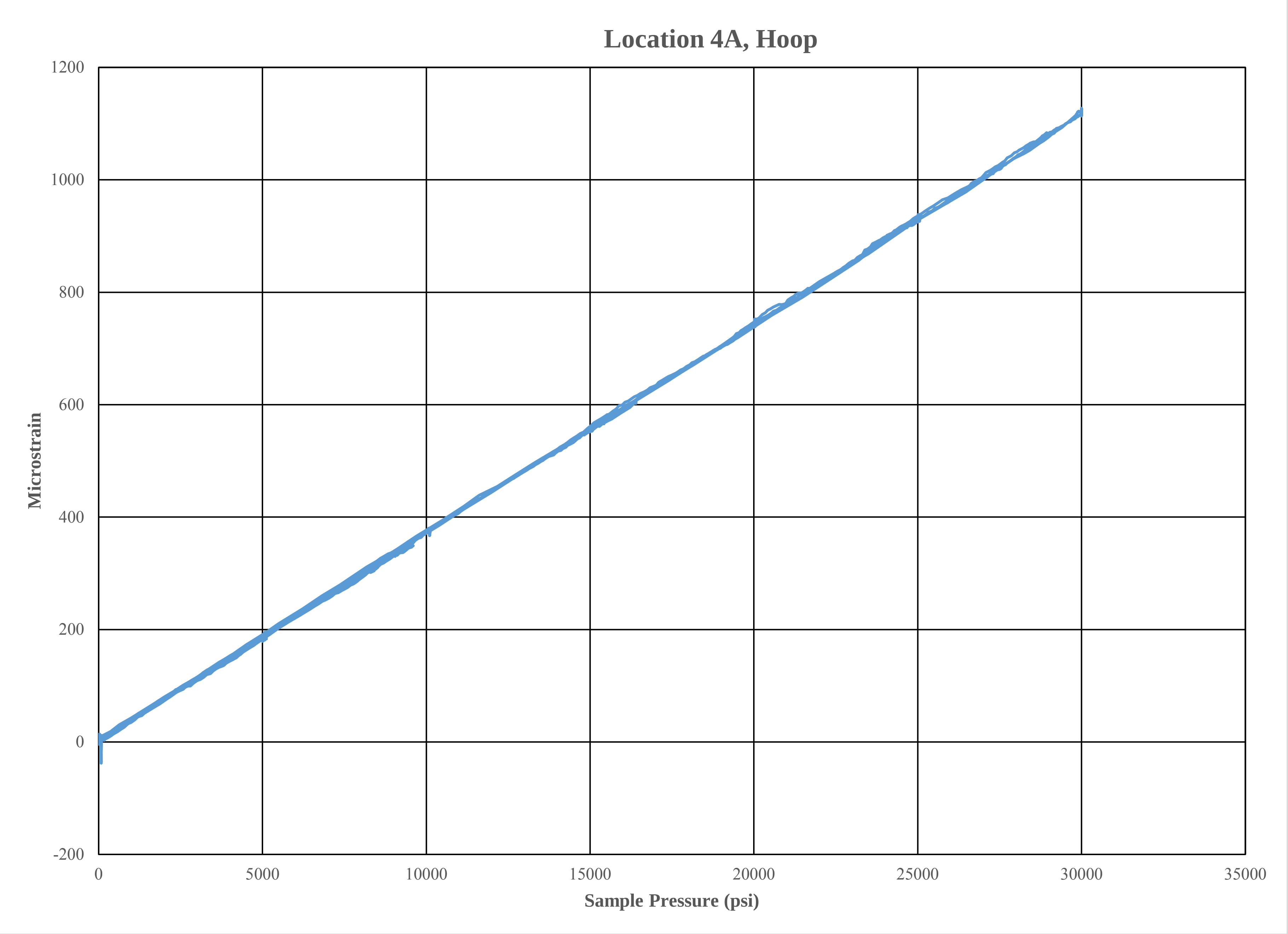
Location 2B, Hoop
Microstrain
4000
3500
3000
2500
2000
1500
1000
500
0
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

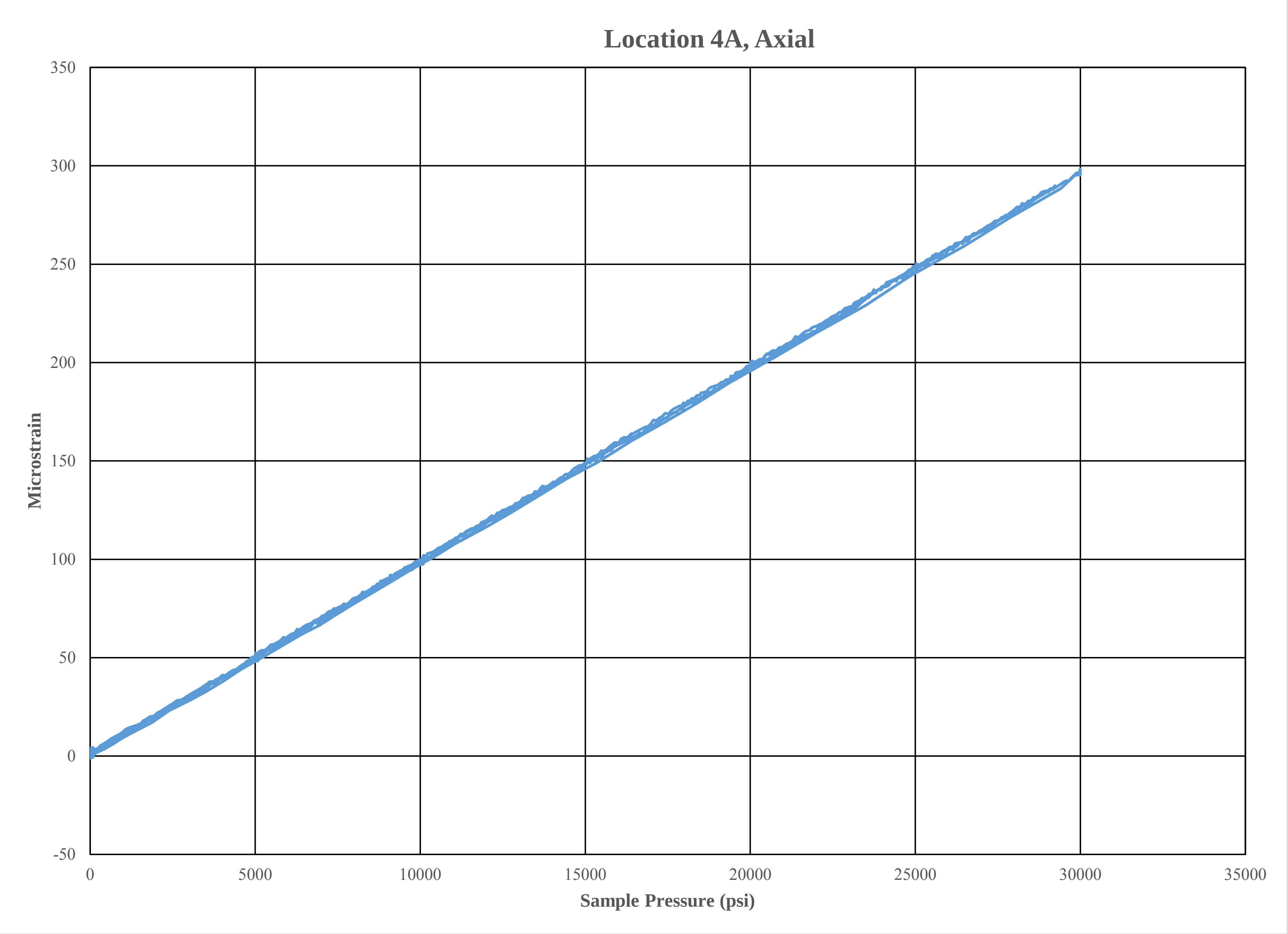

Location 3A, Hoop
Microstrain
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

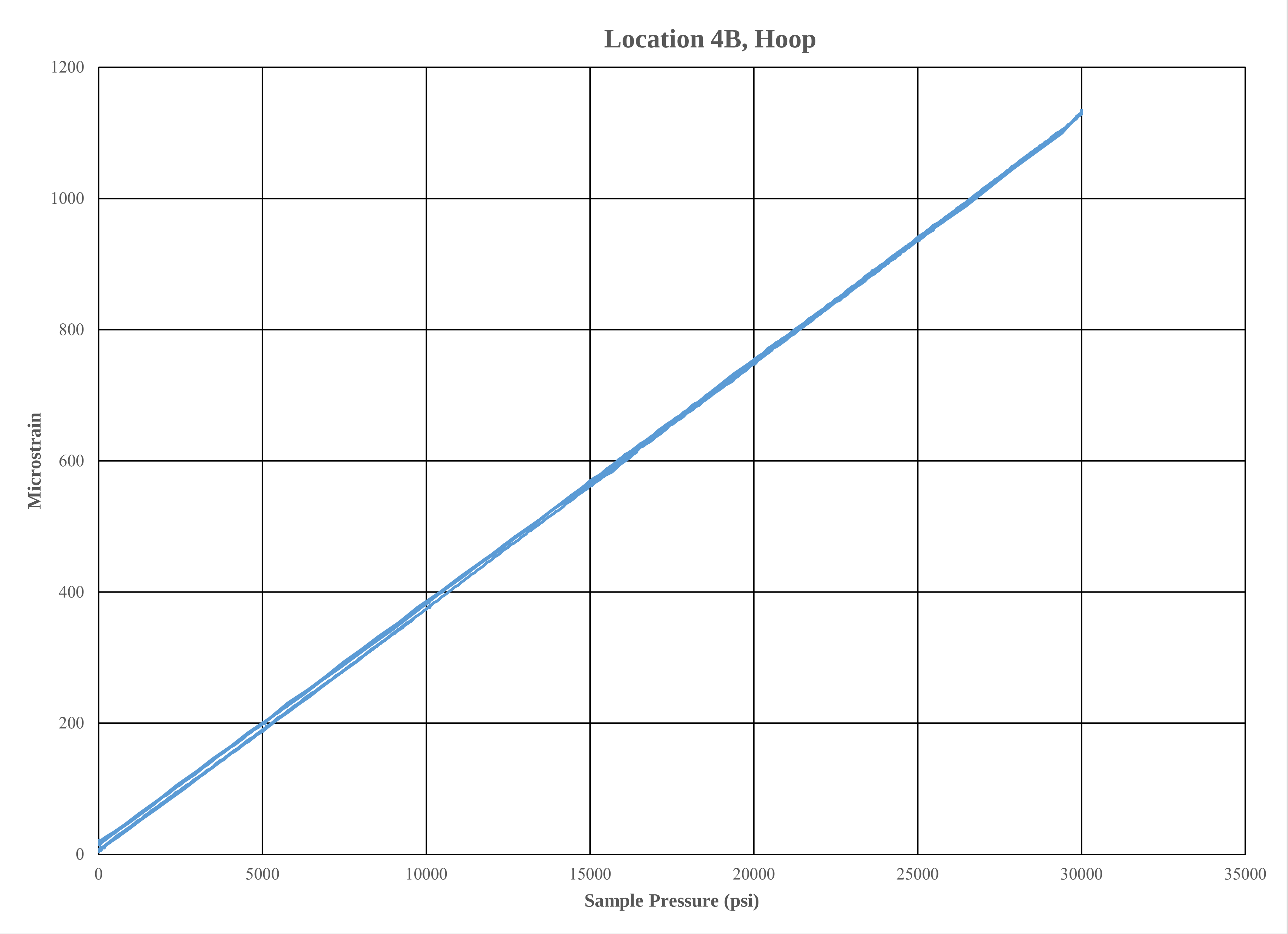

Location 3A, Axial
Microstrain
600
500
400
300
200
100
0
-100
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

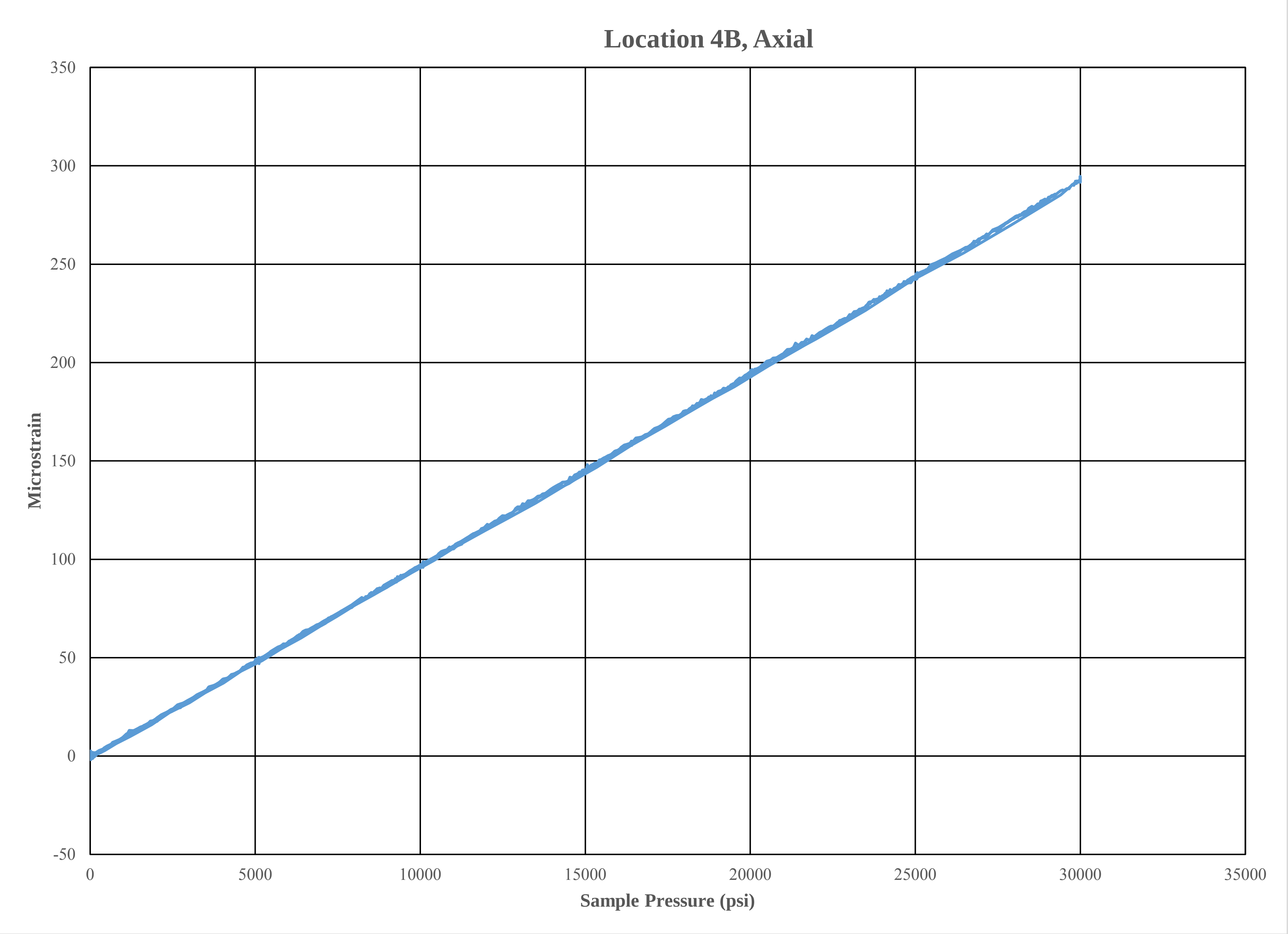

Location 3B, Hoop
Microstrain
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Location 3B, Axial
Microstrain
600
500
400
300
200
100
0
-100
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

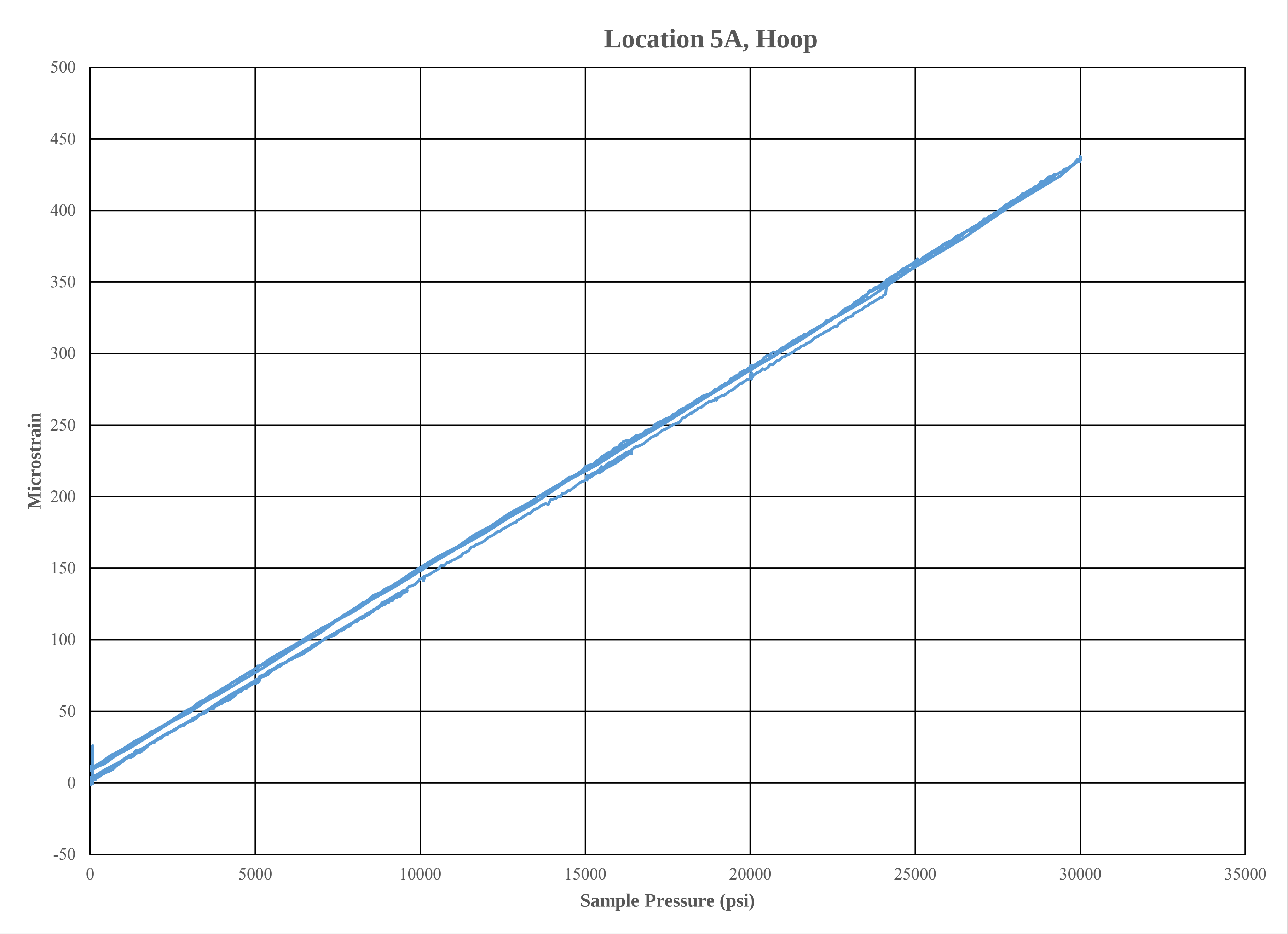

Location 4A, Hoop
Microstrain
1200
1000
800
600
400
200
0
-200
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

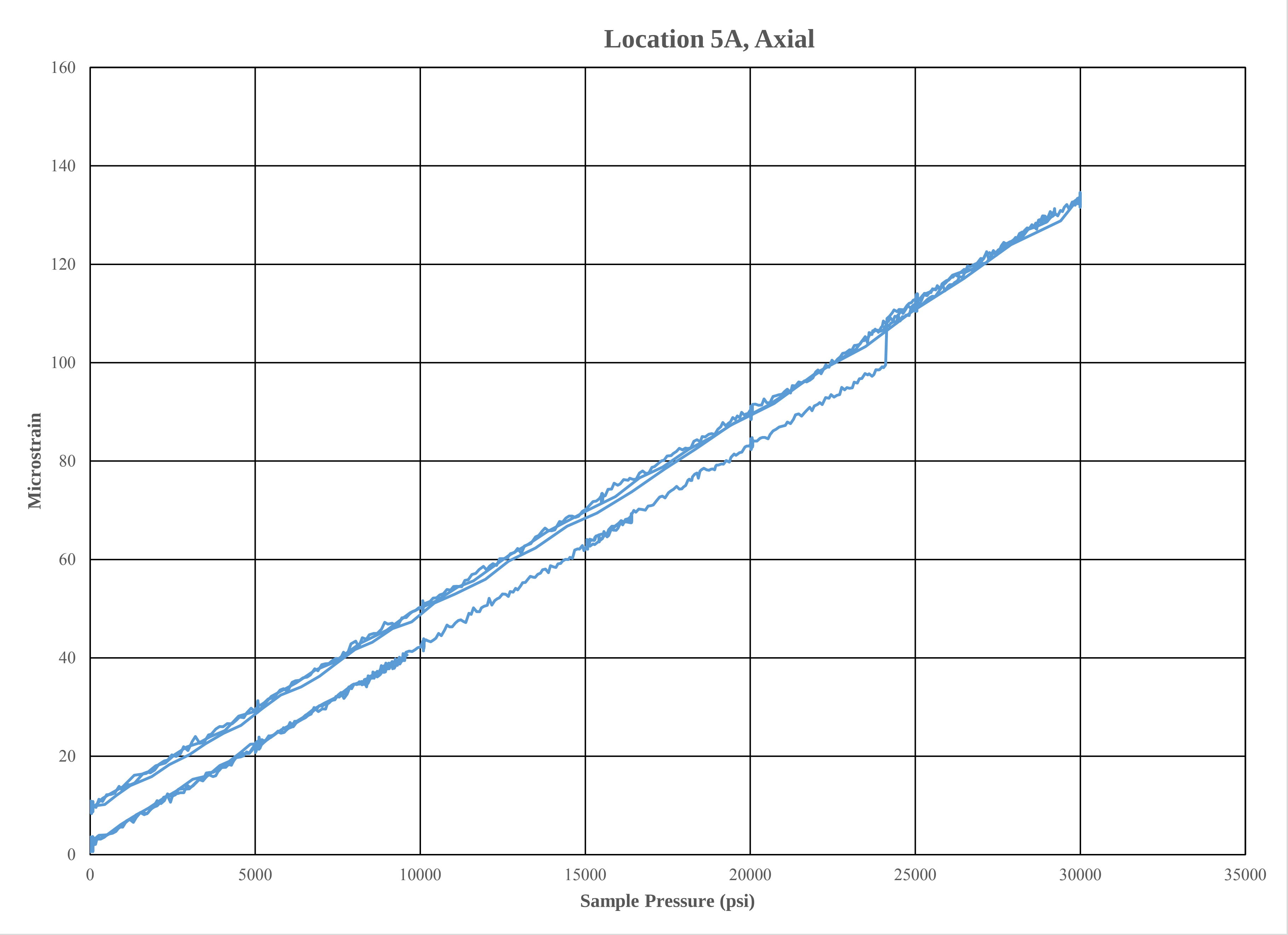

Location 4A, Axial
Microstrain
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

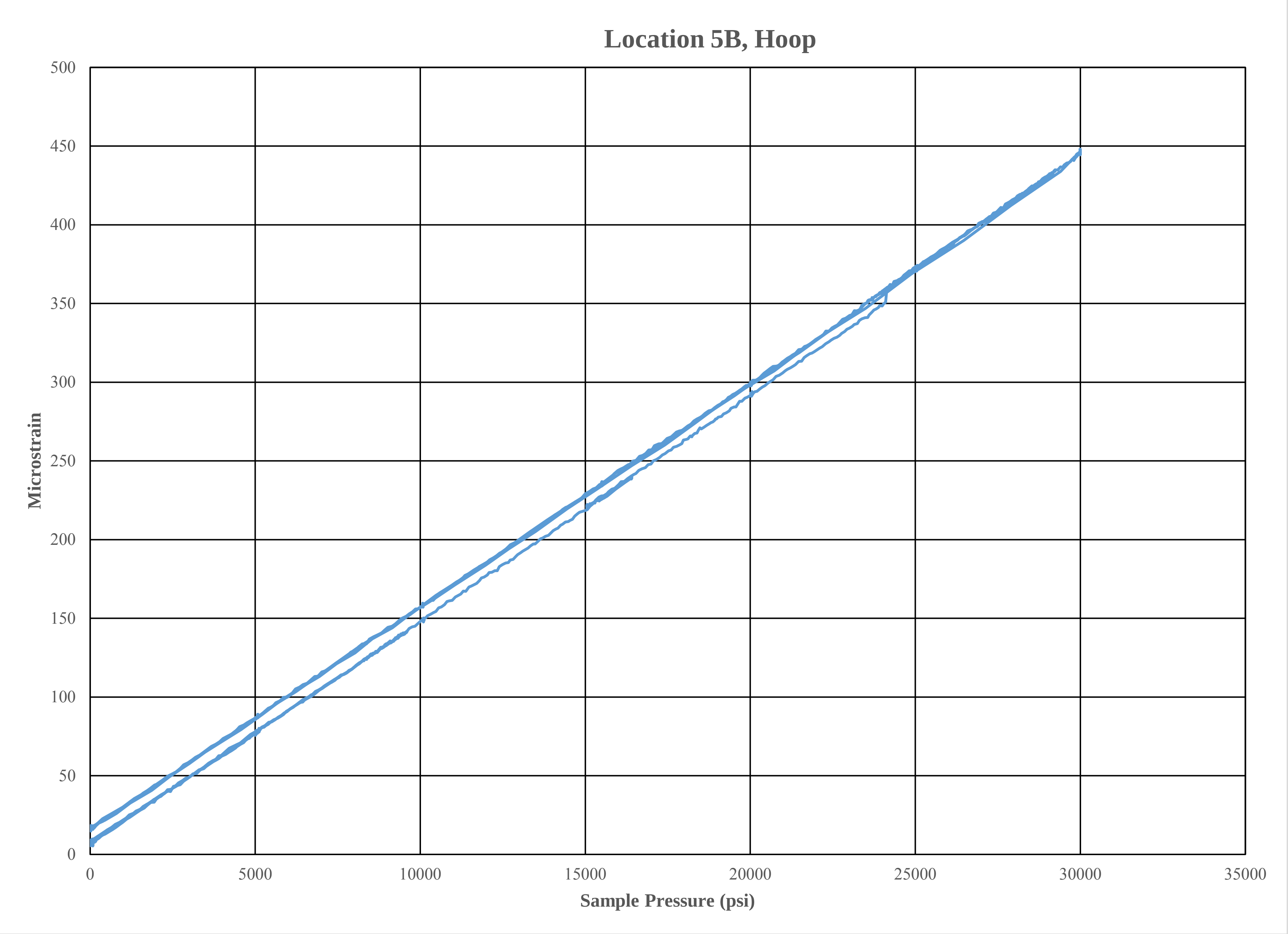

Location 4B, Hoop
Microstrain
0
200
400
600
800
1000
1200
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

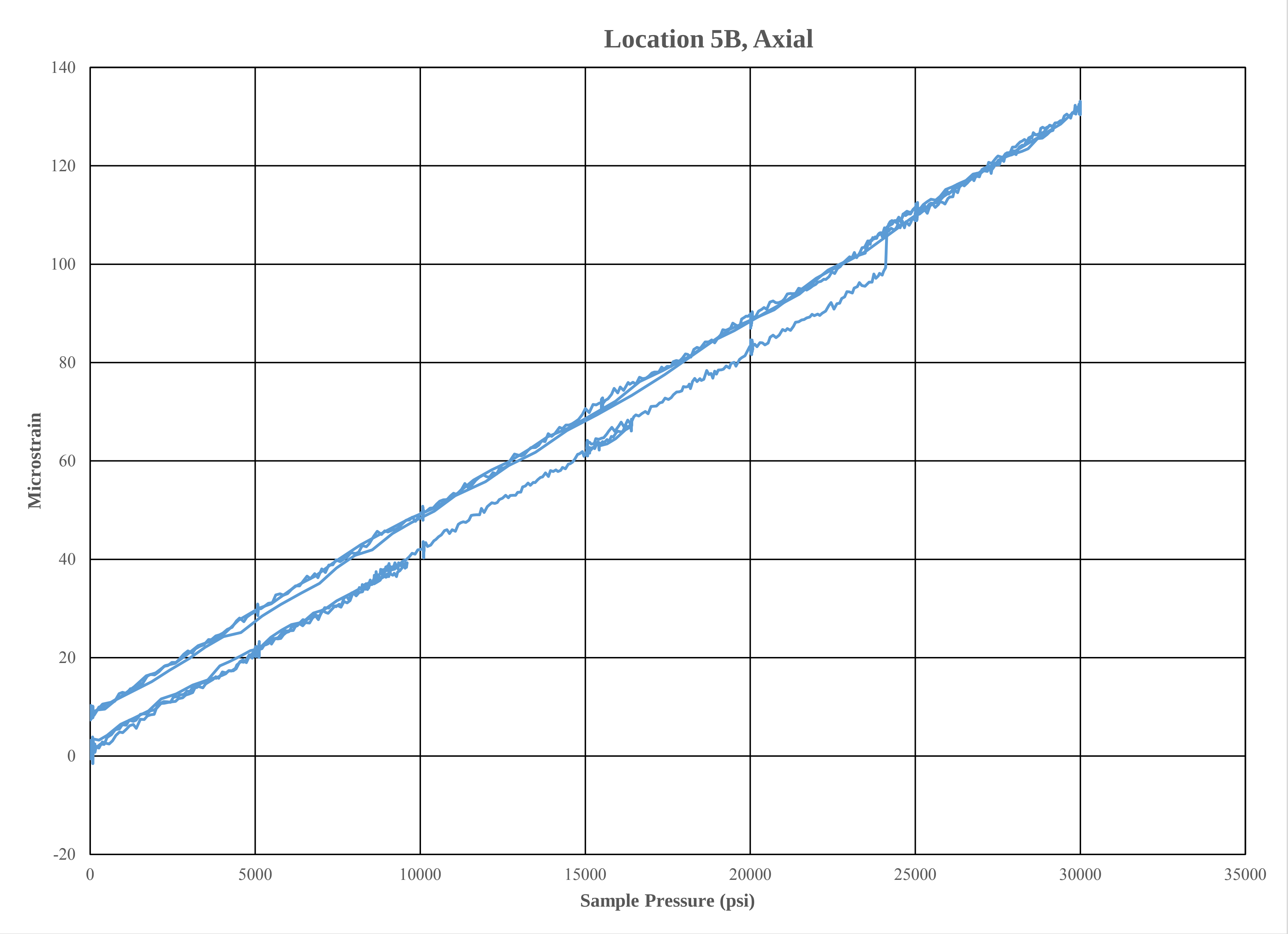


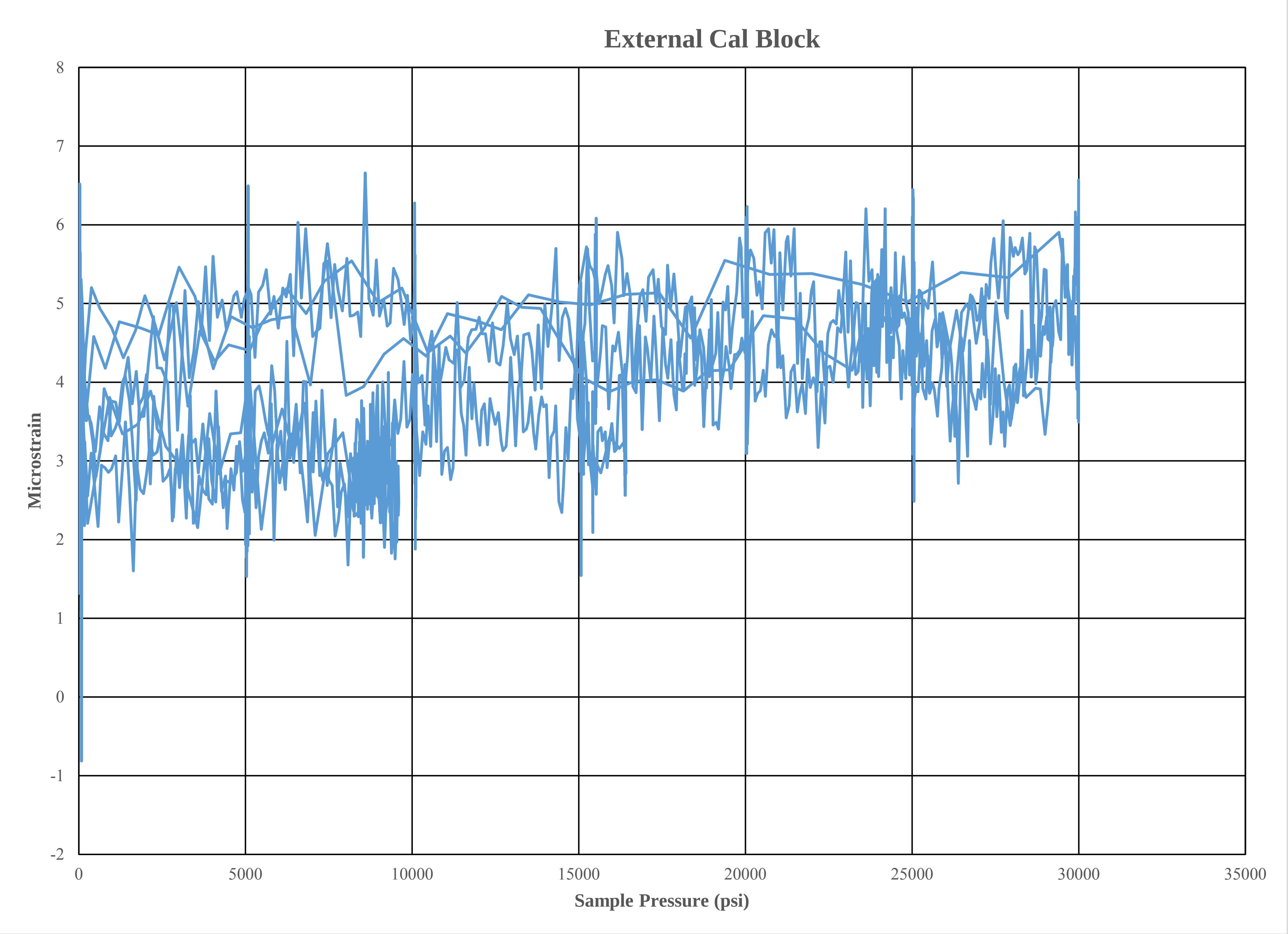
Location 4B, Axial
350
300
250
200
150
100
50
0
-50
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Location 5A, Hoop
Microstrain
Sample Pressure (psi)
500
450
400
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000


Location 5A, Axial
Microstrain
160
140
120
100
80
60
40
20
0
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

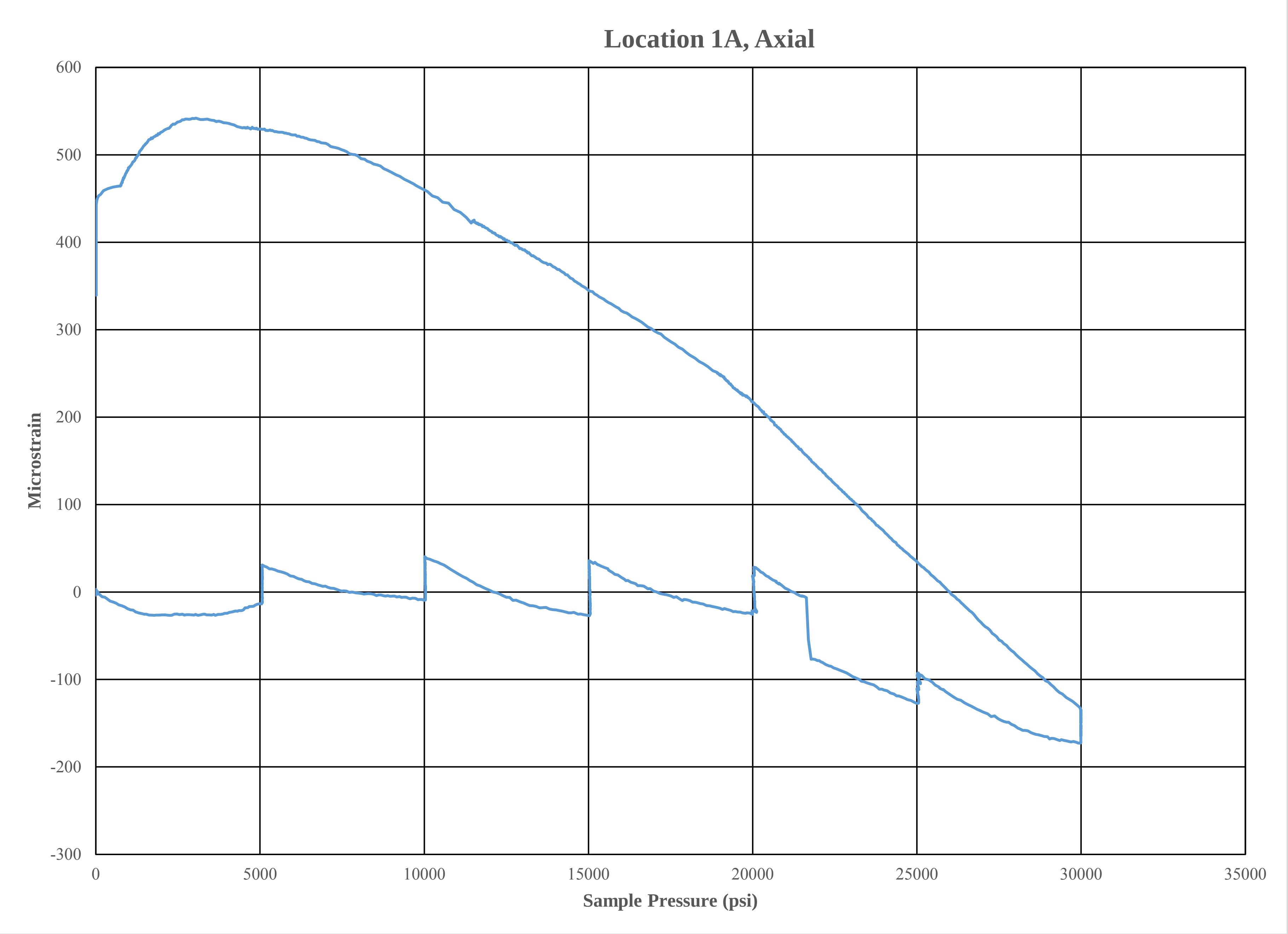

Location 5B, Hoop
Microstrain
0
50
100
150
200
250
300
350
400
450
500
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

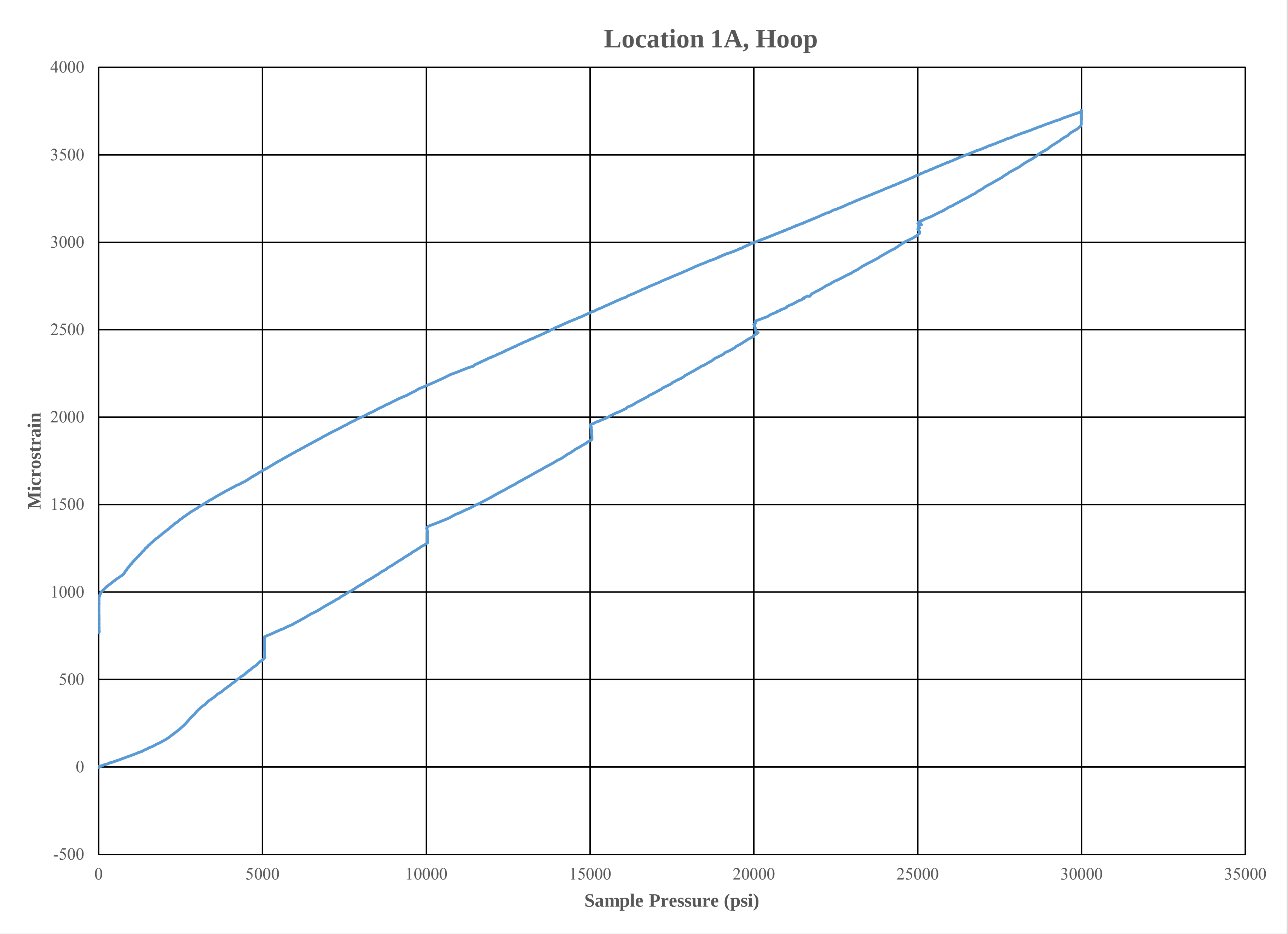

Location 5B, Axial
Microstrain
140
120
100
80
60
40
20
0
-20
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

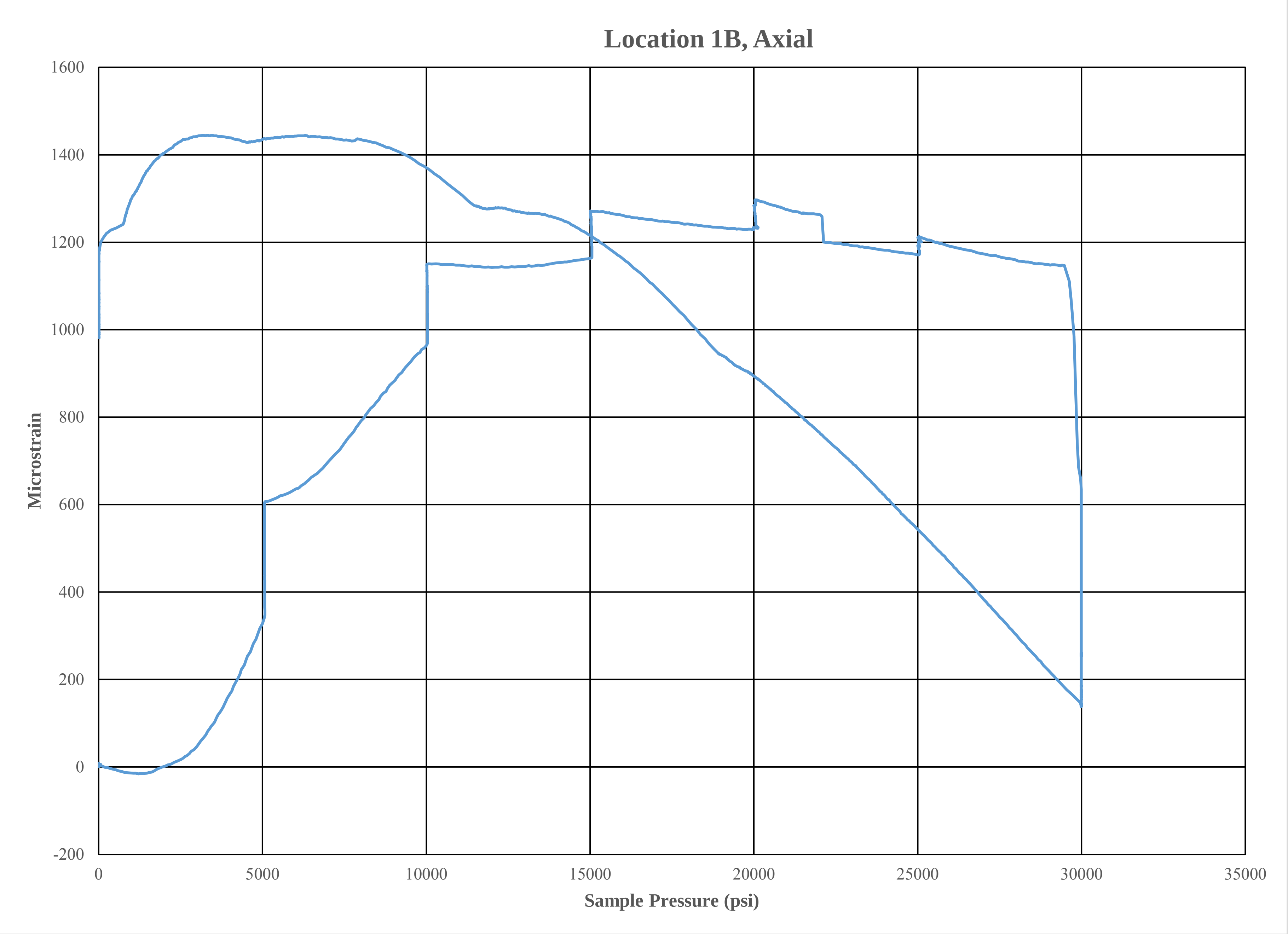

External Cal Block
Microstrain
8
7
6
5
4
3
2
1
0
-1
-2
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

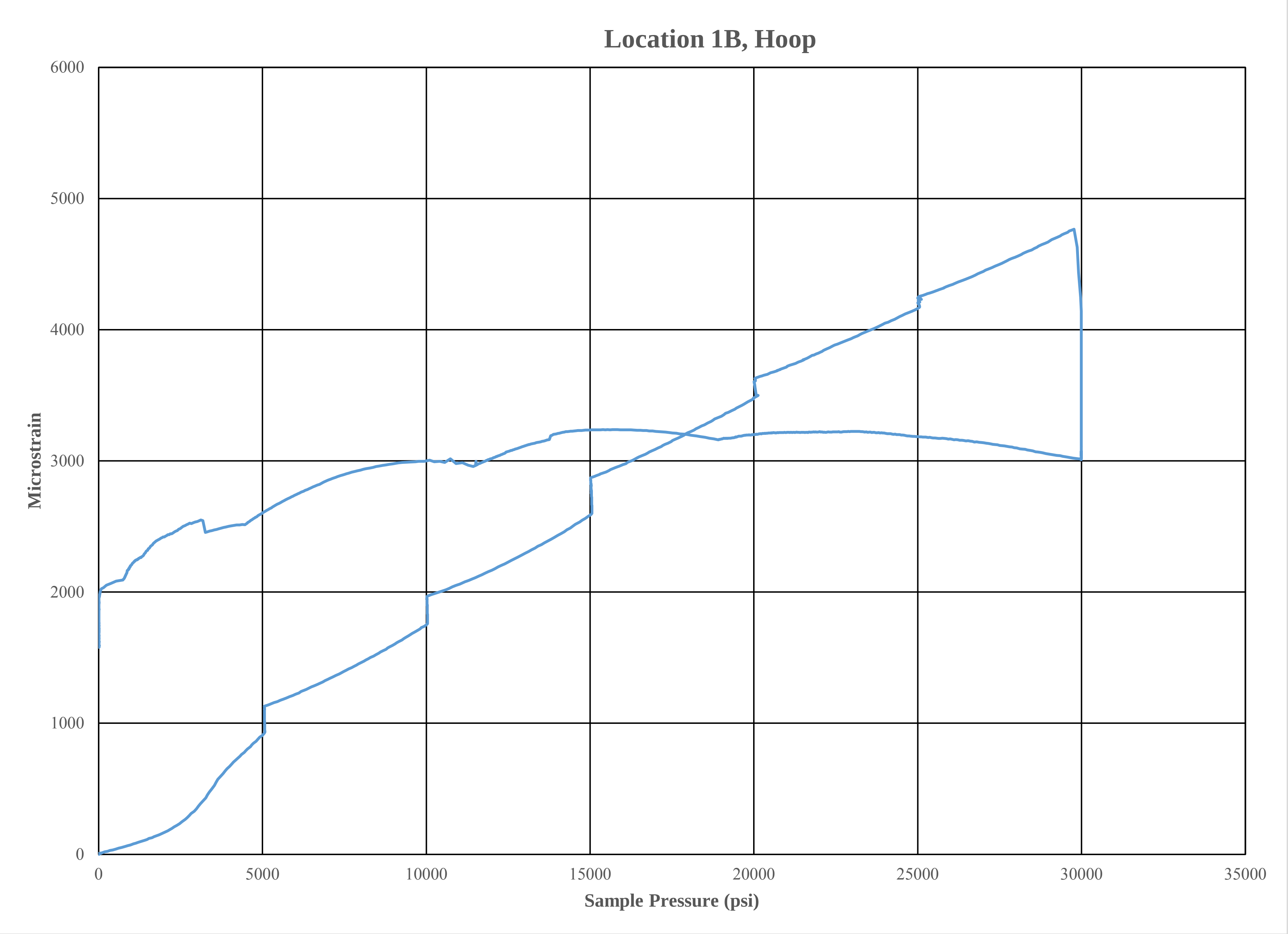
STRAIN DATA-LARGE VALVE BODY

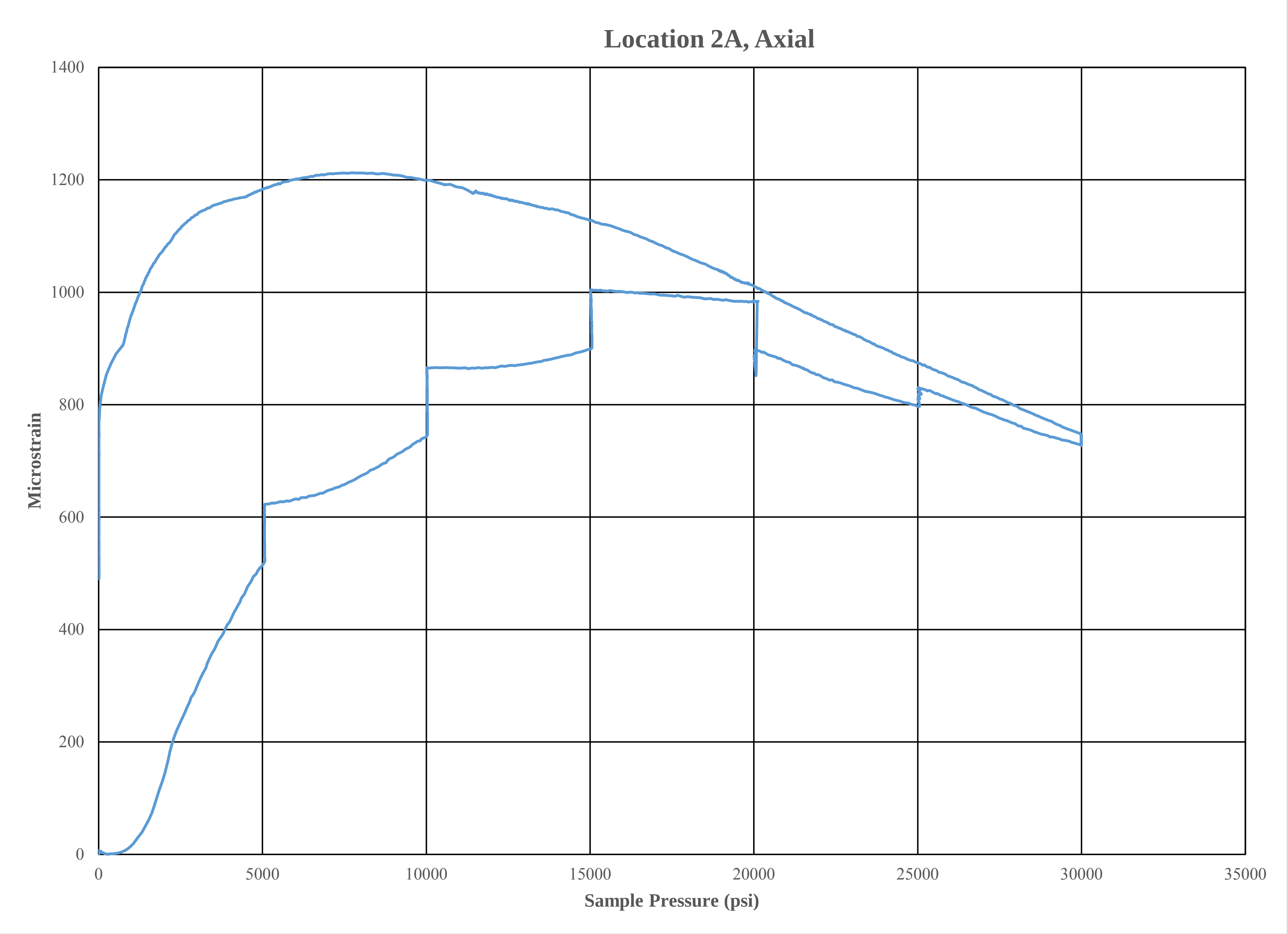
30,000 PSIG HYDROSTATIC TEST

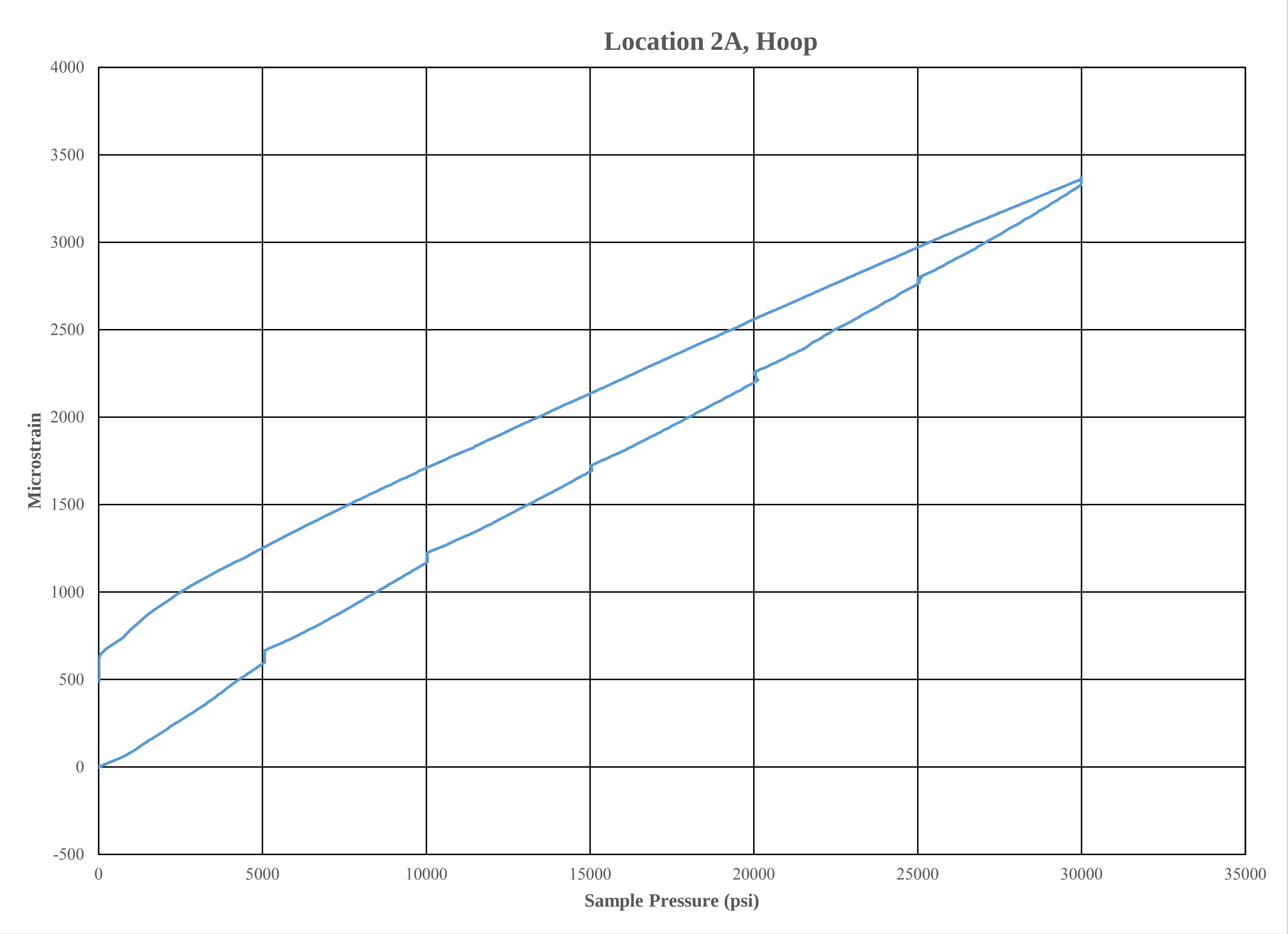

Location 1A, Axial
Microstrain
600
500
400
300
200
100
0
-100
-200
-300
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

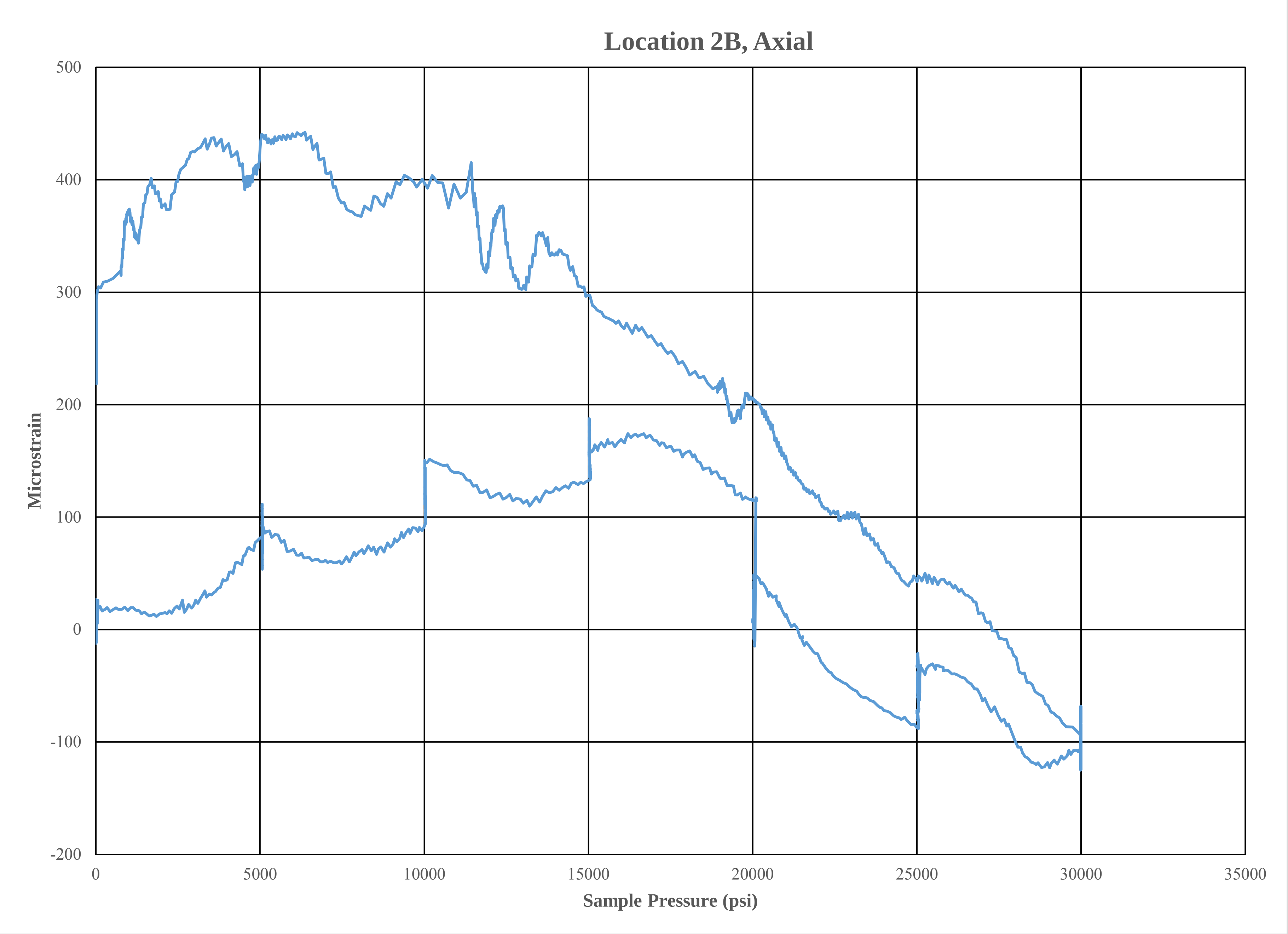

Location 1A, Hoop
Microstrain
4000
3500
3000
2500
2000
1500
1000
500
0
-500
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

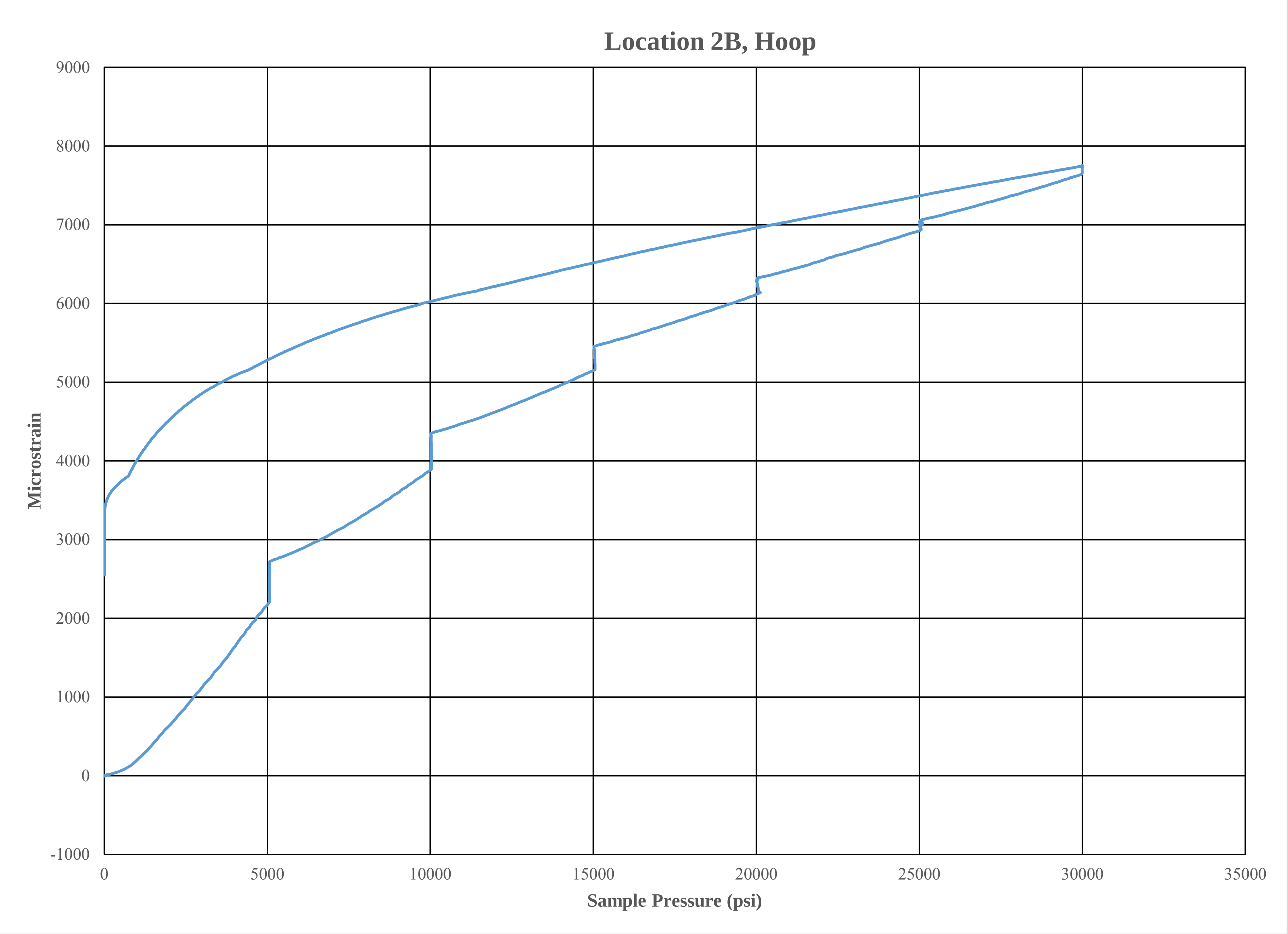

Location 1B, Axial
Microstrain
1600
1400
1200
1000
800
600
400
200
0
-200
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Location 1B, Hoop
Microstrain
Sample Pressure (psi)
0
1000
2000
3000
4000
5000
6000
0
5000
10000
15000
20000
25000
30000
35000

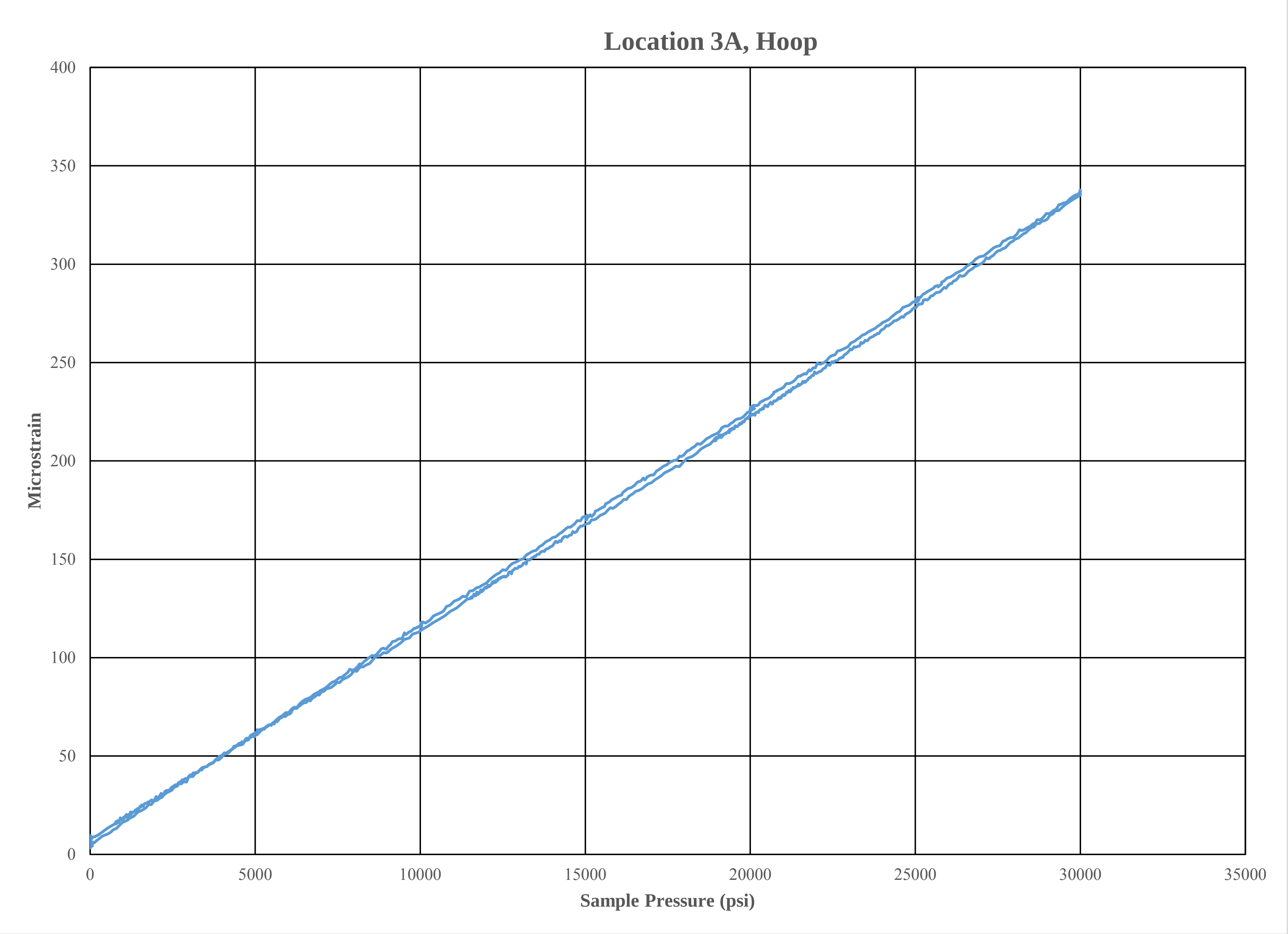

Location 2A, Axial
1400
1200
1000
800
600
400
200
0
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

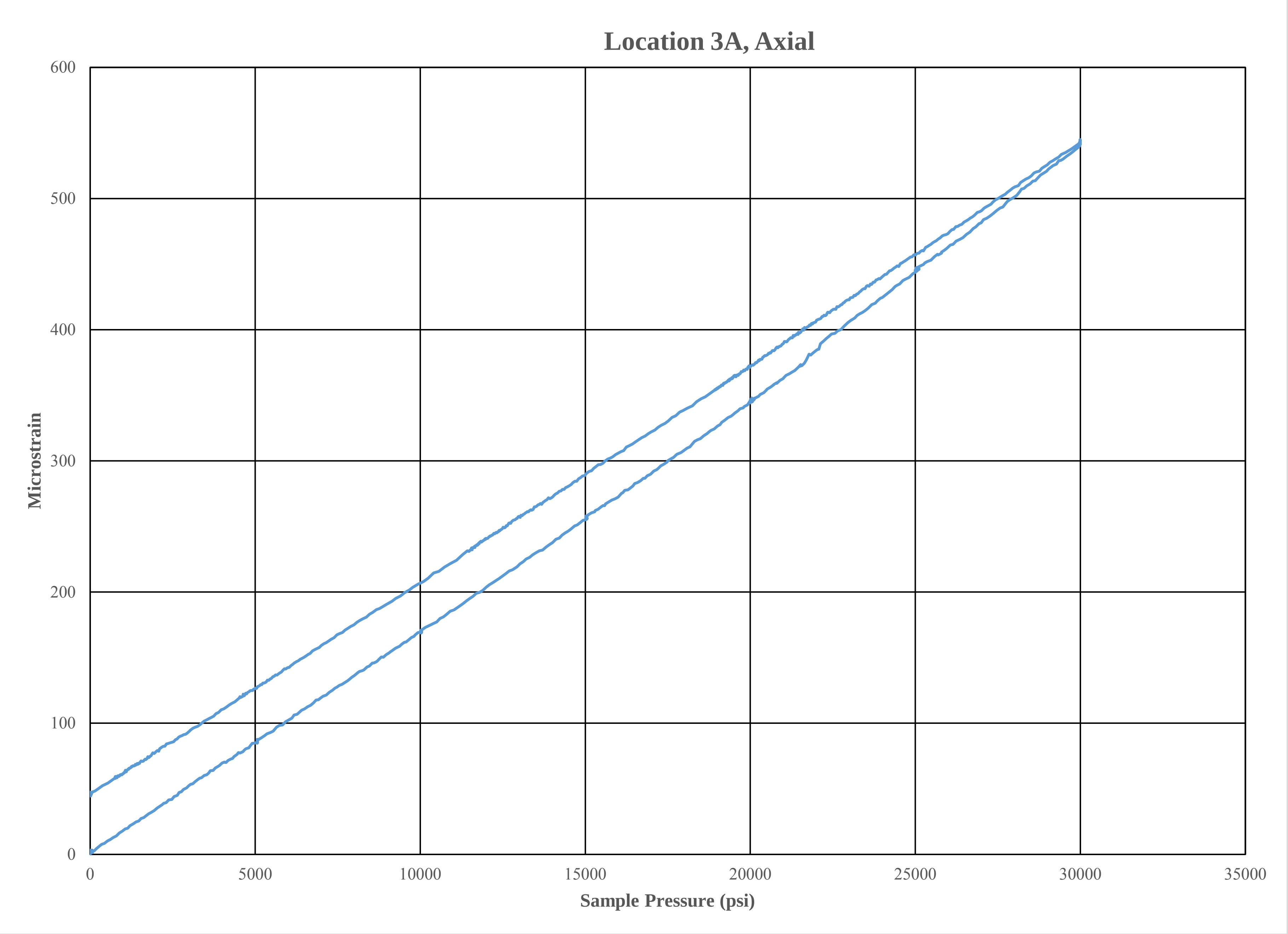

Location 2A, Hoop
Microstrain
4000
3500
3000
2500
2000
1500
1000
500
0
-500
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

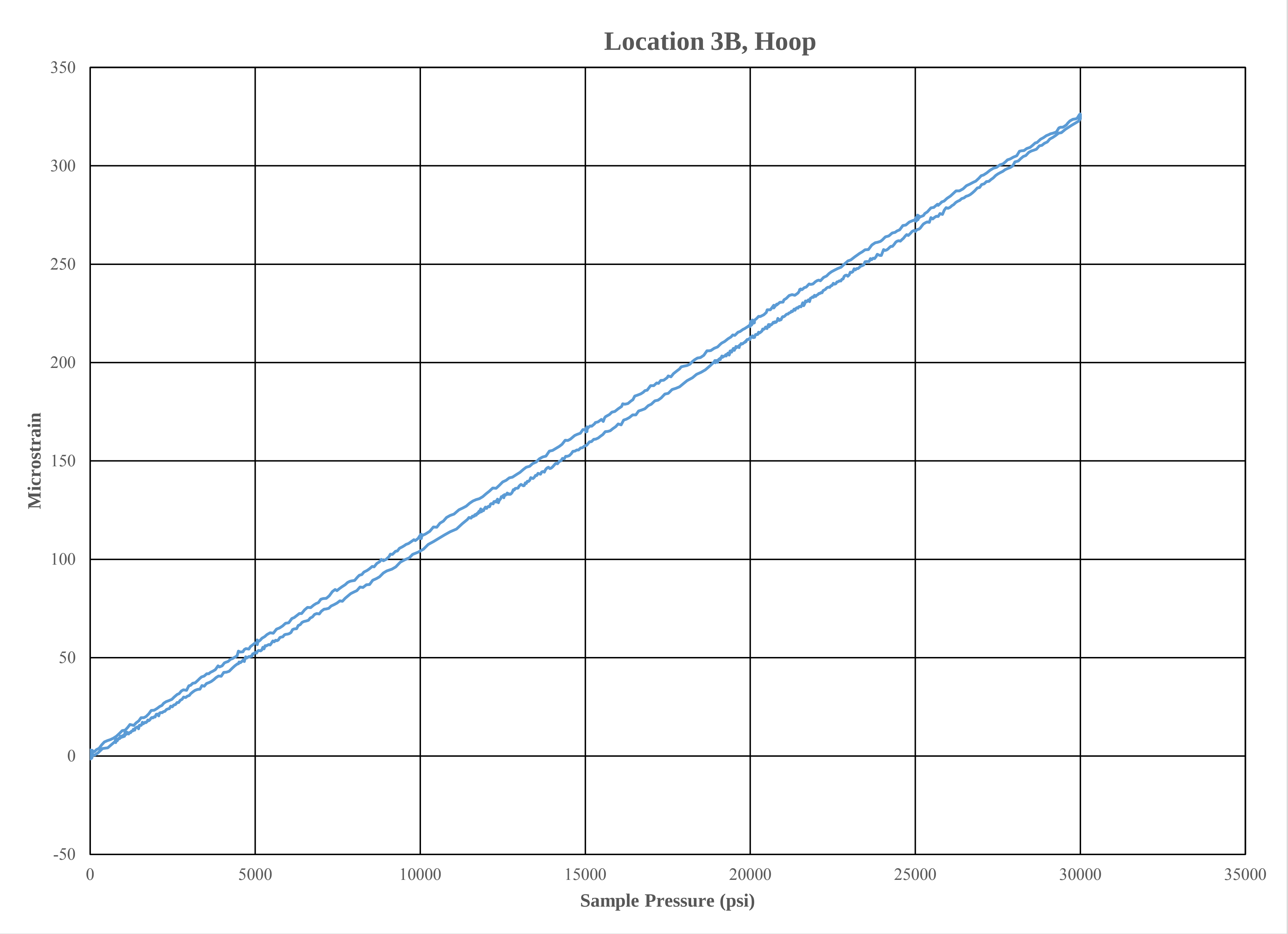

Location 2B, Axial
500
400
300
200
100
0
-100
-200
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)



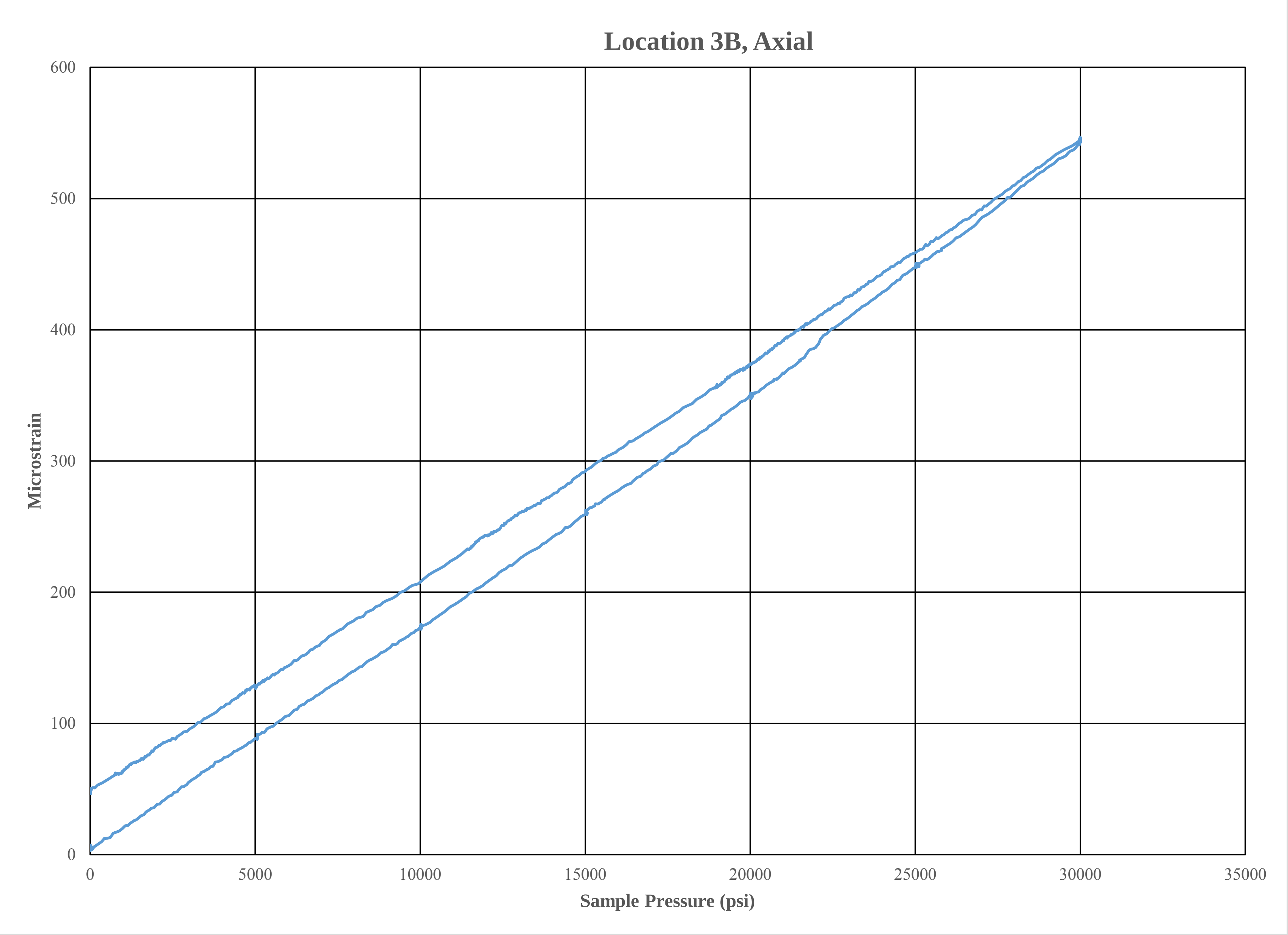
Location 2B, Hoop
Microstrain
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

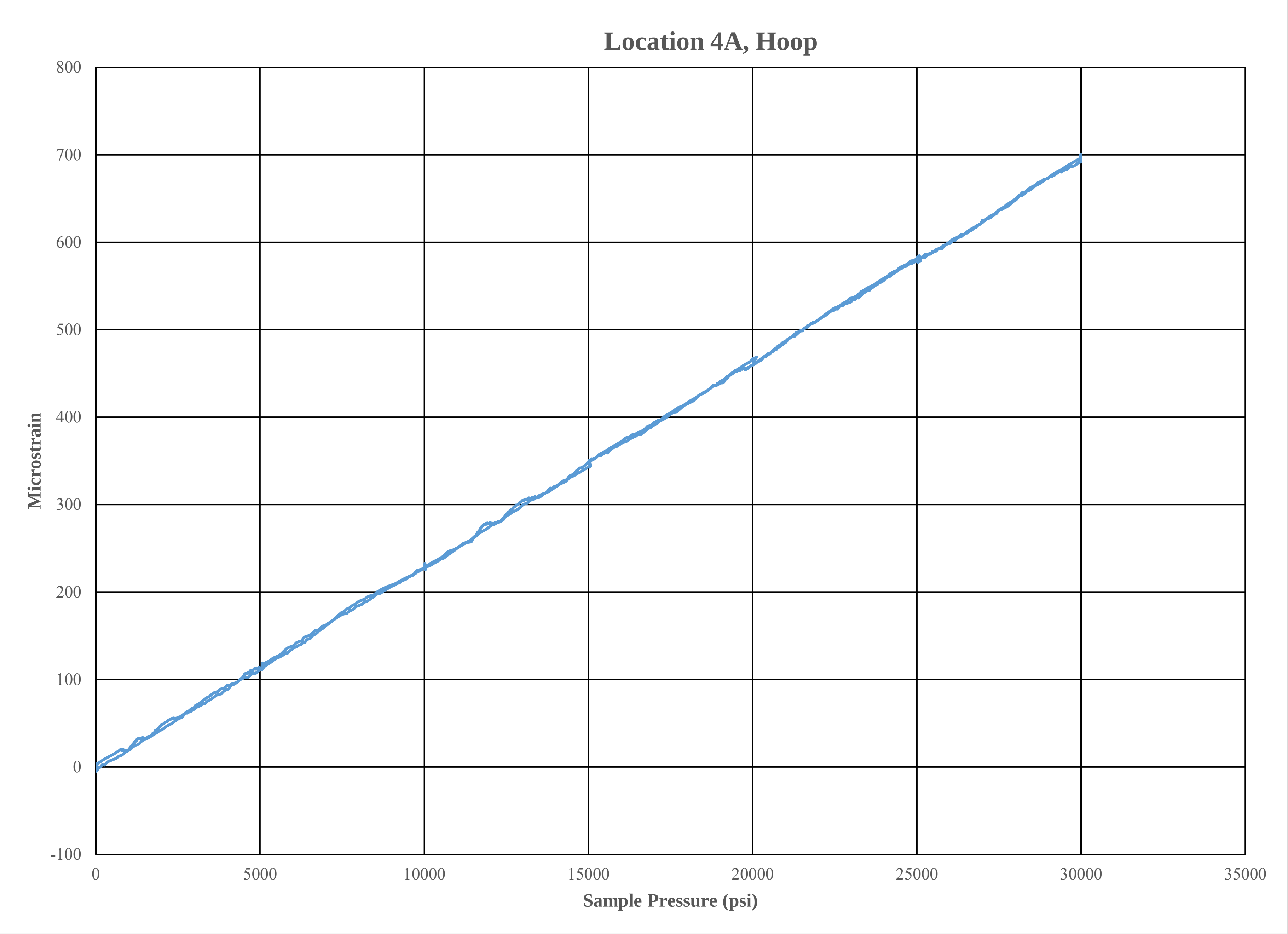

Location 3A, Hoop
Microstrain
Sample Pressure (psi)
0
50
100
150
200
250
300
350
400
0
5000
10000
15000
20000
25000
30000
35000

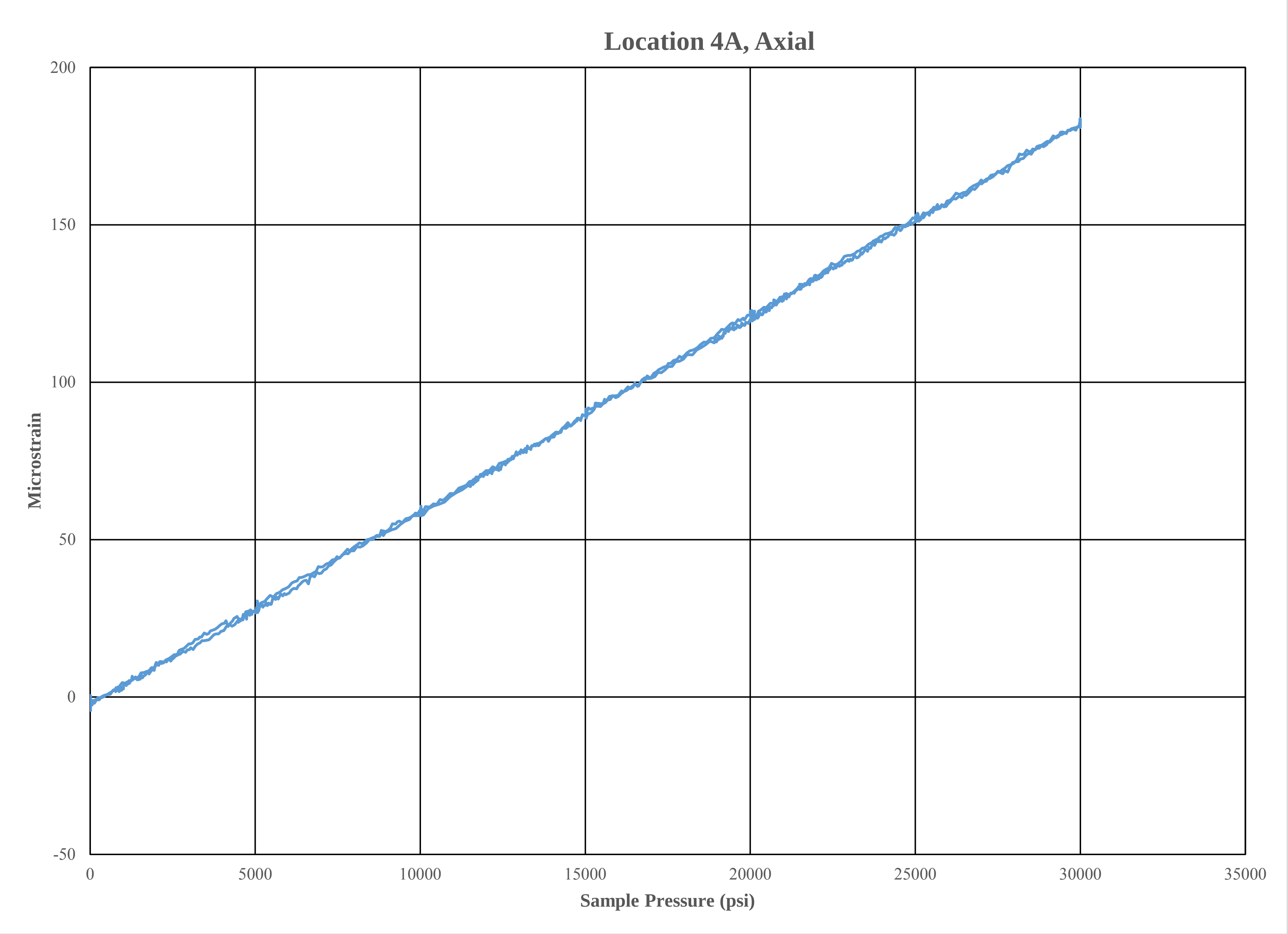

Location 3A, Axial
Microstrain
0
100
200
300
400
500
600
Sample Pressure (psi)
0
5000
10000
15000
20000
25000
30000
35000

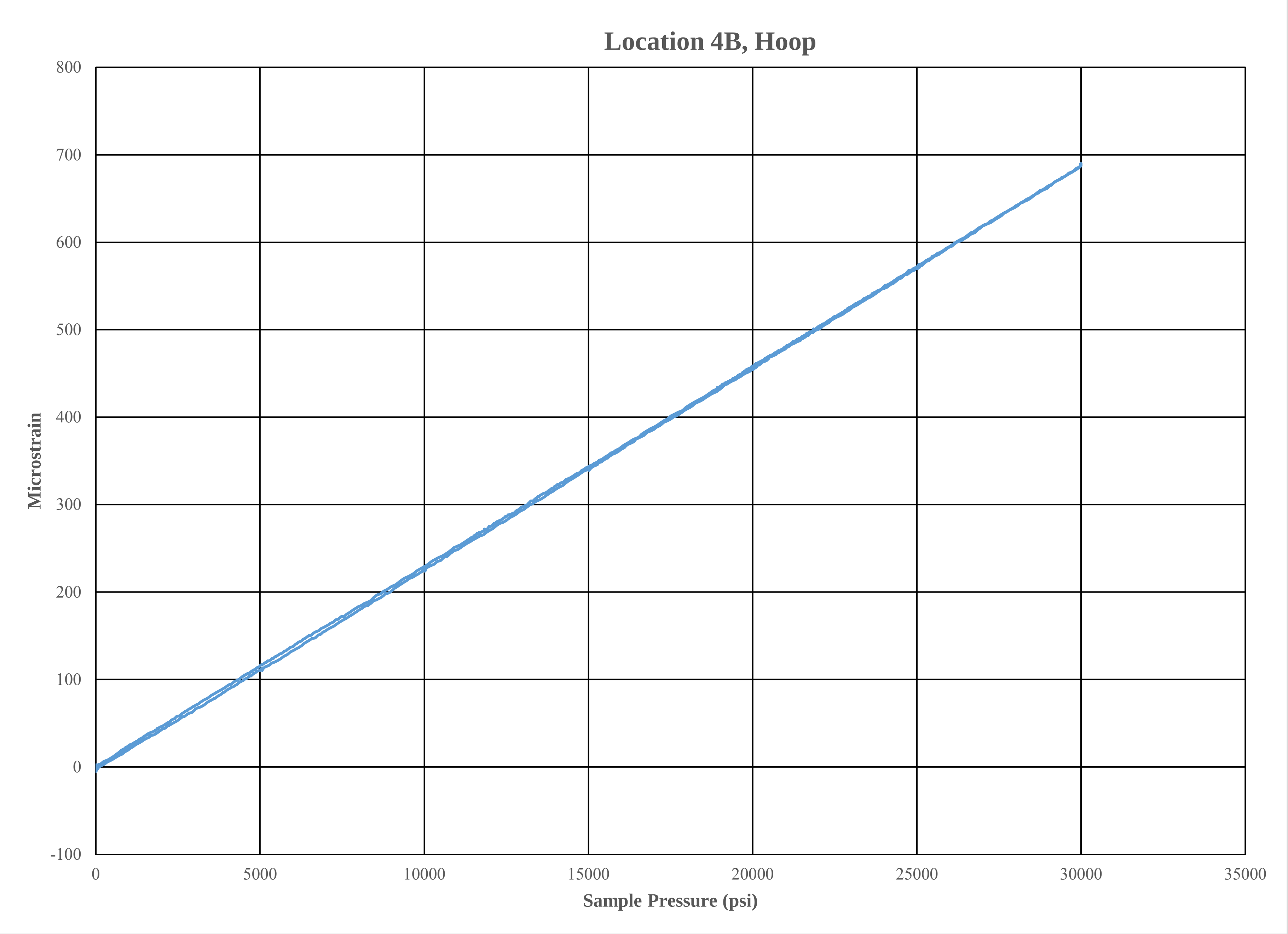


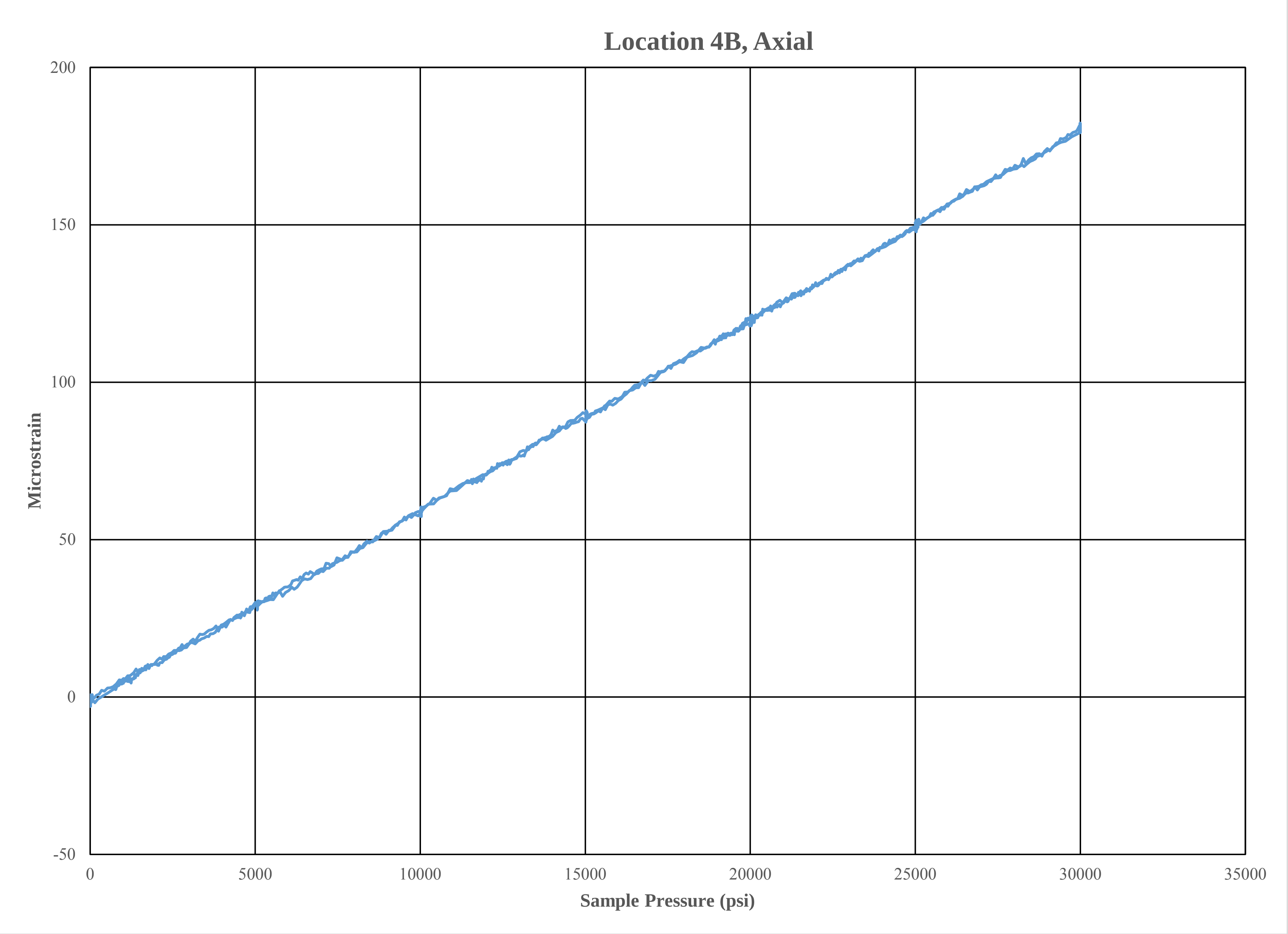
Location 3B, Hoop
Microstrain
Sample Pressure (psi)
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000

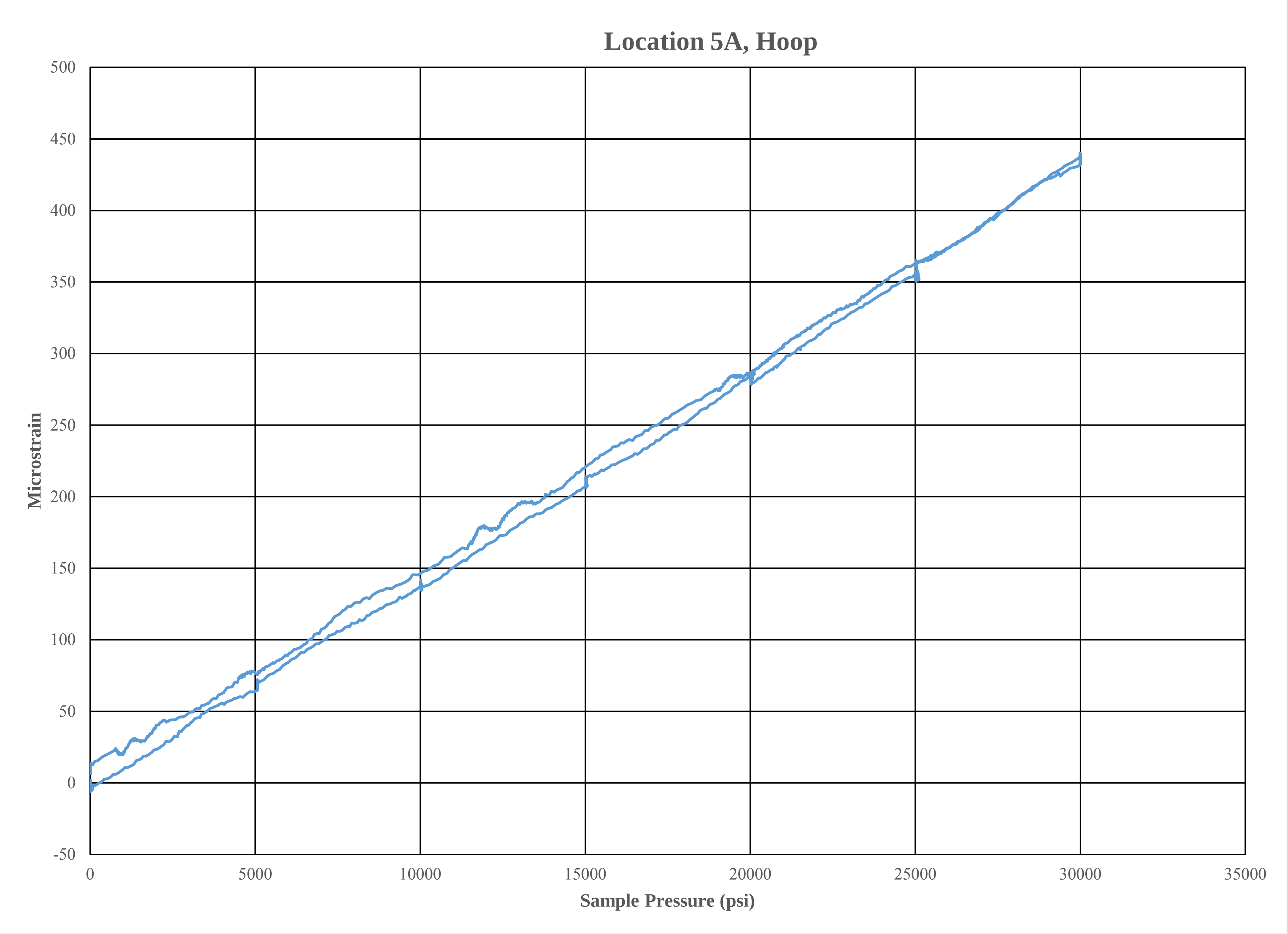

Location 3B, Axial
600
500
400
300
200
100
0
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

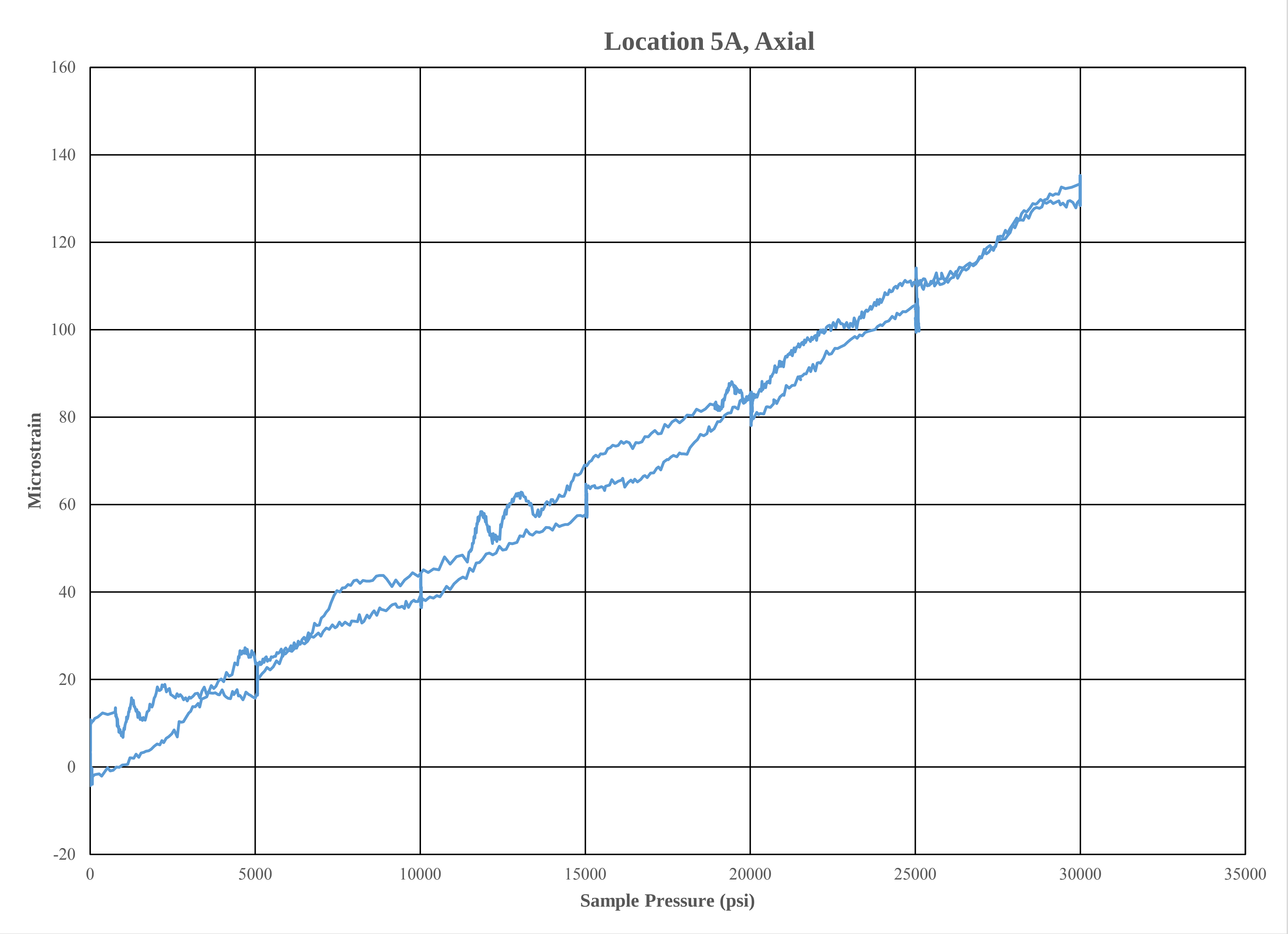

Location 4A, Hoop
Microstrain
800
700
600
500
400
300
200
100
0
-100
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

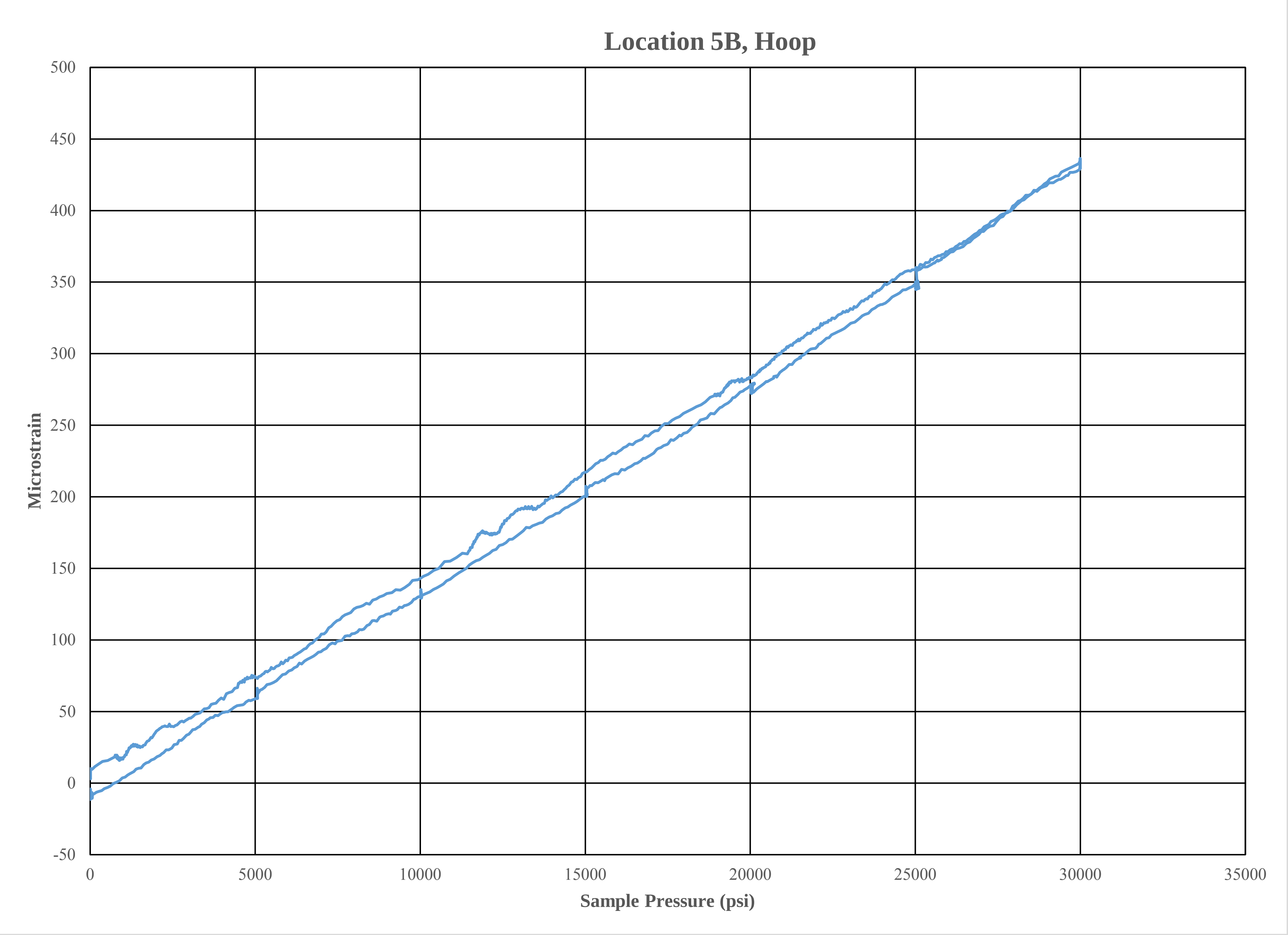

Location 4A, Axial
Microstrain
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

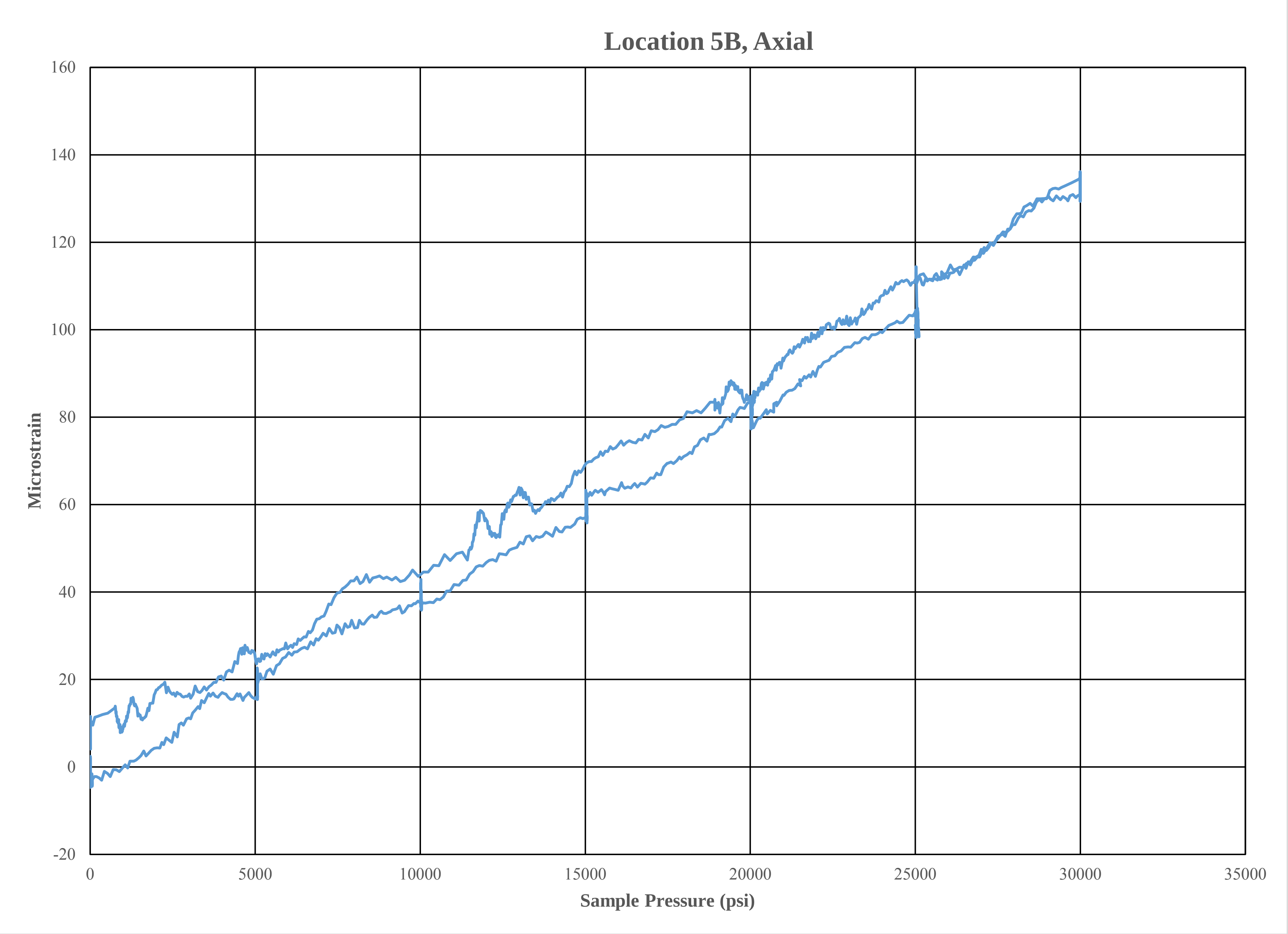

Location 4B, Hoop
Microstrain
800
700
600
500
400
300
200
100
0
-100
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Location 4B, Axial
Microstrain
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

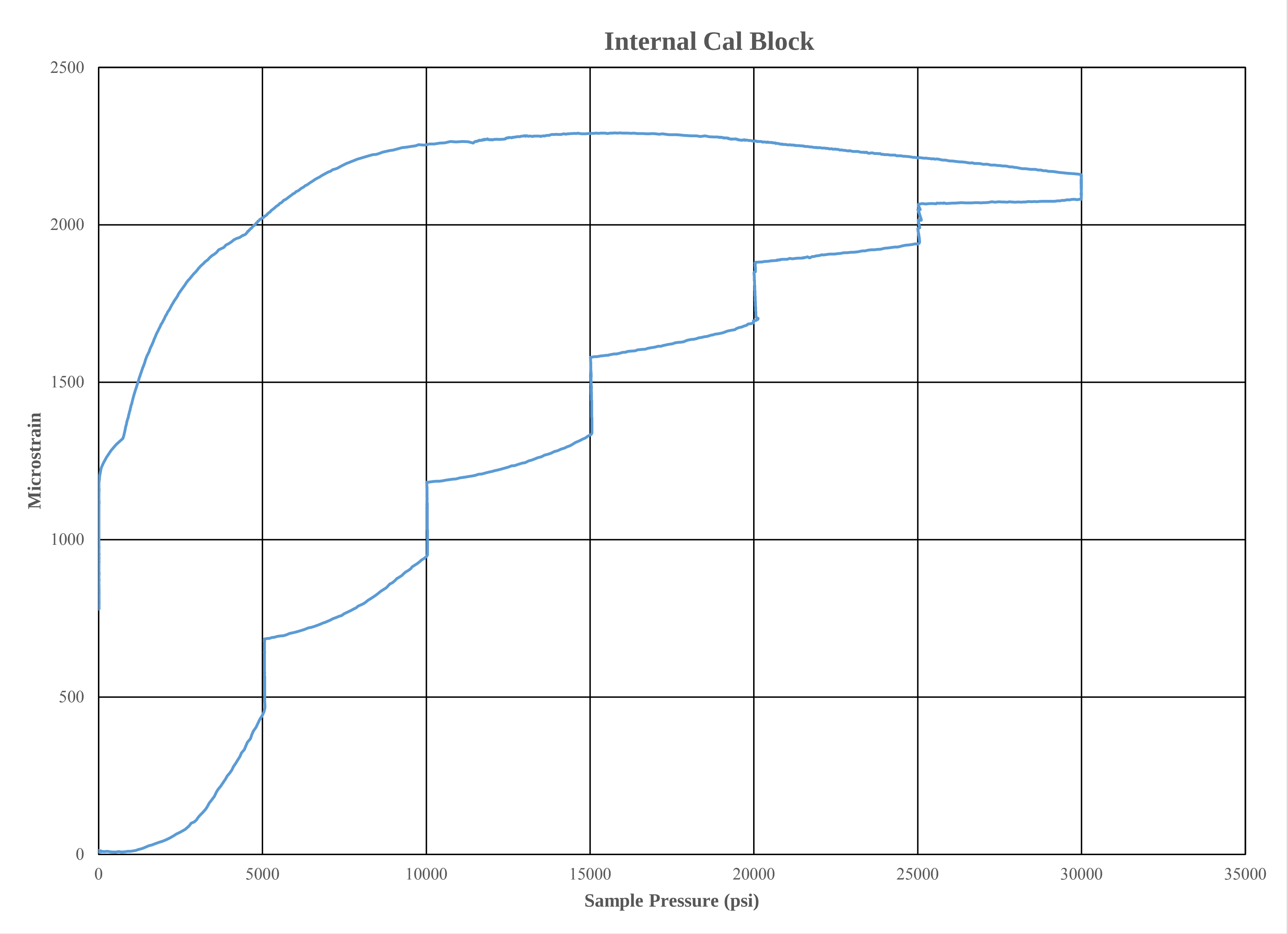

Location 5A, Hoop
Microstrain
500
450
400
350
300
250
200
150
100
50
0
-50
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)

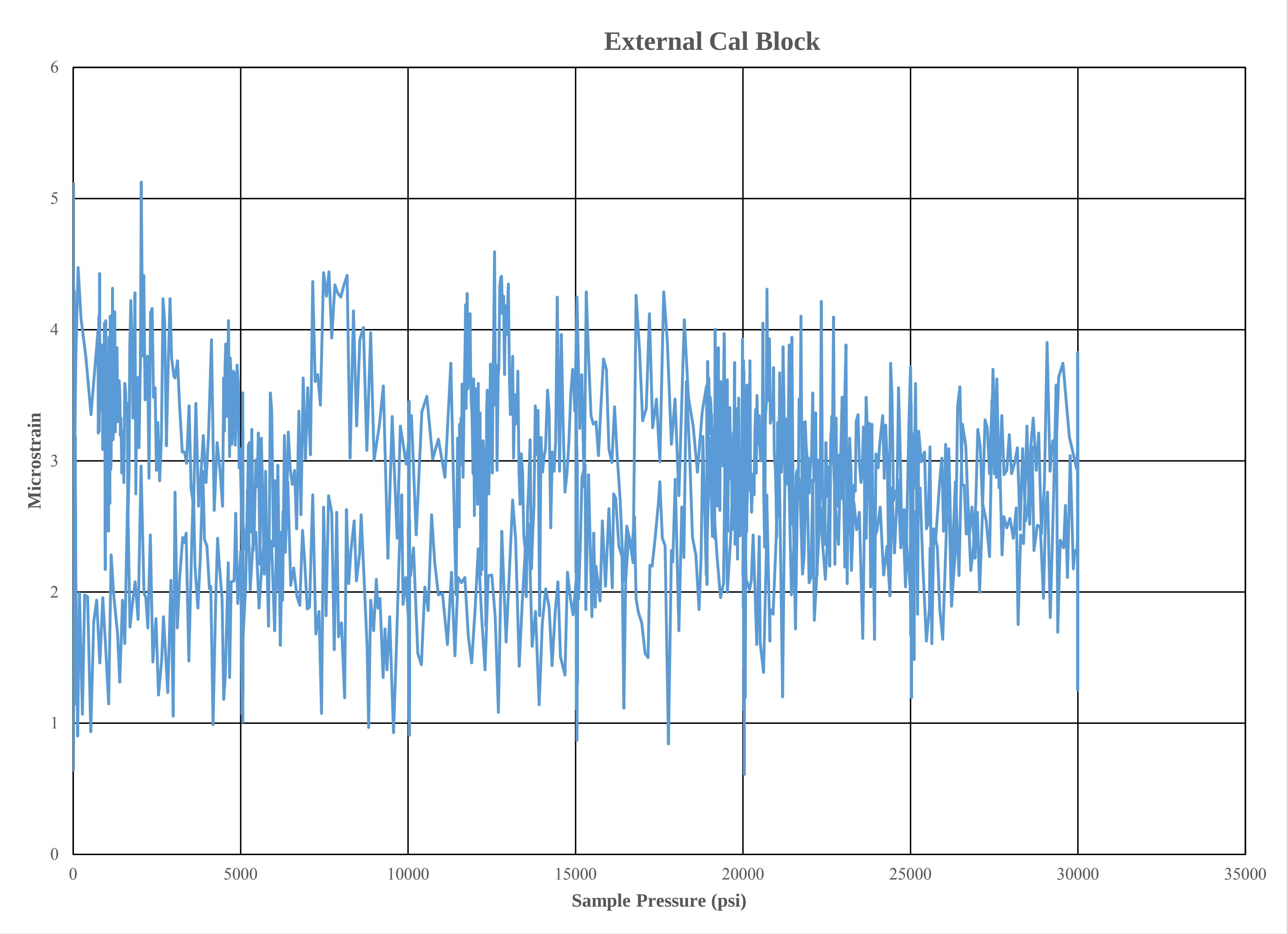

Location 5A, Axial
Microstrain
160
140
120
100
80
60
40
20
0
-20
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Location 5B, Hoop
500
450
400
350
300
250
200
150
100
50
0
-50
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)



Location 5B, Axial
160
140
120
100
80
60
40
20
0
-20
Microstrain
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


Internal Cal Block
Microstrain
2500
2000
1500
1000
500
0
0
5000
10000
15000
20000
25000
30000
35000
Sample Pressure (psi)


External Cal Block
Microstrain
0
1
2
3
4
5
6
Sample Pressure (psi)
0
5000
10000
15000
20000
25000
30000
35000

APPENDIX II

EQUIPMENT CALIBRATION SHEETS

Southwest Research Institute

Calibration Certificate

ACCREDITED

Calibration Laboratory
Certificate # 3759.01

Cost Center:	18 MECHANICAL & MATERIALS ENGINEERING	Certificate Number:	41643
Asset Number:	020122	Calibrated:	11/5/2015
Description:	PRESSURE TRANSDUCER	Calibration Due:	5/5/2016
Manufacturer:	SENSOTEC	Data Type:	FOUND / LEFT
Model Number:	A5/B489-02	Temp./RH:	68 °F / 41 %
Serial Number:	559498	Work Order #	403135480
Calibration Procedure:	PRESSURE GAUGES		

This certificate documents traceability to the International System of Units (SI) through the National Institute of Standards and Technology (NIST) or other national metrology institute. The laboratory quality system is compliant to ISO/IEC 17025 2005, ANSI/NCSL Z540-1-1994 and relevant requirements of ISO 9001-2008. This certificate shall not be reproduced, except in full, without written approval of Southwest Research Institute Calibration Laboratory and shall not be used to claim product endorsement by SwRI® or any agency of the U.S. Government.

Results of this calibration relate only to the instrument described above at the time of calibration and does not imply any long term stability. Date due for recalibration is determined by the customer and does not imply the instrument will remain within limits, as any number of factors may cause an out of tolerance condition before this date.

Data type shall be interpreted as follows: Found-left - data recorded and no adjustment or repair was performed. As-left - data recorded after adjustment or repair was performed. As-found data are reviewed and the customer notified when the as-found results are other than pass and/or greater than 70 percent of the test limit. Pass? or Fail? indicate the measured value, plus or minus the expanded uncertainty, overlap the test limit and it is not possible to state Pass or Fail with a 95% confidence level. No statement of compliance with manufacturer or other specification is made or implied by this certificate. The customer has sole responsibility for determination of in/out-of-tolerance or compliance/noncompliance for the intended use of the instrument.

Measurement uncertainties are calculated in accordance with the methods described in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) as an expanded uncertainty with a coverage factor of k = 2 to approximately a 95% level of confidence. See Remarks or attached Measurement Report with the same Work Order number for data.

Remarks:

Calibrated with display S/N 14831.

Standards Used To Calibrate Equipment

Asset	Manufacturer	Model	Description	Cal. Due Date
017617	FLUKE	PC-7300-2	PISTON CYLINDER, OIL 2MPA/KG	1/16/2016
017619	FLUKE	MS-7000	MASS SET	2/11/2016
020448	FLUKE	MB-7002-0.8	MASS CARRYING BELL	1/27/2016
020449	FLUKE	PG-7302	PLATFORM, OIL 72 KPSI	1/23/2016

Approved By

Calibrated By: RLC
Metrology Technician

Institute Calibration Laboratory, Bldg. 64, San Antonio, TX 78227, ext. 5215

Southwest Research Institute
Calibration Laboratory
Measurement Report

Work Order:	403135480	Mfr:	Sensotec	Technician:	RLC
Asset No.:	020122	Model:	A5/B489-02	Type Data:	Found-left
Serial No.:	559498	Type:	Pressure Transducer	Cal Date:	5-Nov-15

Remarks: Calibrated with display S/N 14831. Shunt values: Position 1 = 4865, Position 4 = 1671.

Function/Range	Test Point	TI Reading	Difference	± Limit	± Uncertainty	Result	% Limit
Voltage output for	psi	psi	psi	psi	psi		
pressure applied	0	0	0	50	2.5	Pass	0%
	2000	2008	-8			Pass	16%
	4000	4014	-14			Pass	28%
	6000	6015	-15			Pass	30%
	8000	8013	-13			Pass	26%
	10000	10009	-9			Pass	18%
	8000	8016	-16			Pass	32%
	6000	6018	-18			Pass	36%
	4000	4017	-17			Pass	34%
	2000	2010	-10			Pass	20%
	0	0	0			Pass	0%

END OF REPORT

U:\CC30\ICL\Data Sheets\Pressure\Sensotec A-5 Series 10000 psi Transducer w-display_28 Jan 15

Southwest Research Institute

Calibration Certificate

Calibration Laboratory
Certificate # 3759.01

Cost Center:	18 MECHANICAL & MATERIALS ENGINEERING	Certificate Number:	41919
Asset Number:	020121	Calibrated:	11/11/2015
Description:	PRESSURE TRANSDUCER	Calibration Due:	5/11/2016
Manufacturer:	SENSOTEC	Data Type:	FOUND / LEFT
Model Number:	HP/8810-02	Temp./RH:	68 °F / 40 %
Serial Number:	889788	Work Order #	403135553
Calibration Procedure:	PRESSURE GAUGES		

This certificate documents traceability to the International System of Units (SI) through the National Institute of Standards and Technology (NIST) or other national metrology institute. The laboratory quality system is compliant to ISO/IEC 17025 2005, ANSI/NCSL Z540-1-1994 and relevant requirements of ISO 9001-2008. This certificate shall not be reproduced, except in full, without written approval of Southwest Research Institute Calibration Laboratory and shall not be used to claim product endorsement by SwRI® or any agency of the U.S. Government.

Results of this calibration relate only to the instrument described above at the time of calibration and does not imply any long term stability. Date due for recalibration is determined by the customer and does not imply the instrument will remain within limits, as any number of factors may cause an out of tolerance condition before this date.

Data type shall be interpreted as follows: Found-left - data recorded and no adjustment or repair was performed. As-left - data recorded after adjustment or repair was performed. As-found data are reviewed and the customer notified when the as-found results are other than pass and/or greater than 70 percent of the test limit. Pass? or Fail? indicate the measured value, plus or minus the expanded uncertainty, overlap the test limit and it is not possible to state Pass or Fail with a 95% confidence level. No statement of compliance with manufacturer or other specification is made or implied by this certificate. The customer has sole responsibility for determination of in/out-of-tolerance or compliance/noncompliance for the intended use of the instrument.

Measurement uncertainties are calculated in accordance with the methods described in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) as an expanded uncertainty with a coverage factor of k = 2 to approximately a 95% level of confidence. See Remarks or attached Measurement Report with the same Work Order number for data.

Remarks:
Calibrated to 72500 psig with display S/N 1303324.

Standards Used To Calibrate Equipment

Asset	Manufacturer	Model	Description	Cal. Due Date
017616	FLUKE	PC-7300-5	PISTON CYLINDER, OIL 5MPA/KG	11/7/2016
017619	FLUKE	MS-7000	MASS SET	2/11/2016
020448	FLUKE	MB-7002-0.8	MASS CARRYING BELL	1/27/2016
020449	FLUKE	PG-7302	PLATFORM, OIL 72 KPSI	1/23/2016

Approved By

Calibrated By: RLC
Metrology Technician

Southwest Research Institute
Calibration Laboratory
Measurement Report

Work Order:	403135553	Mfr:	Honeywell	Technician:	RLC
Asset No.:	020121	Model:	HP/8810-02	Type Data:	Found-left
Serial No.:	889788	Type:	Pressure Transducer	Cal Date:	11-Nov-15

Remarks: Calibrated with display S/N 1303324, from 0 to 72500 psig per customer request.

Function/Range	Test Point	TI Reading	Difference	± Limit	± Uncertainty	Result	% Limit
Displayed pressure	psi	psi	psi	psi	psi		
	0	0	0	500	37	Pass	0%
	14500	14499	-1			Pass	0%
	29000	28998	-2			Pass	0%
	43500	43496	-4			Pass	1%
	58000	57915	-85			Pass	17%
	72500	72507	7			Pass	1%
	58000	57918	-82			Pass	16%
	43500	43485	-15			Pass	3%
	29000	29000	0			Pass	0%
	14500	14494	-6			Pass	1%
	0	-18	-18			Pass	4%

END OF REPORT

Southwest Research Institute

Calibration Certificate

Calibration Laboratory
Certificate # 3759.01

Cost Center:	18 MECHANICAL & MATERIALS ENGINEERING	Certificate Number:	47924
Asset Number:	016644	Calibrated:	3/4/2016
Description:	THERMOCOUPLE CALIBRATOR	Calibration Due:	3/4/2017
Manufacturer:	FLUKE	Data Type:	FOUND / LEFT
Model Number:	714	Temp./RH:	73.6ºF / 43 %
Serial Number:	1131008	Work Order #	403137749
Calibration Procedure:	FLUKE 71X SERIES		

This certificate documents traceability to the International System of Units (SI) through the National Institute of Standards and Technology (NIST) or other national metrology institute. The laboratory quality system is compliant to ISO/IEC 17025 2005, ANSI/NCSL Z540-1-1994 and relevant requirements of ISO 9001-2008. This certificate shall not be reproduced, except in full, without written approval of Southwest Research Institute Calibration Laboratory and shall not be used to claim product endorsement by SwRI® or any agency of the U.S. Government.

Results of this calibration relate only to the instrument described above at the time of calibration and does not imply any long term stability. Date due for recalibration is determined by the customer and does not imply the instrument will remain within limits, as any number of factors may cause an out of tolerance condition before this date.

Data type shall be interpreted as follows: Found-left - data recorded and no adjustment or repair was performed. As-left - data recorded after adjustment or repair was performed. As-found data are reviewed and the customer notified when the as-found results are other than pass and/or greater than 70 percent of the test limit. Pass? or Fail? indicate the measured value, plus or minus the expanded uncertainty, overlap the test limit and it is not possible to state Pass or Fail with a 95% confidence level. No statement of compliance with manufacturer or other specification is made or implied by this certificate. The customer has sole responsibility for determination of in/out-of-tolerance or compliance/noncompliance for the intended use of the instrument.

Measurement uncertainties are calculated in accordance with the methods described in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) as an expanded uncertainty with a coverage factor of k = 2 to approximately a 95% level of confidence. See Remarks or attached Measurement Report with the same Work Order number for data.

Remarks:

Standards Used To Calibrate Equipment

Asset	Manufacturer	Model	Description	Cal. Due Date
004164	FLUKE	5500A/SC300	CALIBRATOR MULTI - PRODUCT	2/26/2017
012066	AGILENT-HP	3458A OPT 002	MULTIMETER	7/23/2016

Approved By

Calibrated By: CER
Metrology Technician

Southwest Research Institute
Calibration Laboratory
Measurement Report

Work Order:	403137749	Mfr.	Fluke	Technician:	CER
Asset No.	016644	Model	714	Type Data:	Found-left
Serial No.	1131008	Type	Thermocouple Calibrator	Cal Date:	4-Mar-16
Remarks:					

Function/Range	Test Point	TI Reading	Difference	± Limit	± Uncertainty	Result	% Limit
Type J Read	°C	°C	°C	°C	°C		
	-200.0	-200.3	-0.3	0.6	0.44	Pass	50%
	0.0	-0.1	-0.1	0.4	0.18	Pass	25%
	800.0	800.0	0.0	0.4	0.29	Pass	0%
	1200.0	1200.1	0.1	0.5	0.29	Pass	20%
	°F	°F	°F	°F	°F		
	-320.0	-320.5	-0.5	1.4	0.7	Pass	36%
	32.0	31.8	-0.2	0.9	0.3	Pass	22%
	2000.0	2000.0	0.0	0.9	0.5	Pass	0%
Type K Read	°C	°C	°C	°C	°C		
	-190.0	-190.2	-0.2	0.9	0.49	Pass	22%
	0.0	-0.1	-0.1	0.6	0.21	Pass	17%
	1300.0	1300.0	0.0	0.6	0.47	Pass	0%
	°F	°F	°F	°F	°F		
	-300.0	-300.3	-0.3	1.6	0.71	Pass	19%
	32.0	31.8	-0.2	1.0	0.36	Pass	20%
	2300.0	2300.0	0.0	1.0	0.84	Pass	0%
mV Read	mVolts	mVolts	mVolts	mVolts	mVolts		
	-10.000	-10.000	0.000	0.012	0.015	Pass	0%
	30.000	30.002	0.002	0.025	0.015	Pass	8%
	75.000	75.006	0.006	0.021	0.015	Pass	29%
mV Source	mVolts	mVolts	mVolts	mVolts	mVolts		
	-10.000	-9.992	0.008	0.012	0.001	Pass	66%
	30.000	30.003	0.003	0.025	0.001	Pass	14%
	75.000	74.998	-0.002	0.021	0.001	Pass	12%
Type J Source	°C	°C	°C	°C	°C		
	-200.00	-199.64	0.36	0.60	0.33	Pass	60%
	0.00	0.00	0.00	0.40	0.17	Pass	0%
	800.00	800.15	0.15	0.40	0.27	Pass	37%
	1200.00	1200.08	0.08	0.50	0.27	Pass	16%

END OF REPORT

Southwest Research Institute

Calibration Certificate

ACCREDITED

Calibration Laboratory
Certificate # 3759.01

Cost Center:	18 MECHANICAL ENGINEERING	Certificate Number:	49570
Asset Number:	021857	Calibrated:	3/31/2016
Description:	PRESSURE TRANSDUCER	Calibration Due:	9/30/2016
Manufacturer:	HONEYWELL	Data Type:	AS LEFT
Model Number:	TJE	Temp./RH:	68 °F / 39 %
Serial Number:	1467253	Work Order #	403138268
Calibration Procedure:	PRESSURE GAUGES		

This certificate documents traceability to the International System of Units (SI) through the National Institute of Standards and Technology (NIST) or other national metrology institute. The laboratory quality system is compliant to ISO/IEC 17025 2005, ANSI/NCSL Z540-1-1994 and relevant requirements of ISO 9001-2008. This certificate shall not be reproduced, except in full, without written approval of Southwest Research Institute Calibration Laboratory and shall not be used to claim product endorsement by SwRI® or any agency of the U.S. Government.

Results of this calibration relate only to the instrument described above at the time of calibration and does not imply any long term stability. Date due for recalibration is determined by the customer and does not imply the instrument will remain within limits, as any number of factors may cause an out of tolerance condition before this date.

Data type shall be interpreted as follows: Found-left - data recorded and no adjustment or repair was performed. As-left - data recorded after adjustment or repair was performed. As-found data are reviewed and the customer notified when the as-found results are other than pass and/or greater than 70 percent of the test limit. Pass? or Fail? indicate the measured value, plus or minus the expanded uncertainty, overlap the test limit and it is not possible to state Pass or Fail with a 95% confidence level. No statement of compliance with manufacturer or other specification is made or implied by this certificate. The customer has sole responsibility for determination of in/out-of-tolerance or compliance/noncompliance for the intended use of the instrument.

Measurement uncertainties are calculated in accordance with the methods described in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) as an expanded uncertainty with a coverage factor of k = 2 to approximately a 95% level of confidence. See Remarks or attached Measurement Report with the same Work Order number for data.

Remarks:

Calibrared with display S/N 1423727.

Standards Used To Calibrate Equipment

Asset	Manufacturer	Model	Description	Cal. Due Date
017616	FLUKE	PC-7300-5	PISTON CYLINDER, OIL 5MPA/KG	11/7/2016
017619	FLUKE	MS-7000	MASS SET	4/9/2018
020448	FLUKE	MB-7002-0.8	MASS CARRYING BELL	1/26/2017
020449	FLUKE	PG-7302	PLATFORM, OIL 72 KPSI	1/25/2017

Authorized Signatory

Calibrated By: PWC
Metrology Technician

Institute Calibration Laboratory, Bldg. 64, San Antonio, TX 78227, ext. 5215

Southwest Research Institute
Calibration Laboratory
Measurement Report

Work Order:	403138268	Mfr:	Honeywell	Technician:	PWC
Asset No.:	021857	Model:	TJE	Type Data:	As-found
Serial No.:	1467253	Type:	Pressure Transducer	Cal Date:	29-Mar-16

Remarks: Calibrated with display S/N 1423727.

Function/Range	Test Point	TI Reading	Difference	± Limit	± Uncertainty	Result	% Limit
Displayed pressure	psi	psi	psi	psi	psi		
	0	-12	-12	30	3.3	Pass	40%
	6000	5999	-1			Pass	3%
	12000	12010	10			Pass	33%
	18000	18017	17			Pass	57%
	24000	24020	20			Pass	67%
	30000	30020	20			Pass	67%
	24000	24027	27			Pass	90%
	18000	18027	27			Pass	90%
	12000	12021	21			Pass	70%
	6000	6010	10			Pass	33%
	0	-8	-8			Pass	27%

END OF REPORT

Southwest Research Institute
Calibration Laboratory
Measurement Report

Work Order:	403138268	Mfr:	Honeywell	Technician:	PWC
Asset No.:	021857	Model:	TJE	Type Data:	As-left
Serial No.:	1467253	Type:	Pressure Transducer	Cal Date:	31-Mar-16

Remarks: Calibrated with display sn 1423727. Adjusted.

Function/Range	Test Point	TI Reading	Difference	± Limit	± Uncertainty	Result	% Limit
Displayed pressure	psi	psi	psi	psi	psi		
	0	1	1	30	3.3	Pass	3%
	6000	6003	3			Pass	10%
	12000	12004	4			Pass	13%
	18000	18005	5			Pass	17%
	24000	24009	9			Pass	30%
	30000	30002	2			Pass	7%
	24000	24015	15			Pass	50%
	18000	18011	11			Pass	37%
	12000	12012	12			Pass	40%
	6000	6010	10			Pass	33%
	0	1	1			Pass	3%

END OF REPORT

APPENDIX III

STRAIN GAGE LOCATIONS

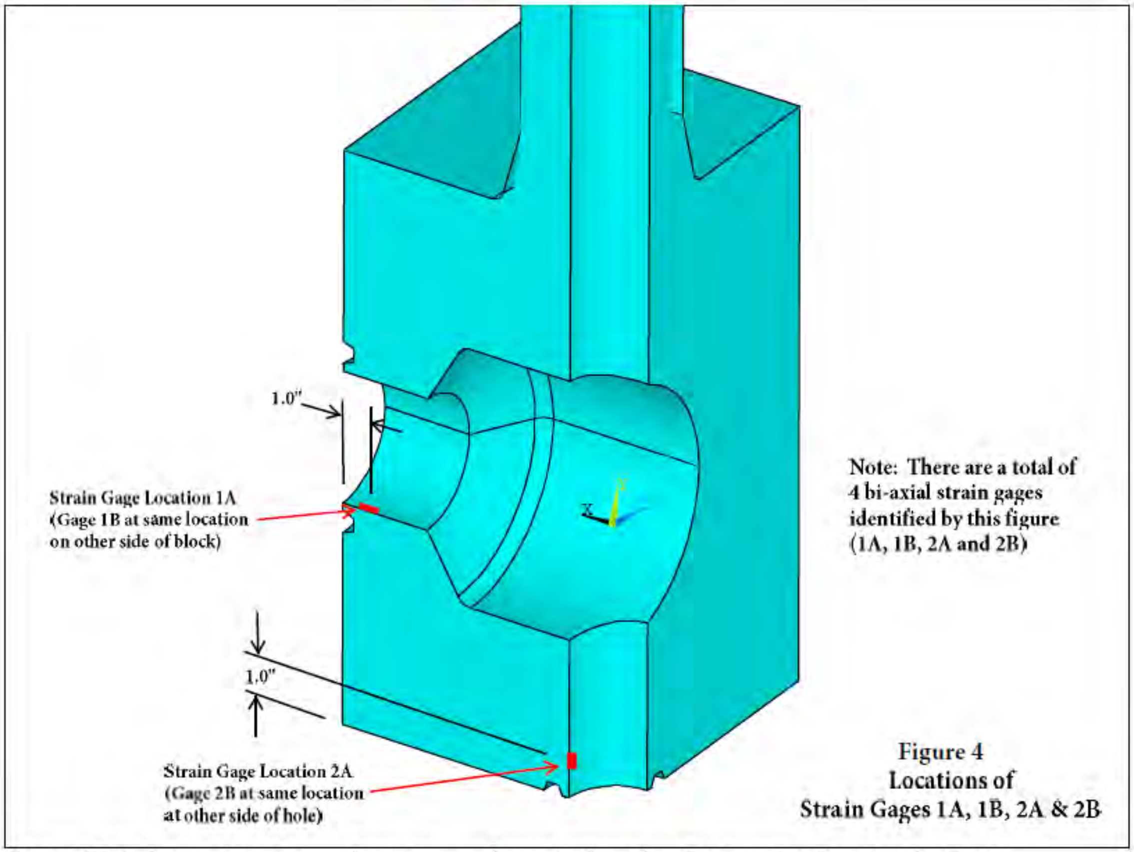


Figure III-1. Internal strain gage locations, as shown in the Aiken Engineering Requiest for Quote.

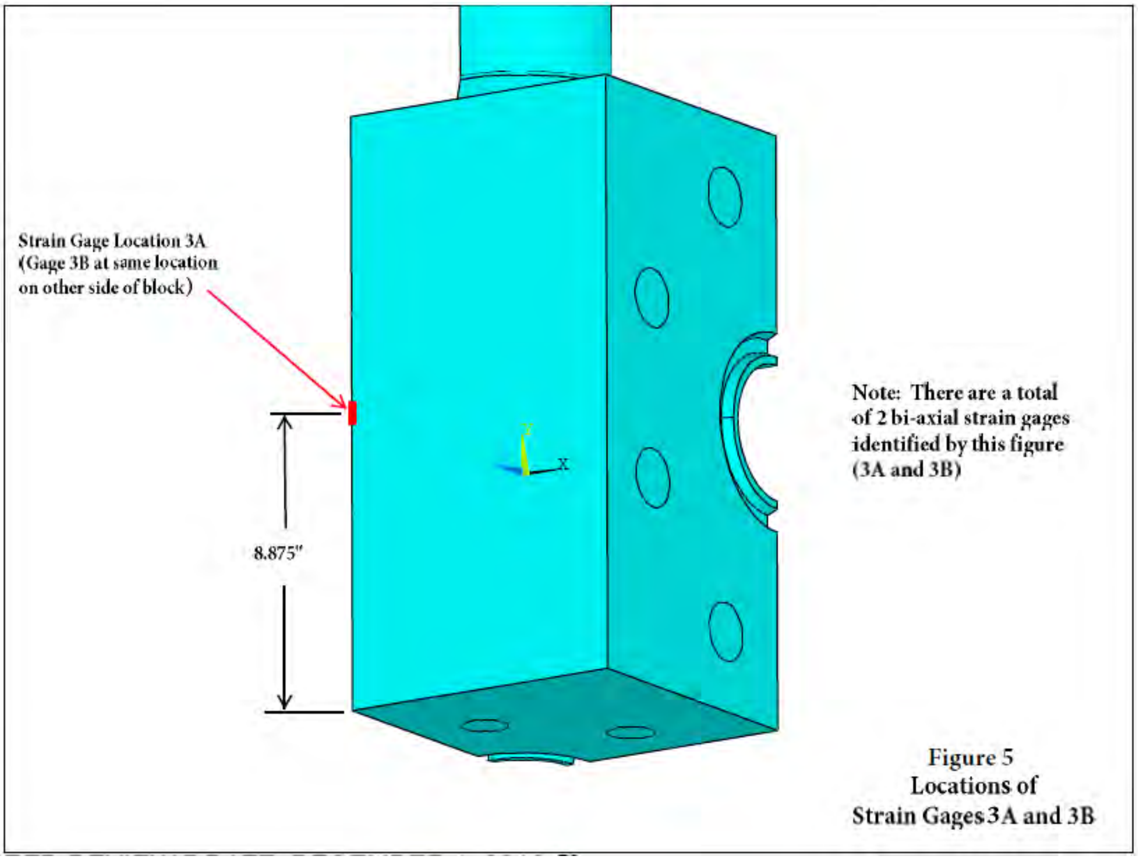


Figure III-2. External strain gage locations, as shown in the Aiken Engineering Requiest for Quote.

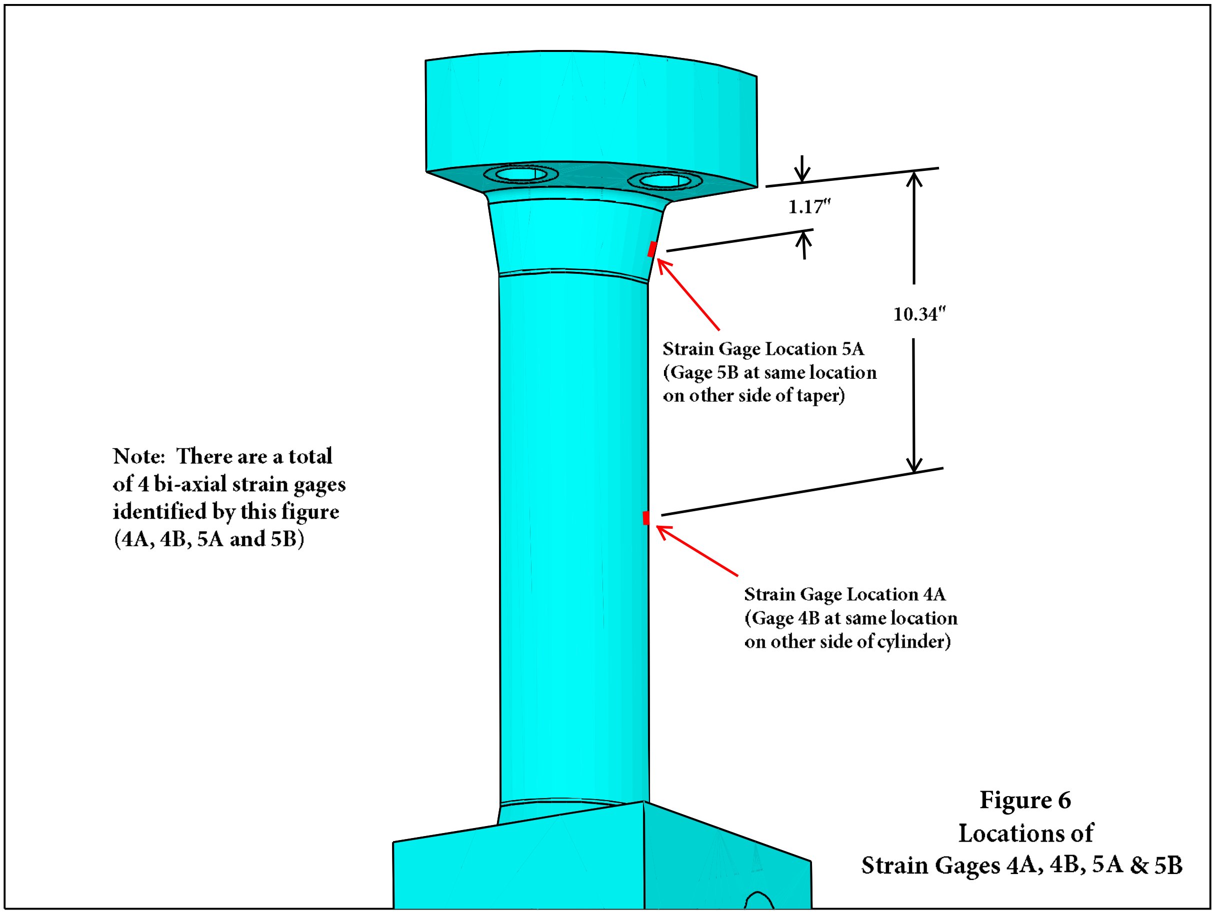


Figure III-3. External strain gage locations, as shown in the Aiken Engineering Requiest for Quote.

APPENDIX IV

PHOTOGRAPHS

Figure IV-1. Small Valve Body

Figure IV-2. Small Valve Body.

Figure IV-3. Small Valve Body.

Figure IV-4. Large Valve Body.

Figure IV-5. Large Valve Body.

Figure IV-6. Large Valve Body.

Figa.rt IV-7. Small Vain Body SecL:Afttr Burst Test.

Figure IV-8. Large Valve Body Neck After Burst Test.

APPENDIX D

VALIDATION OF FEA RESULTS

In Section 6.3 of the main body of this report, collapse pressures from FEAs were compared with burst pressures from hydrotests. For conclusions from this comparison to be correct, it is imperative that FEAs are accurate. The most reliable method of validating the accuracy of a FEA is comparing FEA results with test results. For the purpose of validating FEAs of the test bodies, strain gages were attached to the two test bodies, and strain data were recorded throughout the hydrotest program. Then strains that were measured during hydrotests were compared to strains calculated by the FEAs.

The SwRI test report is included in Appendix C2. Pages C-83 and C-84 show the locations of strain gages on the two test bodies. Ten biaxial strain rosettes were attached to each test body. Five rosettes (1A, 2A, 3A, 4A, and 5A) were placed at critical locations, and the other five (1B, 2B, 3B, 4B, and 5B) were placed at a symmetrical location on the other side of the test body. All of the biaxial rosettes were attached with one gage oriented in the axial direction and another gage oriented in the hoop direction.

Two pairs of rosettes were placed in the small bores inside each test body. These rosettes were designated as 1A, 1B, 2A, and 2B. A review of the strain plots in the SwRI report shows that data from the bore rosettes were not linear and were unstable. This was probably caused by the rosettes' proximity to the seal rings, which could have slipped and moved during hydrotesting. For this reason, the bore gage results were not considered in this study. The study only considered rosettes 3A, 3B, 4A, 4B, 5A, and 5B.

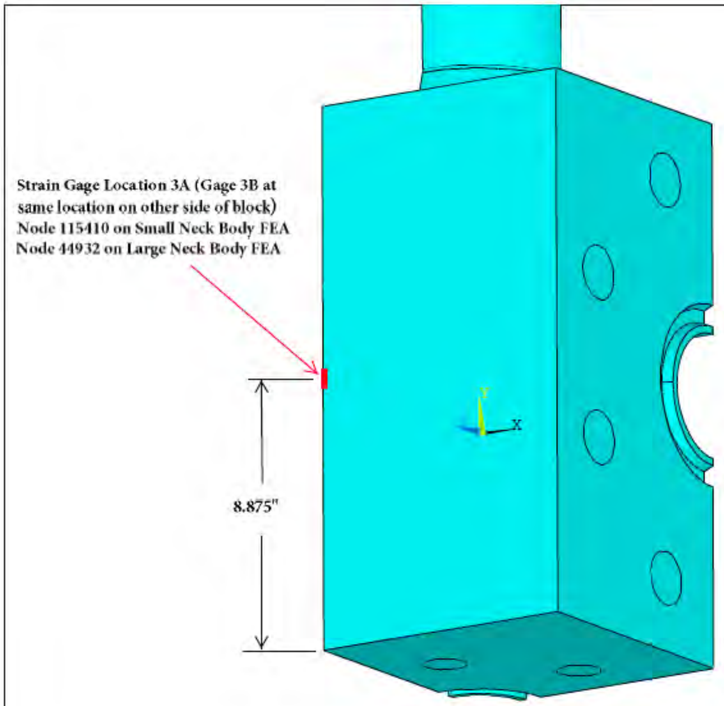
Figure D1 shows the locations of rosettes 3, 4, and 5. Figure D1 also lists the node numbers of finite element models for the two test bodies. Two node numbers are listed at each location. One is for the large neck test body, and the other is for the small neck test body.

The strain data compared with FEA strains was gathered during the initial hydrotest of each body. Plots of the strains during this test are provided in the following pages of the SwRI report:

Pages C-50 through C-71 for the large neck test body
Pages C-27 through C-47 for the small neck test body

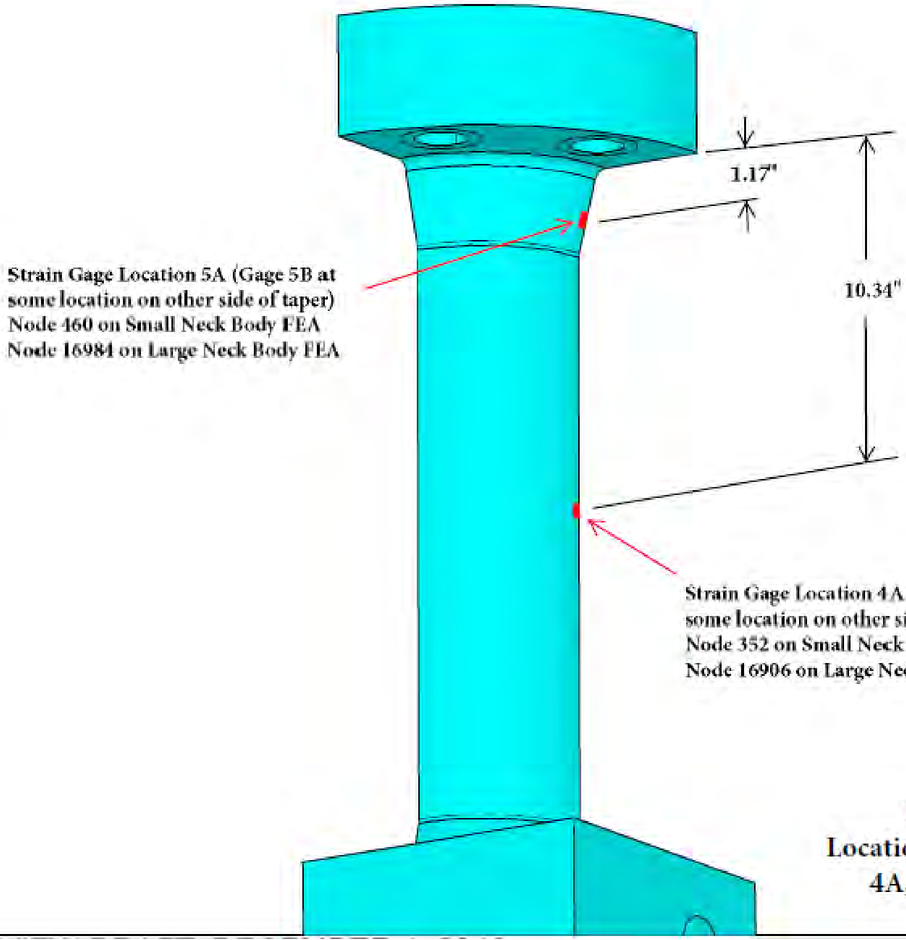
Table D1 compares strains from FEAs with strains from hydrotesting. Table D1.1 compares strains in the large neck test body, and Table D1.2 compares strains in the small neck test body. The last columns in Tables D1.1 and D1.2 show the percentage difference between strains from FEAs and strains from hydrotesting. The comparison is very favorable for gages 3A, 3B, 4A, and 4B, but not for gages 5A and 5B. A review of Figure 6.5 shows that gages 5A and 5B were located very near a flange connection. The flange connection could have caused the poor strain comparison at gages 5A and 5B. Flange preload strains at gage 5 are included in the hydrotest strains, but are not included in the FEA strains. The reason preload strains are not included in the FEA is that Division 2 and 3 procedures do not include preload for a global plastic collapse analysis.

Gages 4A and 4B are at the critical locations in the test bodies because they are located at the rupture locations. Since the comparison of strains from FEAs and tests are within 4 percent at the critical locations, the FEA results at the critical locations are validated by test results.



Strain Gage Location 3A (Gage 3B at same location on other side of block)
Node 115410 on Small Neck Body FEA
Node 44932 on Large Neck Body FEA

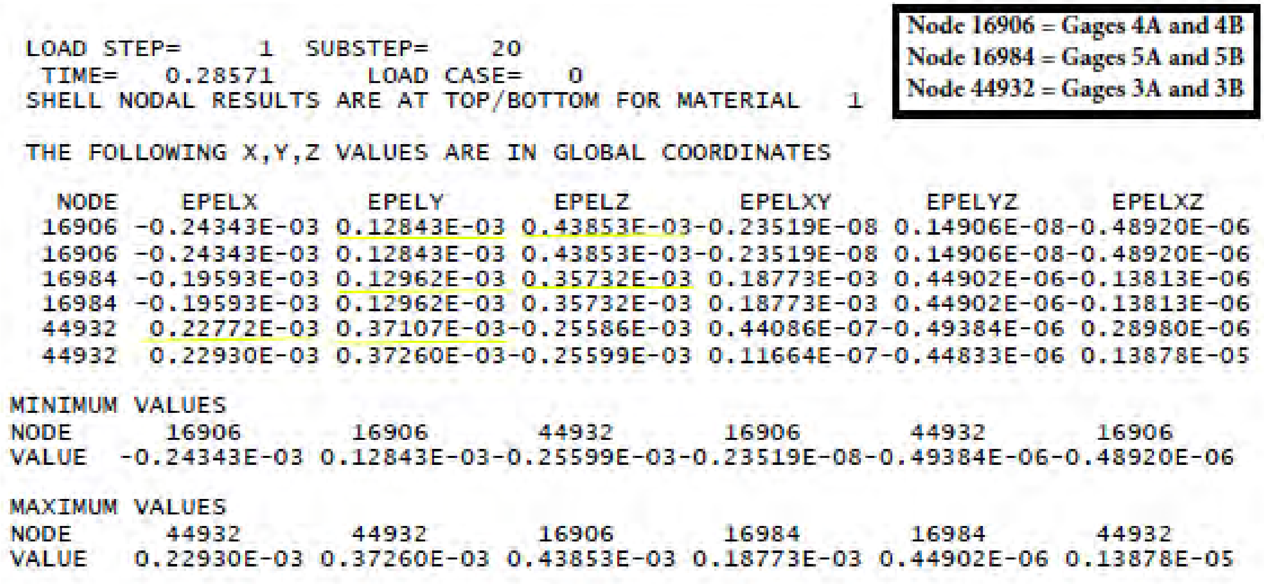
Figure D1.1
Locations of Strain Gages
3A and 3B



Strain Gage Location 5A (Gage 5B at some location on other side of taper)
Node 460 on Small Neck Body FEA
Node 16984 on Large Neck Body FEA

Strain Gage Location 4A (Gage 4B at some location on other side of cylinder)
Node 352 on Small Neck Body FEA
Node 16906 on Large Neck Body FEA

Figure D1.2
Locations of Strain Gages
4A, 4B, 5A and 5B



Node 16906 = Gages 4A and 4B
Node 16984 = Gages 5A and 5B
Node 44932 = Gages 3A and 3B

```
 LOAD STEP=      1  SUBSTEP=    20
  TIME=   0.28571       LOAD CASE=   0
 SHELL NODAL RESULTS ARE AT TOP/BOTTOM FOR MATERIAL   1

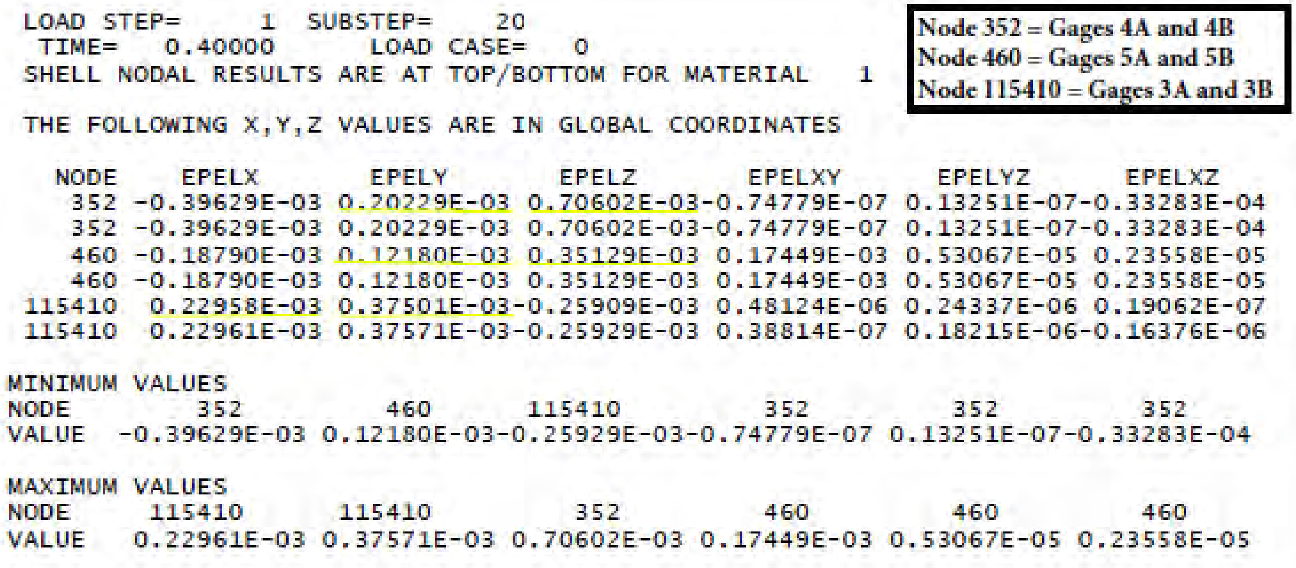
 THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES

    NODE     EPELX        EPELY        EPELZ        EPELXY       EPELYZ       EPELXZ
   16906 -0.24343E-03 0.12843E-03 0.43853E-03-0.23519E-08 0.14906E-08-0.48920E-06
   16906 -0.24343E-03 0.12843E-03 0.43853E-03-0.23519E-08 0.14906E-08-0.48920E-06
   16984 -0.19593E-03 0.12962E-03 0.35732E-03 0.18773E-03 0.44902E-06-0.13813E-06
   16984 -0.19593E-03 0.12962E-03 0.35732E-03 0.18773E-03 0.44902E-06-0.13813E-06
   44932  0.22772E-03 0.37107E-03-0.25586E-03 0.44086E-07-0.49384E-06 0.28980E-06
   44932  0.22930E-03 0.37260E-03-0.25599E-03 0.11664E-07-0.44833E-06 0.13878E-05

MINIMUM VALUES
NODE       16906        16906        44932        16906        44932        16906
VALUE  -0.24343E-03 0.12843E-03-0.25599E-03-0.23519E-08-0.49384E-06-0.48920E-06

MAXIMUM VALUES
NODE       44932        44932        16906        16984        16984        44932
VALUE   0.22930E-03 0.37260E-03 0.43853E-03 0.18773E-03 0.44902E-06 0.13878E-05
```

Table D1.1 Strains from FEA Solution of Large Neck Test Body at 20 ksi



Node 352 = Gages 4A and 4B
Node 460 = Gages 5A and 5B
Node 115410 = Gages 3A and 3B

```
 LOAD STEP=      1  SUBSTEP=    20
  TIME=   0.40000       LOAD CASE=   0
 SHELL NODAL RESULTS ARE AT TOP/BOTTOM FOR MATERIAL   1

 THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES

    NODE     EPELX        EPELY        EPELZ        EPELXY       EPELYZ       EPELXZ
     352 -0.39629E-03 0.20229E-03 0.70602E-03-0.74779E-07 0.13251E-07-0.33283E-04
     352 -0.39629E-03 0.20229E-03 0.70602E-03-0.74779E-07 0.13251E-07-0.33283E-04
     460 -0.18790E-03 0.12180E-03 0.35129E-03 0.17449E-03 0.53067E-05 0.23558E-05
     460 -0.18790E-03 0.12180E-03 0.35129E-03 0.17449E-03 0.53067E-05 0.23558E-05
  115410  0.22958E-03 0.37501E-03-0.25909E-03 0.48124E-06 0.24337E-06 0.19062E-07
  115410  0.22961E-03 0.37571E-03-0.25929E-03 0.38814E-07 0.18215E-06-0.16376E-06

MINIMUM VALUES
NODE         352          460       115410          352          352          352
VALUE  -0.39629E-03 0.12180E-03-0.25929E-03-0.74779E-07 0.13251E-07-0.33283E-04

MAXIMUM VALUES
NODE      115410       115410          352          460          460          460
VALUE   0.22961E-03 0.37571E-03 0.70602E-03 0.17449E-03 0.53067E-05 0.23558E-05
```

Table D1.2 Strains from FEA Solution of Small Neck Test Body at 20 ksi

Table D1 Comparison of Strains from Strain Gages and FEA

Table D1.1 Large Neck Test Body

Strain Gage ID	Strain Gage Direction	SwRI Report Page	Microstrain from Strain Gage	FEA Node Number	Microstrain from FEA	Error between Strain Gage and FEA
3A	Hoop	C-58	240	44932	228	5.0%
3A	Axial	C-59	370	44932	371	-0.3%
3B	Hoop	C-60	225	44932	228	-1.3%
3B	Axial	C-61	375	44932	371	1.1%
4A	Hoop	C-62	455	16906	439	3.5%
4A	Axial	C-63	125	16906	128	-2.4%
4B	Hoop	C-64	450	16906	439	2.4%
4B	Axial	C-65	125	16906	128	-2.4%
5A	Hoop	C-66	290	16984	357	-23.1%
5A	Axial	C-67	90	16984	130	-44.4%
5B	Hoop	C-68	280	16984	357	-27.5%
5B	Axial	C-69	85	16984	130	-52.9%

Note: Plot on SwRI report for gages 5A and 5B indicate a problem with the rossettes

Table D1.2 Small Neck Test Body

Strain Gage ID	Strain Gage Direction	SwRI Report Page	Microstrain from Strain Gage	FEA Node Number	Microstrain from FEA	Error between Strain Gage and FEA
3A	Hoop	C-35	225	115410	230	-2.2%
3A	Axial	C-36	360	115410	375	-4.2%
3B	Hoop	C-37	225	115410	230	-2.2%
3B	Axial	C-38	360	115410	375	-4.2%
4A	Hoop	C-39	730	352	706	3.3%
4A	Axial	C-40	195	352	202	-3.6%
4B	Hoop	C-41	730	352	706	3.3%
4B	Axial	C-42	195	352	202	-3.6%
5A	Hoop	C-43	285	460	351	-23.2%
5A	Axial	C-44	85	460	122	-43.5%
5B	Hoop	C-45	300	460	351	-17.0%
5B	Axial	C-46	90	460	122	-35.6%

Note: Plot on SwRI report for gages 5A and 5B indicate a problem with the rossettes

APPENDIX E

PRESSURE RATINGS BY PROOF TESTING

Many pressure codes designate methods for determining pressure ratings based on a hydrostatic proof test. Generally, the procedure is to build a prototype of the component or the assembly and apply an incrementally larger hydrostatic pressure until burst occurs. The allowable pressure rating is the hydrostatic test pressure at burst multiplied by a load reduction factor that is specified by the code.

The following is a discussion of the requirements in the pressure codes considered in this study that allow use of the proof test to establish pressure rating. This is followed by calculations for allowable pressure ratings by proof test methods for the two test bodies in this study.

Pressure Ratings of Test Bodies by Proof Test Rules in API 6A

Section 4.3.3.5.1, titled “Design Qualification by Proof Test,” describes the procedure in API 6A for establishing pressure rating by proof test. If the actual yield strength from tensile testing is known, then the equation for pressure rating is

$$P = 0.5\ W\ (Sy/Sr)$$

where,

P = pressure rating
W = the maximum hydrostatic pressure when the test was stopped
Sy = specified minimum yield strength
Sr = actual average

The specified and actual yield strengths of the test bodies are

Sy = 75,000 psi
Sr = 92,200 psi

The burst pressures of the two test bodies were

Pbs = 51,469 psi…….burst pressure of small neck test body
Pbl = 67,959 psi…….burst pressure of large neck test body

Hence, according to API 6A rules, the maximum allowable pressure ratings by proof test are

Prs = (0.5) (51,469) (75,000/92,200)
Prs = 20,934 psi……allowable pressure rating of small neck test body by API 6A

Prs = (0.5) (67,959) (75,000/92,200)
Prs = 27,641 psi…….allowable pressure rating of large neck test body by API 6A

Pressure Ratings of Test Bodies by Rules in ASME Section VIII Division 3

Article KD-1254, titled “Determination of Maximum Design Pressure at Room Temperature,” also describes procedures for establishing pressure rating by proof test. When actual yield strengths have been determined by tensile tests, the basic equation for pressure rating is

$$P = (1/1.732)\ CP\ (Sy/Sr)$$

where,

CP = collapse pressure or the maximum hydrostatic pressure when the test was stopped

Hence, the maximum allowable pressure ratings for the test bodies based on proof test are

$$Prs = (1/1.732)\ (51{,}469)\ (75{,}000/92{,}200)$$

Prs = 24,173 psi……maximum allowable pressure rating of small neck test body

$$Prs = (1/1.732)\ (67{,}959)\ (75{,}000/92{,}200)$$

Prs = 31,918 psi……maximum allowable pressure rating of large neck test body

Pressure Rating by Proof Test Rules in ASME Section VIII Division 2

Division 2 does not include a procedure for establishing maximum allowable pressure ratings by proof test.

APPENDIX F

MISCELLANEOUS DOCUMENTS

Forged Products, Inc.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091
Phone 713-462-3416
Fax 713-460-9404

FPI
FORGED PRODUCTS, INC.

CERTIFICATE OF COMPLIANCE

Customer Name:		**Purchase Order No.**	**Part No.**		**Qty**	**Date**
AIKEN ENGINEERING CO.		2456-11-10-2015 LN 1	2456-200 Rev 0		2	2/17/2016
Description			**Serial Number(s)**	**Drawing Number (s)**		
TEST BODY, API 17 EVAL 3-1/16 – 20K (F22)			AH450-2E1 AH450-2E2	PN2456-200 Rev 3		
Heat No.	**Lot #**	**FPI W/O**	**Applicable Specifications**			
AH450	543959	87473	**D2456-1 Rev 01**			

I hereby certified that the goods described above are in compliance with the stated drawings, specification and engineering documents required by the purchase order.

Additionally, each part received a visual and dimensional inspection and were (was) found in acceptable condition.

Respectfully,

02/17/2016

Rigoberto Cendejas
Forged Products Inc
(832) 590-7921
rcendejas@fpitx.com

Forged Products, Inc.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091 · (713) 462-3416

CERTIFIED TEST REPORT

JOB NO.	DATE SHIPPED
87473	

CUSTOMER	CUSTOMER'S ORDER NO.	LN	DRAWING NO.	REV	PART NO	REV
AIKEN ENGINEERING	2456-11-10-2015	1	PN2456-200	3	2456-200	0

PART(S) DESCRIPTION	SPECIFICATION NO.	REV	GRADE	CERTIFICATION TYPE
TEST BODY, API 17 EVAL 3-1/16 -20K (F22)	D2456-1	1	A182 F22	EN 10204 / ISO 10474 TYPE 3.1

CHEMICAL COMPOSITION

	HEAT #	MILL SOURCE	QTY		C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Cu	Cb	Ti	Sn	N			CE
SN	**AH450**	EQS	2	LADLE	.15	.58	.010	.006	.24	.45	2.42	1.11	.018	.020	.15	.006	.003	.008	.0071			1.00
	AH450-2E1; AH450-2E2			PA	.015	.58	.014	.008	.26	.42	2.42	1.07			.160							

HEAT TREATMENT (TEMPERATURES ARE REPORTED IN FARENHEIT, TIME IS REPORTED IN HOURS)

SN	NORMALIZE			AUSTENITIZE		QUENCH			TEMPER			LOAD		HBW			BATCH #	FURNACE TYPE
	TEMP (°F)	TIME	COOL	TEMP (°F)	TIME	COOLANT	START	FINISH	TEMP (°F)	TIME	COOL	PART	QTC	PART	QTC			
AH450-2E1; AH450-2E2	1750	6.00	AIR	1700	6.00	WATER	71	73	1230	10.00	WATER	2	PROL	SEE REP.	N/A	N/A	543959	AMS 2750

PHYSICAL PROPERTIES (All mechanical properties obtained in the Longitudinal direction unless otherwise specified)

BATCH #	YIELD STRENGTH (PSI)	TENSILE STRENGTH (PSI)	ELONG (%)	RED. OF AREA (%)	TEST SPECIMEN			TYPE CHARPY	TEMP (°F)	ABSORBED ENERGY (FT-LBS)			LATERAL EXPANSION (MILS)			SHEAR (%)		
					SIZE (IN)	HARDNESS (HBW)												
543959	92,200	111,100	24.00	74.30	0.501	236	237	LCVN	0	147	153	156	81	85	86	100	100	100

ADDITIONAL TESTING

TEST TYPE	SPECIFICATION	REV	TEST RESULTS
UT Examination	ASTM A388		NO REJECTABLE INDICATIONS PER API 6A PSL 3
MP Examination	ASTM E709		NO REJECTABLE INDICATIONS PER API 6A PSL3
			NO WELD REPAIR PERFORMED ON ANY OF THE PRODUCTS LISTED.

ENCLOSURES

☒ Steel Mill Certificate(s)
☒ Heat Treat Cert & Chart(s)
☒ UT Report(s)
☒ Final Hardness Report(s)
☒ Dimensional Report(s)
☒ MP Report(s)
☒ Certificate of Compliance
☒ Visual Inspection Report(s)
☐ Other:

NO WELD REPAIR PERFORMED ON ANY OF THE PRODUCTS LISTED.

ADDITIONAL CERTIFICATIONS

☒ NACE MR0175
☒ FORGE RATIO: PART 6.42 :1 X-SECT Prolongation 0.00 :1
☒ GRAIN SIZE: ASTM 5 OR FINER

I CERTIFY THAT THIS IS A TRUE COPY OF ORIGINAL TEST SHEET NOW ON FILE AT THE OFFICE OF FORGED PRODUCTS, INC. AND THAT THE ITEMS ON THIS REPORT WERE MANUFACTURED IN THE UNITED STATES OF AMERICA.

2/18/2016

QUALITY ASSURANCE

PO #2456-11-10-2015 LN 1, PN 2456-200 Rev 0, Heat #AH450, Lot #543659, SN AH450-2E1 & AH450-2E2

ELLWOOD QUALITY STEELS COMPANY
A PENNSYLVANIA BUSINESS TRUST
700 MORAVIA STREET, NEW CASTLE, PA 16101

(724) 658-6788
Telefax (724) 658-6802

Page 1

CERTIFIED TEST REPORT

Date: 7/17/13

Report of Tests of: (2), 40" x 53" x 112" - Grade F22 MX Ingot(s)

For Company: Forged Products Inc
6505 North Houston Rosslyn Rd.
Houston, TX 77091

Customer's Order: 11340-#9,#10
Date of Order: 7/5/13
Our Shop Order: 100914
Specification: CS-F22 MX REV.02

QA APPROVED
BY OM
DATE 12/8/15
87473

CHEMICAL ANALYSIS

Heat #	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Al	Hppm	Ti	Sn
AH450	.15	.58	.010	.006	.24	.45	2.42	1.11	.018	.15	.020	1.3	.003	.008
	B	Nb	Ca	N										
	.0003	.006	.0025	.0071										

The material was melted using the electric furnace-ladle refined-vacuum degassed process and was subsequently bottom poured.

The material has been melted using a fine grain melt practice capable of meeting ASTM 5 or finer.

The material was calcium treated.

CE = 1.00

J factor = 148

The material was produced in accordance with the EQS Quality Manual dtd. 8/3/09, Rev. 1 which meets the intent of the latest revisions to ISO 9001:2008, ISO 10012-1, MIL-I-45208, NCA-3800, and 10-CFR-50 App. B for quality assurance, inspection and calibration systems.

I certify that the reported results and statements of the certificate represent the actual attributes of the material furnished and are in full compliance with all purchase order/ specification requirements. The recording of false, fictitious or fraudulent statements or entries on this document may be punishable as a felony under Federal Statutes. During the manufacturing process, tests, and inspections, the material did not come in direct contact with mercury or any of its compounds nor with any mercury containing device employing a single boundary of containment. No welding or weld repair was performed on this material. The material was produced free of radioactive elements.

Chris McVay
Chris McVay
Metallurgist

LONE STAR HEAT TREATING CORP.
HOUSTON, TEXAS
"CONSISTENTLY BETTER"
SINCE 1945

3939 Blaffer
Houston, Tx 77026
Ph. 713-672-6616
Fax (713) 672-9509

Certificate of Heat Treatment
Work Order No: 543959

Cust No: 002202
Cust Name: FORGED PRODUCTS
Quantity: 2

Cust PO#: 87473

Matl: F22

Cert Date: 01/08/2016

Description: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG

Process: (3RD PARTY WITNESS) NORMALIZE, WATER QUENCH & TEMPER TO 217-237 HBW PER HT DATA SHEET 100% INSPECTION 3 PLACES, 120 DEG APART 4 PLACES ON OTHER END PER DWG T/C REQD

Controlled by Furnace Instrument:

THERMOCOUPLE IN LOAD T/C# E6453

PROCESS	TEMP	TIME	COOLING METHOD
NORMALIZED	1750 F	6.0 HOURS	AIR COOLED
HARDENED	1700 F	6.0 HOURS	WATER 71-73F
TEMPERED	1230 F	10.0 HOURS	WATER COOLED

HARDNESS INSPECTION:

2 PIECES CHECKED 7 PLACES EACH 223-235 HBW

Furnaces and instruments are calibrated to AMS 2750E. Reported heat treat times and temperatures are taken from the furnace chart recorder. Mechanical testing conforms to the requirements of ASTM A370 and only applies to the sample tested or inspected. Frequency of all testing is dictated by specification and/or customer purchase order. All work is performed and accepted, unless otherwise agreed to in writing, in accordance with the Lone Star Heat Treating Corporation Master Services Agreement Terms and Conditions which may be found at www.lsht.com and our quality manual QM-01 Rev. 13. While at Lone Star Heat Treating this material did not come in contact with mercury nor was it subject to any weld repairs.

ASQ Quality Evaluations, Inc. Management System Certification
ANAB ACCREDITED
AS9100C
Certificate No: 47512

Lone Star Heat Treating Corp.

Danny Bierman
Prod. Mgr.

LONE STAR HEAT TREATING CORP.
HOUSTON, TEXAS

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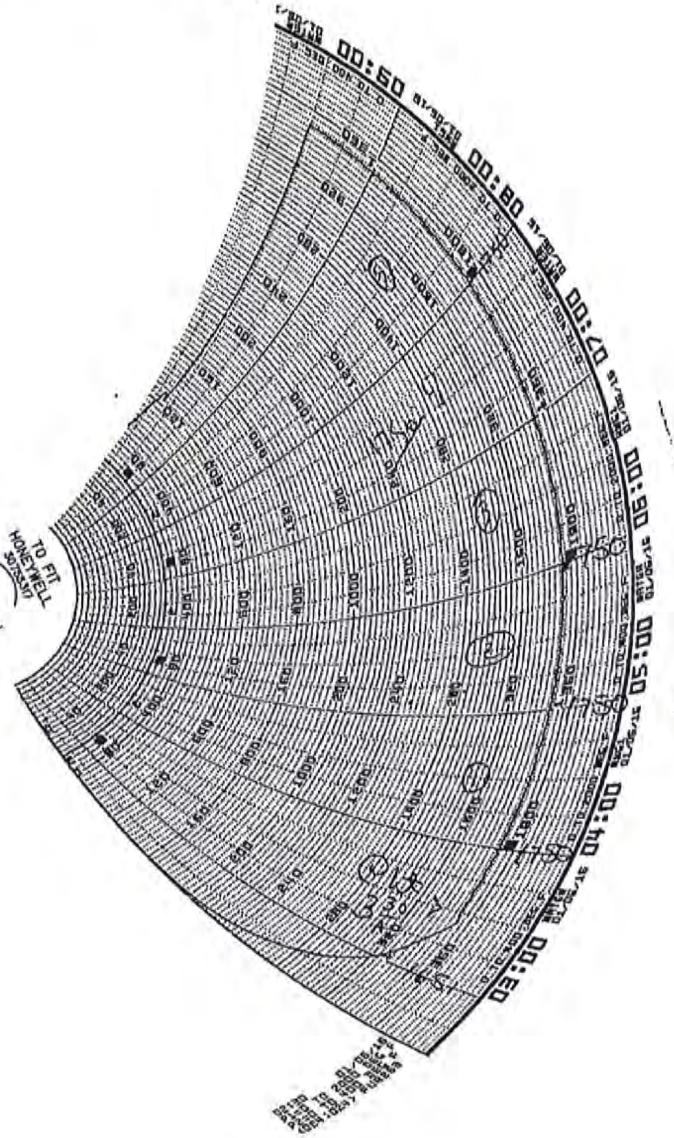
Certificate of Heat Treatment
Work Order No: 543959

Cust No: 002202
Cust PO#: 87473
Cust Name: FORGED PRODUCTS
Quantity: 2
Matl: F22
Weight: 5200
Description: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG

01-06-16 253/2 NORM 1750 6HRS @ A/C 543959



Furnace Chart

LONE STAR HEAT TREATING CORP.
HOUSTON, TEXAS
"CONSISTENTLY BETTER"
SINCE 1948

3939 Blaffer
Houston, Tx 77026
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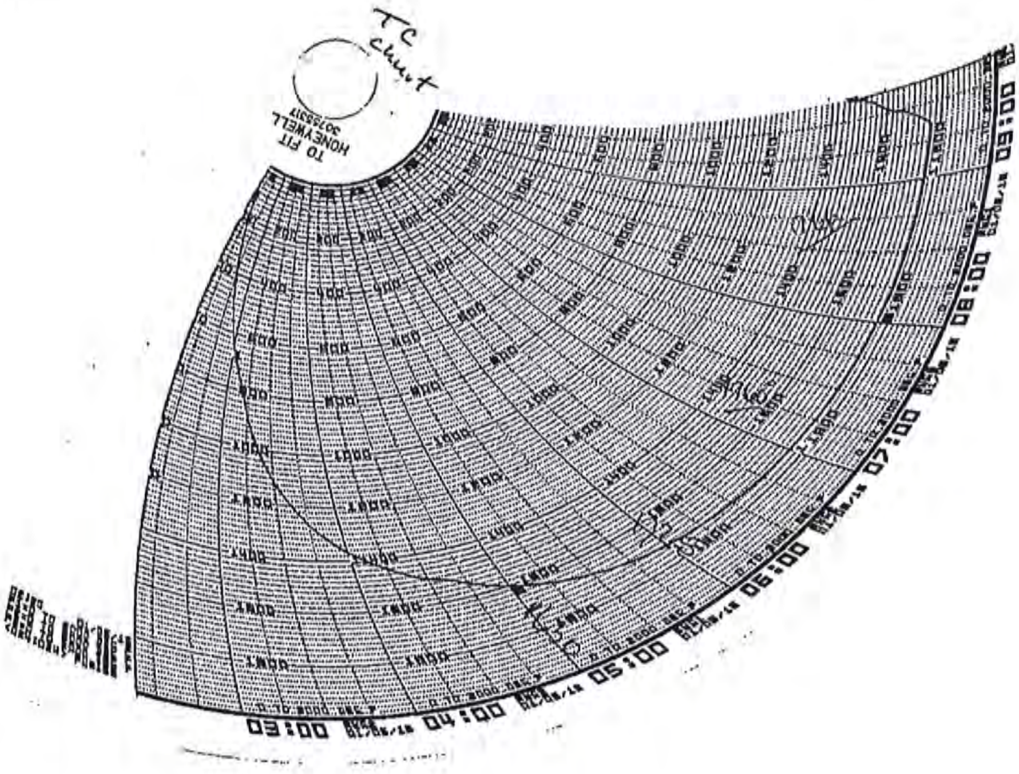
Certificate of Heat Treatment
Work Order No: 543959

Cust No: 002202
Cust PO#: 87473
Cust Name: FORGED PRODUCTS
Quantity: 2
Matl: F22
Weight: 5200
Description: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG

01-06-16 253/2 NORM 1750 6 HRS @ H/C 543959



LONE STAR HEAT TREATING CORP.
HOUSTON, TEXAS
"CONSISTENTLY BETTER"
SINCE 1949

Certificate of Heat Treatment
Work Order No: 543959

3939 Blaffer
Houston, Tx 77026
Ph. 713-672-6616
Fax (713) 672-9509

Cust No: 002202

Cust PO#: 87473

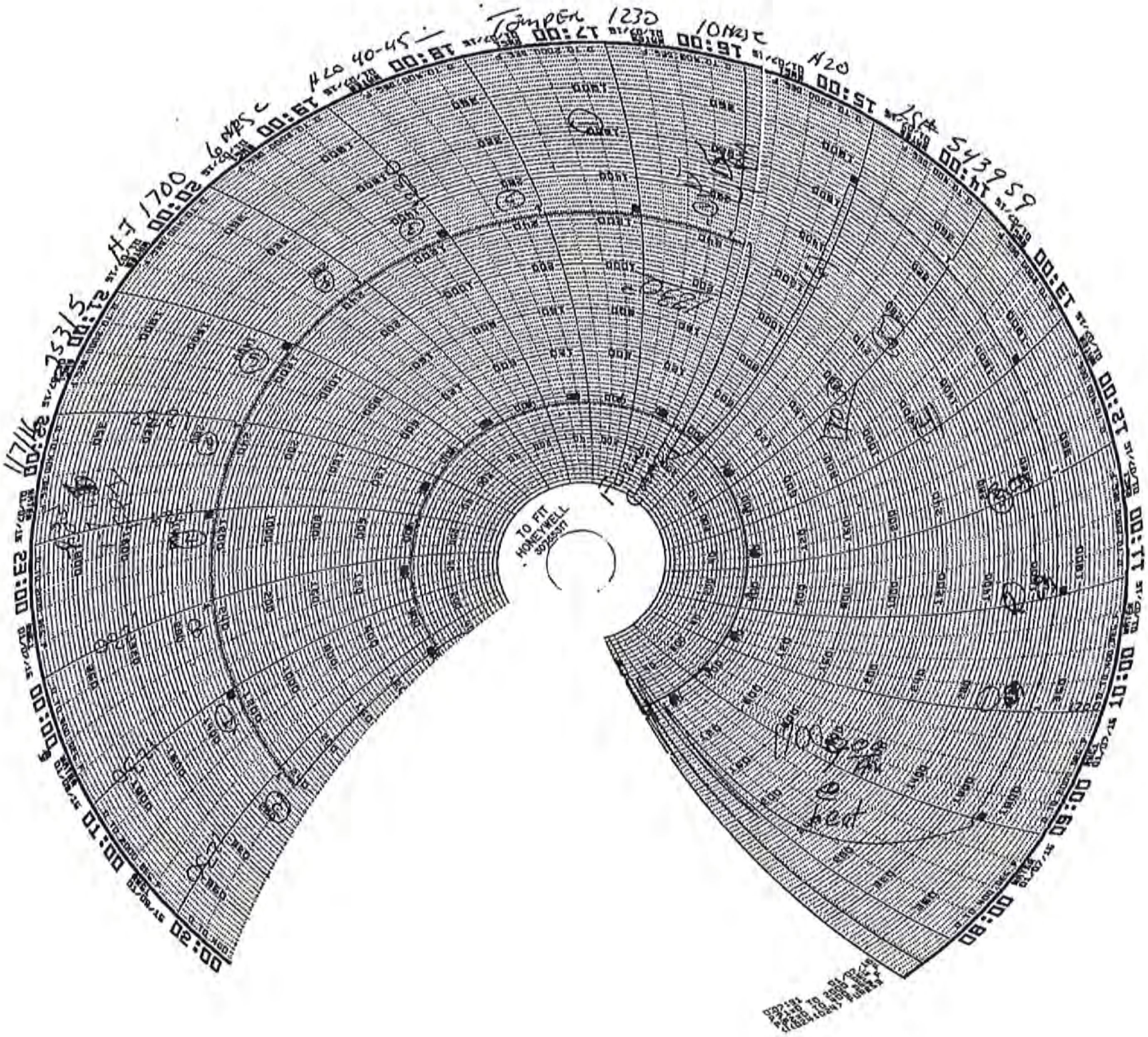
Cust Name: FORGED PRODUCTS

Quantity: 2

Matl: F22

Weight: 5200

Description: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG



LONE STAR HEAT TREATING CORP.
HOUSTON, TEXAS

3939 Blaffer
Houston, Tx 77026
Ph. 713-672-6616
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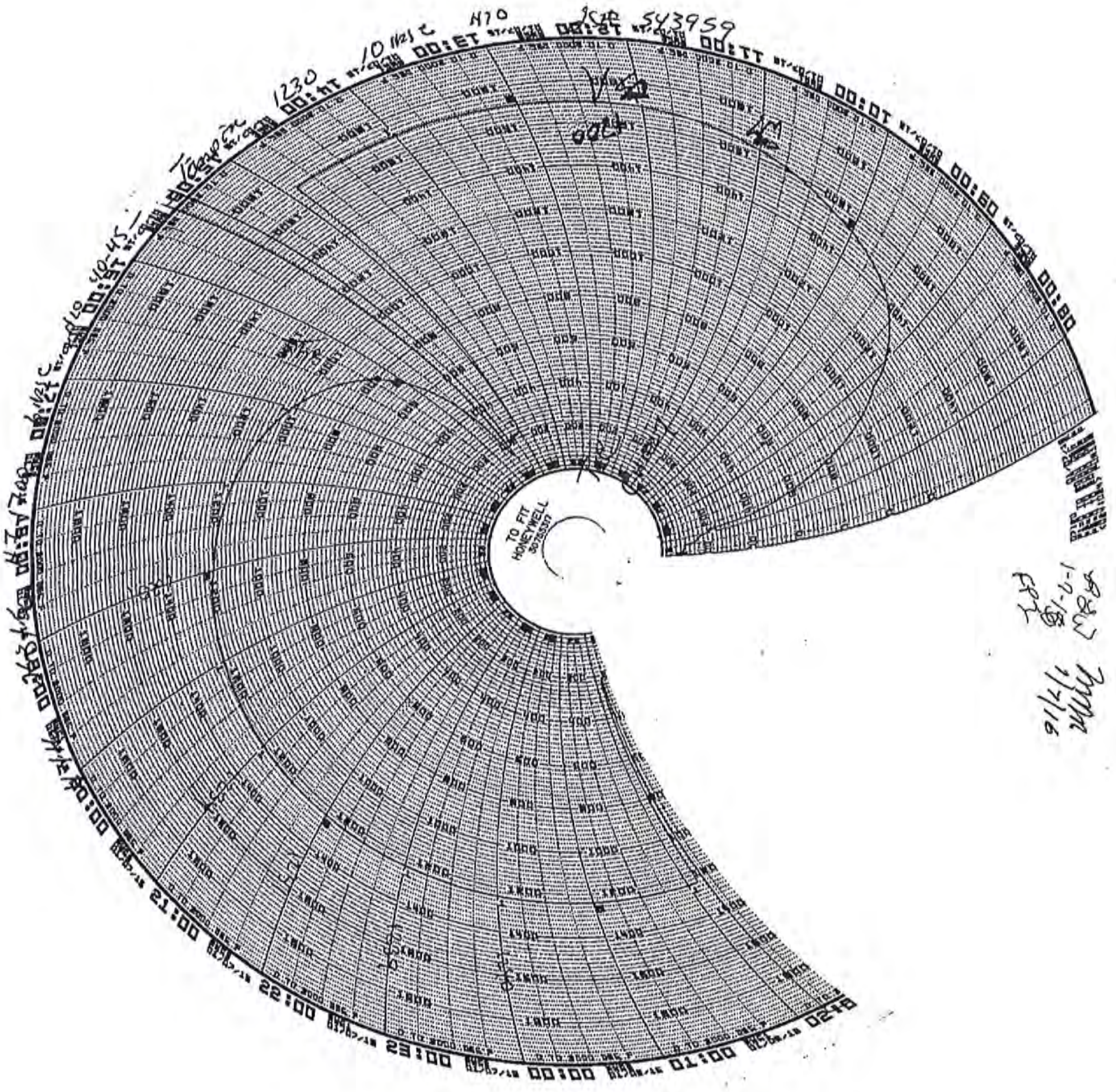
Certificate of Heat Treatment
Work Order No: 543959

Cust No: 002202
Cust PO#: 87473
Cust Name: FORGED PRODUCTS
Quantity: 2
Matl: F22
Weight: 5200
Description: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG



Lone Star Heat Treating Corp.
Customer Receipt

QAF-015

Date:	01/05/2016					Wo #:	543959
Cust #:	002202	Customer:	FORGED PRODUCTS			Phone #:	(713) 462-3416
Cust PO#:	87473	Due Date:				Contact:	HEATHER RAMIREZ
Sticker #:	669	Location:	db	Material: F22	Qty: 2		Weight: 5200

Desc: ROUGH MACHINED JOB 87473 HN AH450
18 1/4"SQ X 14 1/2"OD X 1@ 42 3/4"LG 1@ 49 3/4"LG

Process: (3RD PARTY WITNESS) NORMALIZE, WATER QUENCH & TEMPER TO 217-237 HBW PER HT DATA SHEET 100% INSPECTION 3 PLACES, 120 DEG APART 4 PLACES ON OTHER END PER DWG T/C REQD

Ship To: FORGED PRODUCTS
6506 N. HOUSTON ROSSLYN ROAD
HOUSTON, TX 77091

ALL WORK IS ACCEPTED SUBJECT TO OUR "STATEMENT OF LIMITED LIABILITY" a copy of which is available upon request.

SIMPLY STATED: all work is accepted subject to the following conditions:

ALL WORK IS PERFORMED AND ACCEPTED, UNLESS OTHERWISE AGREED TO IN WRITING, IN ACCORDANCE WITH THE LONE STAR HEAT TREATING CORPORATION MASTER SERVICES AGREEMENT TERMS AND CONDITIONS WHICH MAY BE FOUND AT THE FOLLOWING LOCATION: WWW.LSHT.COM. THE MASTER SERVICES AGREEMENT TERMS AND CONDITIONS ARE EXPRESSLY INCORPORATED HEREIN BY REFERENCE AS IS SET FORTH HERE IN FULL AND ARE COMPLETELY BINDING UPON THE PARTIES.

Accu Test Labs L.L.P.

Accredited
ISO 9001 / 17025

P.O. Box 802404 ◆ Houston, TX 77280-2404 ◆ Telephone (713) 460-3655 ◆ Fax (713) 460-3695

Report Date: 01/13/16
Report No: **740351.00**
Rev.: A
Cust Acct: FOR091

To: Forged Products
Attn: Accounts Payable
6505 N. Houston-Rosslyn Road
Houston, TX 77091

Ordered By:
PO#: 87473
Material: AISI F22 18.25"OD x 6"Long Test Piece
ID/Heat: AH450 Delivery Ticket:9180 Line/Rel:1,247
Job Info: DWG#2456-200-TST-SAW

Tensile Test Results

No./Location	Size (in.)	Area (in^2)	Ult. Load (lbs.)	Yield (psi)	Tensile (psi)	Elong. (%)	R. of A. (%)	Hardness
1	.501			92,200	111,100	24.0	74.3	236 HBW 237 HBW

Unless otherwise stated, yield stress is 0.2% offset, gauge length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

Charpy Test Results

No.	Temp	Location	Foot-Pounds	% Shear	Mils Lat Exp
1	0°F	LCVN	147-153-156	100-100-100	81-85-86

Unless otherwise stated, Charpy Impact specimens are V-notch 10 x 10 mm.

RDW
1-13-15

Witnessed by: Lee White, Forged Products, 1/13/16
Witnessed by: Maurice Peltier, Aiken Engineering, 1/13/16

mcP
1-13-15

Document Reviewed By: Yvonne Barajas
Yvonne Barajas
Documentation Specialist

Accu Test Labs
L.L.P.

Accredited
ISO 9001 / 17025

P.O. Box 802404 ◆ Houston, TX 77280-2404 ◆ Telephone (713) 460-3655 ◆ Fax (713) 460-3695

Report Date: 01/14/16
Report No: **740351.01**
Rev.: A
Cust Acct: FOR091

To: Forged Products
Attn: Accounts Payable
6505 N. Houston-Rosslyn Road
Houston, TX 77091

Ordered By: PO#: 87473
Material: AISI F22 18.25"OD x 6"Long Test Piece
ID/Heat: AH450 Delivery Ticket:9180 Line/Rel:1,247
Job Info: DWG#2456-200-TST-SAW

Chemical Analysis Results

1 C: 0.15 Mn: 0.58 P: 0.014 S: 0.008 Si: 0.26 Cr: 2.42 Mo: 1.07 Ni: 0.42 Cu: 0.16

Chemical analysis results are reported in percent by weight.

Document Reviewed By: Yvonne Barajas
Yvonne Barajas
Documentation Specialist

FORGED PRODUCTS, INC.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091 | P: (713) 462-3416

FPI
FORGED PRODUCTS, INC.

( ) Preliminary Examination (Info Only)
(X) Final Examination

ULTRASONIC EXAMINATION REPORT # 87473 -UT

CUSTOMER PURCHASE ORDER NUMBER:	2456-11-10-2015	FPI W/O NUMBER:	87473
MATERIAL GRADE:	A182 F22	PER DRAWING/SIZE:	PN2456-200
DESCRIPTION:	TEST BODY, API 17 EVAL 3-1/16 -20K (F22)	PART NUMBER:	2456-200
MATERIAL HEAT NUMBER:	AH450 QTY: 2	SERIAL NUMBER:	AH450-2E1 & AH450-2E2
MATERIAL HEAT NUMBER:	QTY:	SERIAL NUMBER:	0
MATERIAL HEAT NUMBER:	QTY:	SERIAL NUMBER:	0
SPECIFICATION:	ASTM A388		
ACCEPTANCE:	API 6A PSL 3		

EQUIPMENT:	OLYMPUS XT	SERIAL NUMBER:	70161012	CALIBRATION DATE:	8/17/2016
LONGITUDINAL TRANSDUCER: SIZE:	1"	MHZ:	2.25 / 5	SERIAL NUMBER:	830357 / 894415
SHEARWAVE TRANSDUCER: SIZE:	NA	MHZ:		SERIAL NUMBER:	
LONGITUDINAL STANDARDIZATION:	1/8", 1/4" FBH AT 80% FSH			DB:	36/44/64
SHEARWAVE STANDARDIZATION:	N/A			DB:	

COUPLANT:	(X) WATER/CELLULOSE GUM	( ) OIL	( ) OTHER:
PART CONDITION:	(X) CLEAN	( ) DIRTY	( ) RUST CONTAMINATED
SURFACE FINISH:	(X) MACHINED 250 RMS	(X) BLAST CLEANED	( ) OTHER:

(X) VOLUMETRIC EXAMINATION PERFORMED PER WORK ORDER REQUIREMENTS
( ) 100% VOLUMETRIC EXAMINATION PERFORMED
(X) TESTING PERFORMED 100% AS FAR AS PRACTICAL DUE TO GEOMETRY
(X) CALIBRATION STANDARD(S): 40QC, 41QC, 42QC, 43QC, 2, 5, 011, 16

DACC was performed.

TRANSDUCER CABLE TYPE: COAXIAL

TRANSDUCER CABLE LENGTH: 6 FT.

NO REJECTABLE INDICATIONS FOUND

WITNESS BY: M.C. Pelt (BIKEN-ENGINEERING)

RESULTS: 2 PCS. ACCEPTABLE 0 PCS. RECORDABLE 0 PCS. REJECTABLE

OPERATOR: Carlos Deras FPI 3 UT DATE: 1/14/2016 LEVEL: II
CARLOS DERAS

Enclosure 2 - Procedure 7.5.2.6

CERTIFICATE
OF
QUALIFICATION

with

Forged Products, Inc.

This certifies that

Carlos Deras

has successfully passed all testing requirements in compliance with the established guidelines of SNT-TC-1A for the following special processes:

Ultrasonic Testing – Level II

And is therefore qualified in accordance with Forged Products, Inc. procedure FP-1000.

July 18, 2014	July 18, 2019
Qualification Date	Expiration Date

Reviewed and Approved by:
Rigoberto Cendejas
FPI VP of Qualtiy - 7/8/2014

Stephen Lewellen   ASNT ACCP Professional Level III   Certificate Number 51312

BREAUX MACHINE WORKS, LP DIMENSIONAL VERIFICATION LOG

PART# NA
DWG #: PN2456-200 REV 3
JOB # 53200
DATE:
PO # 27285 ITEM 1
QTY: 1
CUSTOMER: FORGED PRODUCTS, INC.
CUST. # 87473
DESCRIPTION: TEST BODY, API 17 EVALUATION, 3 1/16 - 20K

	DWG DIMENSIONS	SERIAL # AH450-2E1	HT# AH450	SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
1	22.5°	7883	22.5°				
2	8X Ø $1.50^{+.03}_{-.00}$ THRU		(8X) Ø 1.501 Thru				
3	Ø 11.312±.015	7883	Ø 11.312				
4	8X Ø $1.615^{+.015}_{-.010}$ ↧ 3.0	9380	Ø 8X 1.626 x 3.002 ↓				
5	1-3/4-8UN -2B ↧ 2.188		1¾-8un-2B x 2.180				
6	∨ Ø 1.81 X 90°		Ø 1.81 x 90° ∨				
7	Ø 14.062±.015		Ø 14.062				
8	22.5°		22.5°				
9	17.75±.03		17.762				
10	17.75±.03	9380	17.762				
11	8.88±.03		8.880				
12	17.75±.03		17.762				
13	8.88±.03		8.880				
14	Ø 11.312±.015		Ø 11.313				
15	8X Ø $1.240^{+.015}_{-.010}$ ↧ 2.63		Ø 8X 1.251 x 2.625 ↓				
16	1-3/8-8UN -2B ↧ 1.75		1⅜-8un-2B x 1.75 ↓				

INSPECTOR #5
FEB 11 2016

PART# NA		DWG #: PN2456-200 REV 3			JOB # 53200	DATE:	
PO # 27285 ITEM 1		CUSTOMER: FORGED PRODUCTS, INC.		DESCRIPTION: TEST BODY, API 17 EVALUATION, 3 1/16 - 20K			
QTY: 1		CUST. # 87473					
DWG DIMENSIONS		SERIAL # AH450-2E1	HT# AH450	SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
17	∨ Ø 1.438 X 90°	9380	∨ Ø1.430 x 90°				
18	22.5°	⊥	22.5°				
19	(Ø14.06)	6492	(Ø14.06)				
20	(33.19)		(33.19)				
21	42.06		42.06				
22	8.88±.03	1020	8.880				
23	Ø14.062±.015	9380	Ø14.063				
24	22.5°		22.5°				
25	8X Ø 1.615 $^{+.015}_{-.010}$ ↧ 3.0		8X Ø1.624 x 3.001 ↓				
26	1-3/4-8UN -2B ↧ 2.188		1 3/4-8 UN-2B x 2.190 ↓				
27	∨ Ø 1.81 X 90°	←	∨ Ø1.81 x 90°				
28	Ø 14.06±.06	6492	Ø14.067				
29	Ø 6.75±.06		Ø6.755				
30	Ø 4.685 $^{+.004}_{-.000}$		FLANGE SIDE Ø4.686/Ø4.687				
31	Ø 3.06 $^{+.03}_{-.00}$		Ø3.075				
32	.25±.03		.250				
33	R.12±.03	6492	R.120	↓			

INSPECTOR #5
FEB 11 2016

PART# NA		DWG #: PN2456-200 REV 3		JOB # 53200		DATE:	
PO # 27285 ITEM 1		CUSTOMER: FORGED PRODUCTS, INC.		DESCRIPTION: TEST BODY, API 17 EVALUATION, 3 1/16 - 20K			
QTY: 1		CUST. # 87473					
	DWG DIMENSIONS	SERIAL # AH450-2E1	HT #AH450	SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
34	2X .12 X 45°	6492	.120 X 45° 2x				
35	$3.38^{+.12}_{-.00}$		3.445				
36	3.53±.03		3.530				
37	(15°)		15°				
38	$\varnothing 7.562^{+.000}_{-.120}$		ϕ7.502				
39	(24.31)		24.305				
40	(13.63) 13.56		13.630				
41	33.19±.03		33.19				
42	$\varnothing 7.56^{+.12}_{-.00}$		ϕ7.620				
43	(15°)		15°				
44	3.53±.03	6492	3.530				
45	30°±2°	1020	30°				
46	5.00±.03		5.00				
47	R.50±.03 2X		2X 2x R.50				
48	5.00±.03	1020	5.00				

INSPECTOR #5
FEB 11 2016

PART# NA
DWG #: PN2456-200 REV 3
JOB # 53200
DATE:

PO # 27285 ITEM 1
QTY: 1
CUSTOMER: FORGED PRODUCTS, INC.
CUST. # 87473
DESCRIPTION: TEST BODY, API 17 EVALUATION, 3 1/16 - 20K

	DWG DIMENSIONS	SERIAL # AH450-2E1 HT # AH450		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
49	Ø8.00±.03	1020	Ø 8.005				
50	30°±2°		30°				
51	Ø4.062 $^{+.030}_{-.000}$		Ø4.076				
52	Ø5.930 $^{+.004}_{-.000}$ 2X	1020	2X Ø 5.932				
53	R.38±.03	6492	R.380				
54	R.38±.03		R.380				
55	Ø5.68 $^{+.03}_{-.00}$		Ø5.703				
56	R.38±.03		R.380				
57	R.38±.03		R.380				
58	.06±.02		FLANGE SIDE .060 / .060				
59	45°		45° / 45°				
60	.606 $^{+.004}_{-.000}$		.607 / .607				
61	R.030 2X		2X R.030 / 2X R.030				
62	2X 32		2X 32√ / 32√ 2X				
63	2x 23.00°±.25°	6492	2X 23° / 23° 2X				

INSPECTOR #5
FEB 11 2016

PART# NA			DWG #: PN2456-200 REV 3		JOB # 53200		DATE:
PO # 27285 ITEM 1		CUSTOMER: FORGED PRODUCTS, INC.		DESCRIPTION: TEST BODY, API 17 EVALUATION, 3 1/16 - 20K			
QTY: 1		CUST. # 87473					
DWG DIMENSIONS		SERIAL # AH450-2E1	HT# AH450	SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
64	$.30^{+.02}_{-.00}$	6492	.306 / .309				
65	.06±.02	1020	.06				
66	45°		45°				
67	32√		32✓				
68	23.00°±.25°		23.00°				
69	R.03±.02 2X		2x R.03				
70	$.698^{+.004}_{-.000}$		.700				
71	32√		32✓				
72	23.00°±.25°		23.00°				
73	$.33^{+.02}_{-.00}$	1020	.340				

INSPECTOR #5

INSPECTOR : FEB 11 2016

DATE:

BREAUX MACHINE WORKS, LP DIMENSIONAL VERIFICATION LOG

PART# NA
DWG #: PN2456-500 REV 1
JOB # 53286
DATE:
PO # 27285 ITEM 2
QTY: 1
CUSTOMER: FORGED PRODUCTS, INC.
CUST. # 87473
HT # AH450
DESCRIPTION: TEST BODY WITH REDUCED NECK, API 17 EVALUATION

	DWG DIMENSIONS	SERIAL # AH450-2E2		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
1	22.5°	6492	22.5°				
2	8X Ø1.50 $^{+.03}_{-.00}$ THRU		8X Ø 1.515				
3	Ø11.312±.015		Ø 11.312				
4	8X Ø 1.615 $\frac{+.015}{-.010}$ ↧3.0	9380	1.628x2.995				
5	1-3/4-8UN -2B ↧ 2.188		1¾-8 x 2.190				
6	⌵ Ø 1.81 X 90°		1.81 x 90°				
7	Ø14.062±.015		14.063				
8	22.5°		22.5°				
9	17.75±.03		17.761				
10	17.75±.03	9380	17.761				
11	8.88±.03		8.881		INSPECTOR #5		
12	17.75±.03		17.760		FEB 15 2016		
13	8.88±.03		8.879				
14	Ø11.312±.015		11.312				
15	8X Ø 1.240 $\frac{+.015}{-.010}$ ↧2.63		1.251 x2.625				
16	1-3/8-8UN -2B ↧ 1.75		1⅜-8 x 1.75				
17	⌵ Ø 1.438 X 90°		1.439 x 90°				

PART# NA		DWG #: PN2456-500 REV 1		JOB # 53286		DATE:	
PO # 27285 ITEM 2 QTY: 1		CUSTOMER: FORGED PRODUCTS, INC. CUST. # 87473 HT # AH450		DESCRIPTION: TEST BODY WITH REDUCED NECK, API 17 EVALUATION			
DWG DIMENSIONS		SERIAL # AH450-2E2		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
18	22.5°	9320	22.5°				
19	(Ø 14.06)	↓	(Ø 14.06)	↓			
20	(33.19)		(33.19)				
21	42.06		42.06				
22	8.88±.03	9320	8.881				
23	Ø 14.062±.015	↓	14.062				
24	8X Ø 1.615 $^{+.015}_{-.010}$ ↧ 3.0		1.628 x 2.995				
25	1-3/4-8UN-2B ↧ 2.188		1 3/4-8 x 2.19				
26	∨ Ø 1.81 X 90°		1.81 x 90°				
27	22.5°		22.5°				
28	Ø 14.06±.06	6492	Ø 14.065		INSPECTOR #5 FEB 15 2016		
29	Ø 6.750±.060	↓	Ø 6.750	↓			
30	Ø 4.685 $^{+.004}_{-.000}$ 2X		FLANGE SIDE Ø 4.687 / Ø 4.689				
31	Ø 3.06 $^{+.03}_{-.00}$		Ø 3.065 / 3.080				
32	.25±.03		.250				
33	R.12±.03		R .120				
34	3.38 $^{+.12}_{-.00}$		3.[illegible]5				

PART# NA		DWG #: PN2456-500 REV 1		JOB # 53286		DATE:	
PO # 27285 ITEM 2		CUSTOMER: FORGED PRODUCTS, INC.		DESCRIPTION: TEST BODY WITH REDUCED NECK, API 17 EVALUATION			
QTY: 1		CUST. # 87473 HT# AH450					
	DWG DIMENSIONS	SERIAL # AH450-2E2		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
35	5.03±.03	6492	5.030				
36	$\varnothing 7.562^{+.000}_{-.120}$		ϕ7.562				
37	(24.31)		24.310				
38	(15°)		15°				
39	(10.64)		10.560				
40	33.19±.03		33.195				
41	(15°)		15°				
42	5.03±.03		5.030				
43	$\varnothing 7.56^{+.12}_{-.00}$		ϕ7.620				
44	30°±2°	1020	30°				
45	5.00±.03		5.00				
46	R.50±.03 2X		2x R.50				
47	ϕ8.00±.03		ϕ 8.00				
48	5.00±.03		5.00				
49	30°±2°		30°				
50	$\varnothing 4.062^{+.030}_{-.000}$		ϕ4.090				
51	$\varnothing 5.930^{+.004}_{-.000}$ 2X	1020	ϕ 5.932				
52	2X .12 X 45°	6492	.120x45° 2X				

INSPECTOR #5
FEB 15 2016

PART# NA		DWG #: PN2456-500 REV 1		JOB # 53286		DATE:	
PO # 27285 ITEM 2 QTY: 1		CUSTOMER: FORGED PRODUCTS, INC. CUST. # 87473 HT # AH450		DESCRIPTION: TEST BODY WITH REDUCED NECK, API 17 EVALUATION			
DWG DIMENSIONS		SERIAL # AH450-2E2		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
53	R.38±.03	6492	R.380				
54	R.38±.03		R.380				
55	Ø 4.88 $^{+.03}_{-.00}$		Ø4.896				
56	R.38±.03		R.380				
57	R.38±.03		R.380				
58	.06±.02		FLANGESIDE .062 / .060				
59	45°		45° / 45°				
60	.606 $^{+.004}_{-.000}$		.607 / .608				
61	R.030 2X		R.030 2x / R.030				
62	2X 32√		32√ 2x / 32√		INSPECTOR #5		
63	2x 23.00°±.25°		23° 2x / 23° 2x		FEB 16 2016		
64	.30 $^{+.02}_{-.00}$		.306 / .310				
65	.06±.02	1020	.06				
66	45°		45°				
67	32√		32√				
68	23.00°±.25°		23.00°				
69	R.03±.02 2X	1020	2x R.03				

PART# NA

DWG #: PN2456-500 REV 1

JOB # 53286

DATE:

PO # 27285 ITEM 2

QTY: 1

CUSTOMER: FORGED PRODUCTS, INC.

CUST. # 87473

HT # AH450

DESCRIPTION: TEST BODY WITH REDUCED NECK, API 17 EVALUATION

	DWG DIMENSIONS	SERIAL # AH450-2E2		SERIAL #		SERIAL #	
		EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS	EMP #	ACTUAL DIMENSIONS
70	$.698^{+.004}_{-.000}$	1020	.700				
71	$\sqrt{}$ 32	|	32✓	|			
72	23.00°±.25°	|	23.00°	|			
73	$.33^{+.02}_{-.00}$	1020	.340				

INSPECTOR : ______________________ DATE: ______________

INSPECTOR #5

FEB 15 2016

FORGED PRODUCTS, INC.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091 | P: (713) 462-3416

FPI
FORGED PRODUCTS, INC.

MAGNETIC PARTICLE EXAMINATION REPORT # 87473 -MT

CUSTOMER PURCHASE ORDER NUMBER:	2456-11-10-2015	FPI W/O NUMBER:	87473
MATERIAL GRADE:	A182 F22	PER DRAWING/SIZE:	PN2456-200
DESCRIPTION:	TEST BODY, API 17 EVAL 3-1/16 -20K (F22)	PART NUMBER:	2456-200
MATERIAL HEAT NUMBER:	AH450 QTY: 2	SERIAL NUMBER:	AH450-2E1
MATERIAL HEAT NUMBER:	QTY:	SERIAL NUMBER:	AH450-2E2
MATERIAL HEAT NUMBER:	QTY:	SERIAL NUMBER:	0

SPECIFICATION: ASTM E709

ACCEPTANCE: API 6A PSL3

PART CONDITION: (X) CLEAN ( ) DIRTY ( ) RUST CONTAMINATED
(X) DRY ( ) WET

SURFACE FINISH: (X) MACHINED 250 RMS ( ) BLAST CLEANED ( ) OTHER: ______

EQUIPMENT: Magne-Tech Model 3009 P-01-10 CALIBRATION DATE: 1-5-16

TECHNIQUE: FWDC-Wet Fluresceen, Continuous Method

( ) YOKE SPACING: ______ LIFTING FORCE: ______

( ) DIRECT AMPS: ______

(X) CENTRAL CONDUCTOR: DIAMETER: 1" AMPS: 2300

(X) COILS TURNS: 4 AMPS: 2400

NOTES / COMMENTS :

Chemetall oakite
8800A Batch 65062915
Black light Intensity 3600 mw/cm^2
magnetic Flux Intensity - pie gage - Castrol Strips
no Indications observed
De-MAG = 0 - 3 GAUSS (or less)

RESULTS: 2 PCS. ACCEPTABLE 0 PCS. RECORDABLE 0 PCS. REJECTABLE

FPI
4
MT

OPERATOR: Carlos Deras
CARLOS DERAS
DATE: 2/16/2016
LEVEL: II

CERTIFICATE

OF

QUALIFICATION

with

Forged Products, Inc.

This certifies that

Carlos Deras

has successfully passed all testing requirements in compliance with the established guidelines of SNT-TC-1A for the following special processes:

Magnetic Particle Testing – Level II

And is therefore qualified in accordance with
Forged Products, Inc. procedure FP-1000.

January 12, 2015	January 12, 2020
Qualification Date	Expiration Date

Reviewed and Approved by:
Rigoberto Cendejas
FPI VP of Qualtiy - 01/27/2015

Stephen Lewellen   ASNT ACCP Professional Level III   Certificate Number 51312

Forged Products, Inc.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091
Phone 713-462-3416
Fax 713-460-9404

FORGED PRODUCTS, INC.

NAME: Carlos Deras

NEAR VISION ACUITY: JAEGER NUMBER 1 AT 12 INCHES

	UNCORRECTED	CORRECTED
RIGHT EYE:	✓	
LEFT EYE:	✓	

COLOR CONTRAST DIFFERENTIATION: ISHIHARA COLOR PLATES

NORMAL: ✓ DEFICIENCY: ______

RESTRICTIONS: ✓ NONE

______ VISION CORRECTION (GLASES OR CONTACTS)

REMARKS:

EXAMINER: Stephen Lewellen

TITLE: NDT Level III #51312

DATE: 10/27/2015

Forged Products, Inc.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091 | P: (713) 462-3416

FPI
FORGED PRODUCTS, INC.

Hardness Test Report

MP/QP 2456-200

JOB INFORMATION

Date:	2/16/2016	Purchase Order No.	2456-11-10-2015
Customer Name:	AIKEN ENGINEERING	**Part No.**	2456-200
Job No/Report No:	87473 **Qty:** 2	Dwg No.	PN2456-200
Description:	TEST BODY, API 17 EVAL 3-1/16 -20K (F22)	Test Location:	See Below
Material Specification:	D2456-1	**Material Grade:**	A182 F22

TEST METHOD

☑ BRINELL - (HBW)
3000 Kgf - 10mm Tungsten Carbide Ball

☐ AIR BRINELL - (HBW)
3000 Kgf - 10mm Tungsten Carbide Ball

☐ OTHER

TEST EQUIPMENT

☑ PORTABLE TESTER ☐ PORTABLE W/CHAIN ADAPTER ☐ STATIONARY ☐ OTHER

SERIAL NUMBER	CAL DATE	SERIAL NUMBER	CAL DATE	SERIAL NUMBER	CAL DATE
☑ UL84	12/18/15	☐		☐	

SCOPE

SERIAL NUMBER	CAL DATE	SERIAL NUMBER	CAL DATE	SERIAL NUMBER	CAL DATE	MAGNIFICATION
☑ KING SCAN	12/18/15	☐ 01516		☐		20X
☐ 987		☐ 4		☐		

TEST REQUIREMENTS

TEST SPECIFICATION	NO. OF TEST PER PART	REQUIRED HARDNESS RANGE (HBW)
FP 7.5.1.9; D2456-1 R/1; DWG# PN2456-200	5	197 — 237

HARDNESS TEST RESULTS

If the ambient temperature is below 50°F or above 95°F perform a verification test. ☐ TESTER VERIFIED

SERIAL #	HEAT/LOG #	TEMP. (°F)	A	B	C	D	E	F
AH450-2E1	AH450	62°	234	233	217	228	221	
AH450-2E2	AH450		231	232	227	224	222	

TEST LOCATIONS (OPTIONAL)

VERIFICATION:		
CALIBRATION BLOCKS		RESULTS
232	UPPER	230
214	LOWER	214

SEE MARKED UP DWG # PN2456-500 REV 1

HARDNESS TESTING PERFORMED IN ACCORDANCE WITH THE ABOVE SPECIFICATION REVEALS THAT THE RESULTS OBTAINED
(☑ CONFORM ☐ DO NOT CONFORM) TO THE REQUIRED HARDNESS RANGE

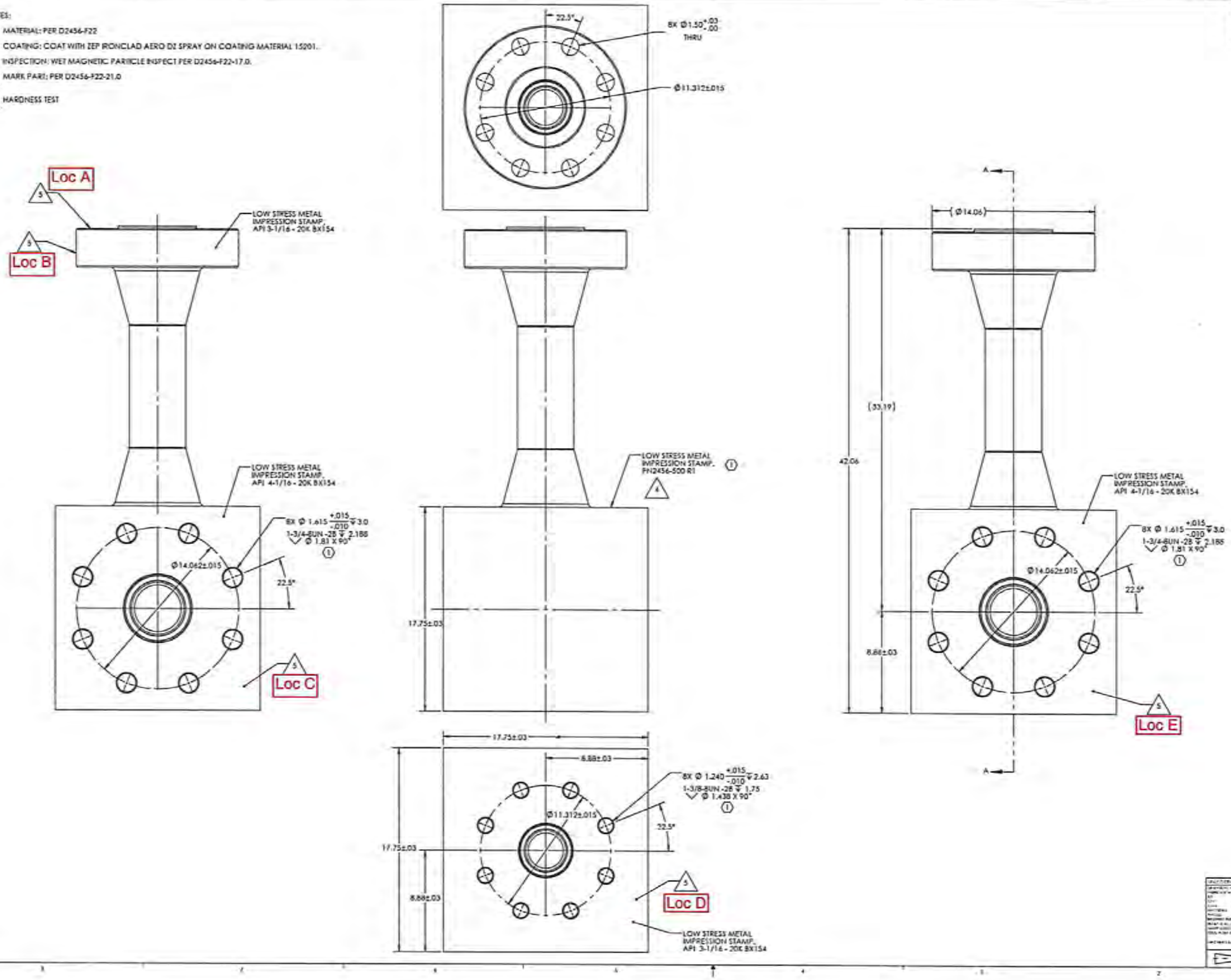
TECHNICIAN: T. L.
DATE: 2/17/16

WITNESS BY:
DATE:

Enclosure 1 - WI 7.5.1.9a Rev. 01

NOTES:

1. MATERIAL: PER D2456-F22
2. ① COATING: COAT WITH ZEP IRONCLAD AERO DZ SPRAY ON COATING MATERIAL 15201.
3. INSPECTION: WET MAGNETIC PARTICLE INSPECT PER D2456-F22-17.0.
4. MARK PART: PER D2456-F22-21.0
5. HARDNESS TEST

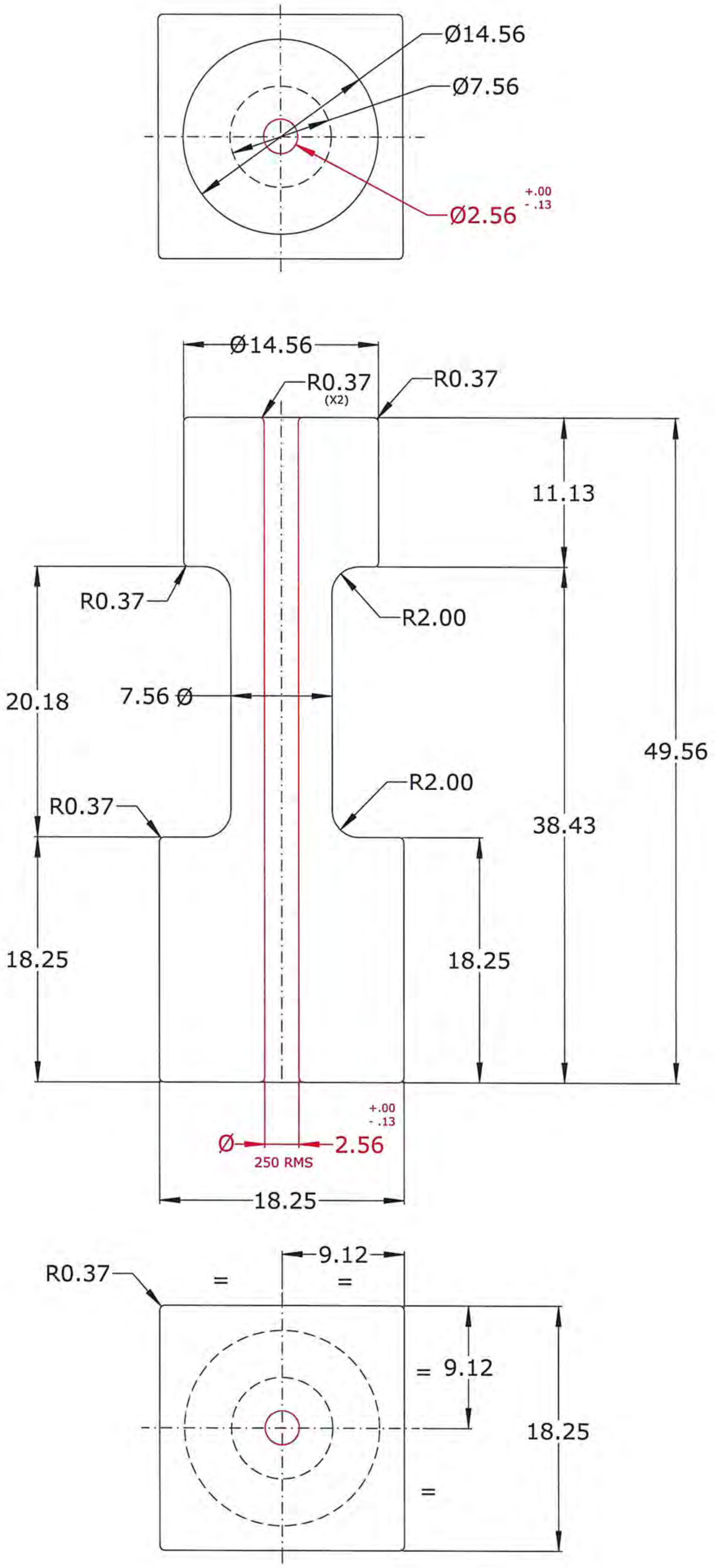


AIKEN ENGINEERING COMPANY

TITLE:
TEST BODY, WITH REDUCED NECK,
API 17 EVALUATION,
3-1/16 - 20K X 4-1/16 - 20K

SIZE	DWG. NO.	REV
D	PN2456-500	1

WEIGHT: 1548.20 Lbs. SHEET 1 OF 2



(DRILL OPERATION)
PRE-HEAT TREAT MACHINE
REF WT# (LBS) 2443

Thermal Treatment Receiving Inspection Report

Supplier:

Process Number:

FPI W/O No: 87473

Heat No: AH450-2E1 Qty: 1 (prel)

Order Qty: 2

Heat No: AH450-2E2 Qty: 1

Qty. Rec:

Heat No: Qty:

Specification: D2456-1

Process Verification: Accept Reject

Required Hardness: /

By: Date:

Special Instructions:

INSPECTION RESULTS

Serial Number	WO / HT Number	Material Condition	Supplier Hardness Results		FPI Hardness Verification		FPI Inspect Hardness	Item Status	
								Accept	Reject
AH450-2E	✓	✓	223	229			228		
			235	223					
			223	223					
			229						
AH450-2E2	✓	✓	229	223					
			223	223					
			223	223					
			229						

Inspected By: Date: 1-10-16

DELIVERY PERFORMANCE DATA

Due Date: Received Date:

FPI
FORGED PRODUCTS, INC.
6506 N. Houston-Rosslyn Rd.
Houston, Texas 77091
Phone: (713) 462-3417

SUBCONTRACT HEAT TREAT DATA SHEET

Vendor: LONE START HEAT TREATING CO.
PO No:
Work Order No: 87473
Material Grade: F22 (CS-F22MX R/4)
Item Serial No(s): AH450-2E1 & -2E2

Date Shipped:
Promised Return Date:
Delivery Ticket No:

Load T.C. Required

Part Size: PER DWG #87473-PHTM & 87473-PHTM-TST
Part Description/Condition: ROUGH MACHINED

3rd Party Witness Required

1 day notification for Quench

LOAD PARTS PER FLM-87473 Rev 0 - INDUCE FLOW THRU I.D. DURING THE QUENCH OPERATION

Total Quantity
Parts: 2
Test Material: 1

Heat No:	AH450	Qty Parts:	2	Qty Test Mat'l:	0	Extension:	1
Heat No:	0	Qty Parts:	0	Qty Test Mat'l:	0	Extension:	0
Heat No:	0	Qty Parts:	0	Qty Test Mat'l:	0	Extension:	0

Part Details
☐ Rough Forging
☒ Rough Machined

Material Weight: 2717 LBS each
2443 LBS each
Max. Section Size: 9.63 IN

Test Material Description
Prolongation
PER DWG 87413-PHTM-TST

Required Thermal Treatment & Acceptance Criteria								*FPI Verification Check*		
								Accept	Reject	By
Normalize:	Min: Max:	1750 1775	°F	5.5	HRS Min.	Comments:	AIR COOL TO BELOW 300°F			
Austenitize:	Min: Max:	1700 1725	°F	5.5	HRS Min.	Comments:	FOLLOWED BY WATER QUENCH			
*Quench:	Coolant:	Water	Start (°F): End (°F):	75 120		Comments:	COOL TO BELOW 400°F USING HORIZONTAL FLOW			
Temper:	Min: Max:	1225	°F	10	HRS Min.	Comments:	WATER COOL TO AMBIENT			
Other:	CYCLE DURATIONS ARE BESED ON FURNACE T.C. THE CONTACT T.C. IS REQUIRED TO REACH SET TEMPERATURE FOR ONE HOUR MININIMUM.									
**Brinell:	Min: Max:	217 237	HBW	No. of Checks:	3	Comments:				

ALL HEAT TREAT CYCLES, INCLUDING ALL RE-TEMPER CYCLES, MUST BE REPORTED ON THE FINAL CERTIFICATION. VENDOR MUST REQUEST APPROVAL FROM FPI PRIOR TO ANY RE-HEAT TREAMENT, INCLUDING RE-TEMPERING.

*Unless specified otherwise, the following statements apply.
Water: The temperature of the water shall not be greater than 100°F at the beginning of the quench & shall not exceed 120°F upon the completion of the quench.
Oil: Temperature shall be within the range recommended by the quenchant manufacturer.
**All hardness testing must be conducted using Brinell type equipment only.

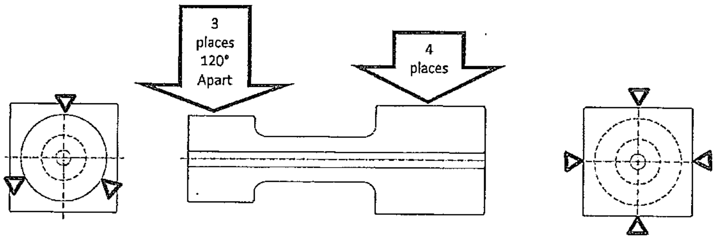
Equipment Qualification:	☒ API 6A Anx M	☒ Mil-H-6875	☐ Other:
Temperature Controlled by:	☐ Furnace T.C. Only	☒ Furnace & Contact T.C.	☐ Contact T.C
Re-Heat Allowance:	☐ One (1)	☒ Other: CONTACT FPI	☐
Hardness Testing per:	☒ ASTM E10	☐ Other:	☐ Other:
Hardness Exam Preparation Depth:	☒ 1/8" (Min) to 3/16" (Max)	☐ 1/4" (Min) to 5/16" (Max)	☐ Other:

Certification must be supplied with shipment unless otherwise specified. Document package must include:

☒ FPI Purchase Order No.
☒ FPI Work Order No.
☒ FPI Delivery Ticket No.
☒ Material Description
☒ Quantity
☒ Heat No.
☒ Material Grade
☒ Thermal Processing
☒ Quench Media
☒ Media Temperatures (Start/Completion)
☒ Hardness Results
☒ Furnace Charts
☒ Statement of Compliance
☒ Authorized Signature

Hardness Test & Thermocouple Location(s) Per Sketch Below

The Shear Pin method or hardness measurements performed with instruments using the rebound method are NOT ACCEPTED.



CONTACT THERMOCOUPLE TO BE PLACED ON THE SURFACE OF THE HEAVIEST SECTION OF THE PART.

THE HOLD TIMES WILL START WHEN THE FURNACE THERMOCOUPLE IS WITHIN 25°F FOR THE AUSTENITIZE CYCLE & 15°F FOR THE TEMPER CYCLE OF THE FURNACE SET POINT. THE CONTACT THERMOCOUPLE MUST REACH THE SET TEMPERATURES WITHIN THE SAME TOLERANCES FOR AT LEAST ONE HOUR PRIOR TO THE END OF THE HEAT TREAT CYCLE.

Prepared By: R. CENDEJAS Date: 11/30/2015 Reviewed By: Date:
Rev 01 - Revised cycle duration & TC requirements - 12/01/2015

Form No. WI 7.5.1.8 Rev. 07

Thermal Treatment Receiving Inspection Report

Supplier:

Process Number:

FPI W/O No: 87473

Heat No: AH450-2E1 Qty: 1 (prol)

Order Qty: 2

Heat No: AH450-2E2 Qty: 1

Qty. Rec:

Heat No: Qty:

Specification: D2456-1

Process Verification: Accept Reject

Required Hardness: /

By: Date:

Special Instructions:

INSPECTION RESULTS

Serial Number	WO / HT Number	Material Condition	Supplier Hardness Results		FPI Hardness Verification		FPI Inspect Hardness	Item Status	
								Accept	Reject
AH450-2E1	✓	✓	223	229			228		
			235	223					
			223	223					
			229						
AH450-2E2	✓	✓	229	223					
			223	223					
			223	223					
			229						

Inspected By: Date: 1-10-16

DELIVERY PERFORMANCE DATA

Due Date: Received Date:

FPI FORGED PRODUCTS, INC.
6506 N. Houston-Rosslyn Rd.
Houston, Texas 77091
Phone: (713) 462-3417

SUBCONTRACT HEAT TREAT DATA SHEET

Vendor: LONE START HEAT TREATING CO.
PO No:
Work Order No: 87473
Material Grade: F22 (CS-F22MX R/4)
Item Serial No(s): AH450-2E1 & -2E2

Date Shipped:
Promised Return Date:
Delivery Ticket No:

Load T.C. Required

Part Size: PER DWG #87473-PHTM & 87473-PHTM-TST
Part Description/Condition: ROUGH MACHINED

3rd Party Witness Required
1 day notification for Quench

LOAD PARTS PER FLM-87473 Rev 0 - INDUCE FLOW THRU I.D. DURING THE QUENCH OPERATION

Total Quantity
Parts: 2
Test Material: 1

Heat No:	AH450	Qty Parts:	2	Qty Test Mat'l:	0	Extension:	1
Heat No:	0	Qty Parts:	0	Qty Test Mat'l:	0	Extension:	0
Heat No:	0	Qty Parts:	0	Qty Test Mat'l:	0	Extension:	0

Part Details
☐ Rough Forging
☒ Rough Machined

Material Weight: 2717 LBS each
2443 LBS each
Max. Section Size: 9.63 IN

Test Material Description
Prolongation
PER DWG 87413-PHTM-TST

Required Thermal Treatment & Acceptance Criteria

							FPI Verification Check		
							Accept	Reject	By
Normalize:	Min: 1750 Max: 1775	°F	5.5	HRS Min.	Comments:	AIR COOL TO BELOW 300°F			
Austenitize:	Min: 1700 Max: 1725	°F	5.5	HRS Min.	Comments:	FOLLOWED BY WATER QUENCH			
*Quench:	Coolant: Water	Start (°F): 75 End (°F): 120			Comments:	COOL TO BELOW 400°F USING HORIZONTAL FLOW			
Temper:	Min: 1225 Max:	°F	10	HRS Min.	Comments:	WATER COOL TO AMBIENT			
Other:	CYCLE DURATIONS ARE BESED ON FURNACE T.C. THE CONTACT T.C. IS REQUIRED TO REACH SET TEMPERATURE FOR ONE HOUR MININIMUM.								
**Brinell:	Min: 217 Max: 237	HBW	No. of Checks: 3		Comments:				

ALL HEAT TREAT CYCLES, INCLUDING ALL RE-TEMPER CYCLES, MUST BE REPORTED ON THE FINAL CERTIFICATION.
VENDOR MUST REQUEST APPROVAL FROM FPI PRIOR TO ANY RE-HEAT TREAMENT, INCLUDING RE-TEMPERING.

*Unless specified otherwise, the following statements apply.

Water: The temperature of the water shall not be greater than 100°F at the beginning of the quench & shall not exceed 120°F upon the completion of the quench.

Oil: Temperature shall be within the range recommended by the quenchant manufacturer.

**All hardness testing must be conducted using Brinell type equipment only.

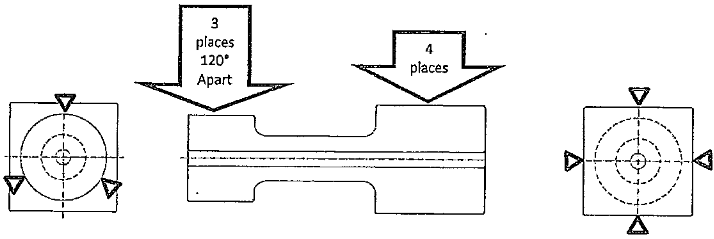
Equipment Qualification:	☒ API 6A Anx M	☒ Mil-H-6875	☐ Other:
Temperature Controlled by:	☐ Furnace T.C. Only	☒ Furnace & Contact T.C.	☐ Contact T.C
Re-Heat Allowance:	☐ One (1)	☒ Other: CONTACT FPI	☐
Hardness Testing per:	☒ ASTM E10	☐ Other:	☐ Other:
Hardness Exam Preparation Depth:	☒ 1/8" (Min) to 3/16" (Max)	☐ 1/4" (Min) to 5/16" (Max)	☐ Other:

Certification must be supplied with shipment unless otherwise specified. Document package must include:

- ☒ FPI Purchase Order No.
- ☒ FPI Work Order No.
- ☒ FPI Delivery Ticket No.
- ☒ Material Description
- ☒ Quantity
- ☒ Heat No.
- ☒ Material Grade
- ☒ Thermal Processing
- ☒ Quench Media
- ☒ Media Temperatures (Start/Completion)
- ☒ Hardness Results
- ☒ Furnace Charts
- ☒ Statement of Compliance
- ☒ Authorized Signature

Hardness Test & Thermocouple Location(s) Per Sketch Below

The Shear Pin method or hardness measurements performed with instruments using the rebound method are NOT ACCEPTED.



CONTACT THERMOCOUPLE TO BE PLACED ON THE SURFACE OF THE HEAVIEST SECTION OF THE PART.

THE HOLD TIMES WILL START WHEN THE FURNACE THERMOCOUPLE IS WITHIN 25°F FOR THE AUSTENITIZE CYCLE & 15°F FOR THE TEMPER CYCLE OF THE FURNACE SET POINT. THE CONTACT THERMOCOUPLE MUST REACH THE SET TEMPERATURES WITHIN THE SAME TOLERANCES FOR AT LEAST ONE HOUR PRIOR TO THE END OF THE HEAT TREAT CYCLE.

Prepared By: R. CENDEJAS Date: 11/30/2015 Reviewed By: Date:
Rev 01 - Revised cycle duration & TC requirements - 12/01/2015

Form No. WI 7.5.1.8 Rev. 07

FRANKLIN
RESEARCH ASSOCIATES
CERTIFICATE OF TESTS

Aiken Engineering Company
9720 Cypresswood Drive, Suite 340
Houston, Texas 77070
Attention: Maurice Peltier
Purchase Order Number: 2456-0222-2016
Part Number: 2456-PRO
AH450-2E1
QTC: 12” x 2.25” x 6”   F22

11354 Jones Road West
Suite E
Houston, Texas 77065
Phone: (281) 894-2245
Fax: (281) 894-2216
Date: February 27, 2016
Laboratory Test Number: 28750

TEST DATA

True Stress/True Strain Information Electronically Transmitted

ROOM TEMPERATURE TENSILE:
Orientation: Longitudinal
Location: ¼ T

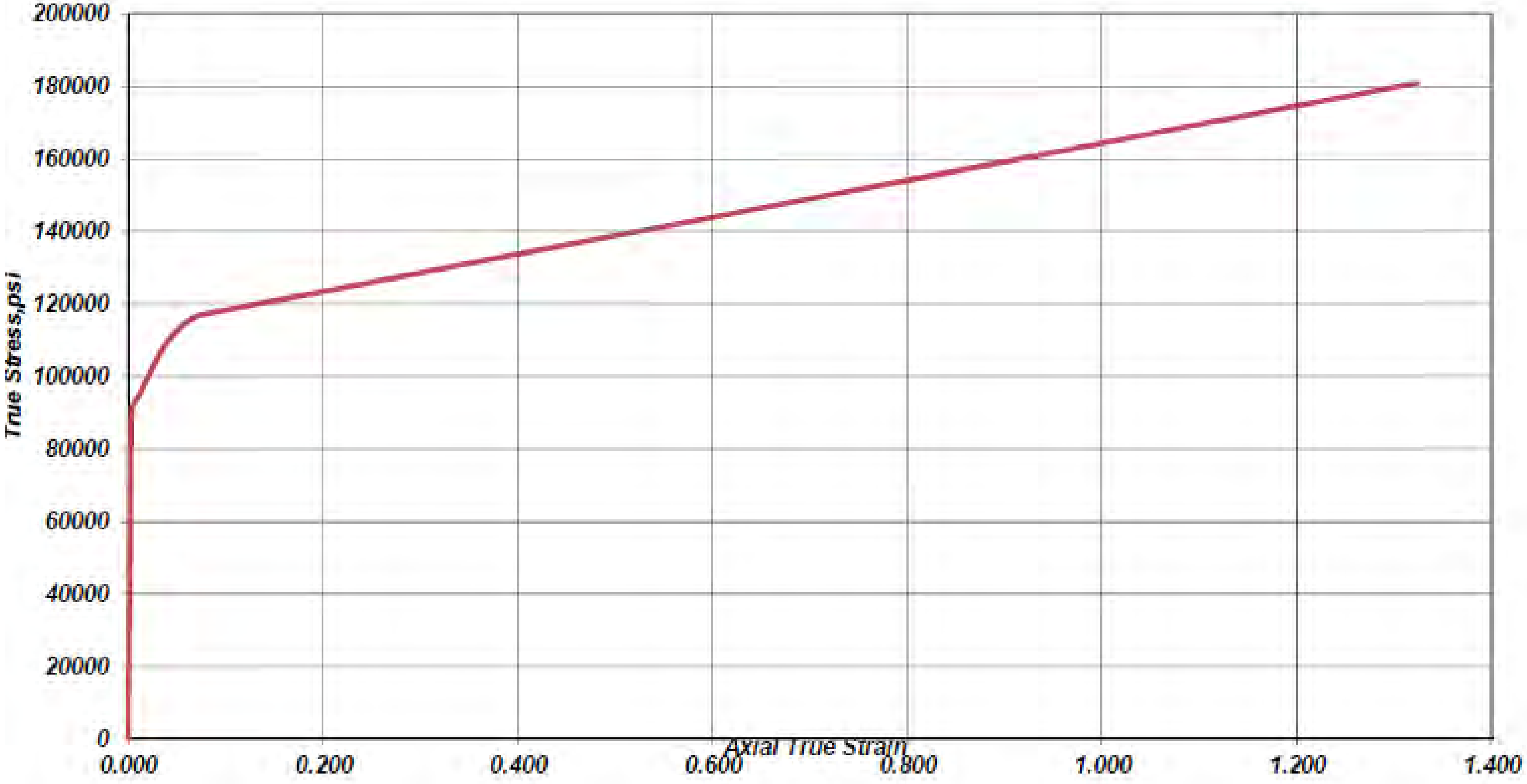
ID	UTS,psi	YS, .2%psi	%EL	%RA	Dia. In.	G/Len.
1	108,700	91,600	25.1	73.4	0.502	2.000

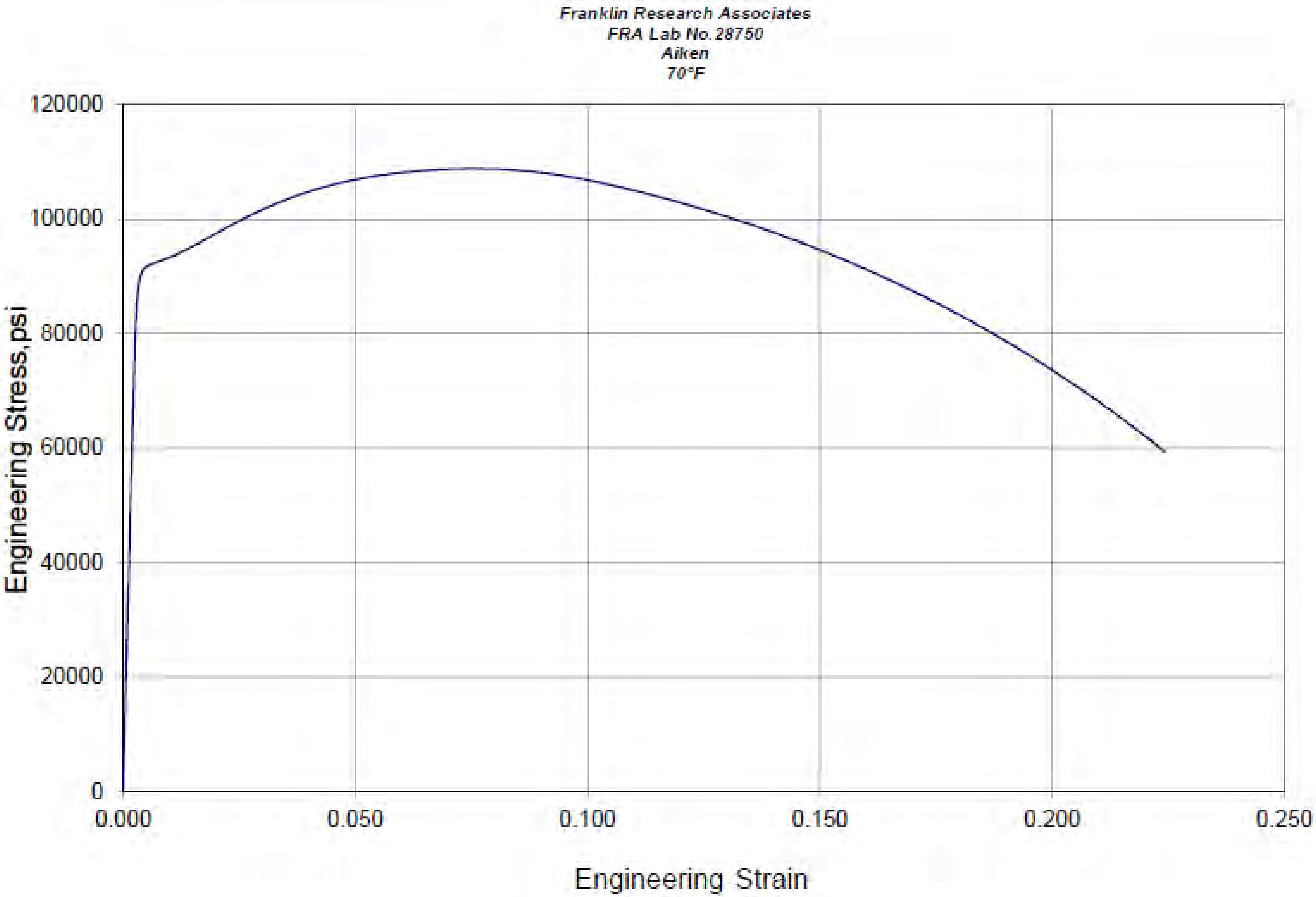
ELEVATED TEMPERATURE TENSILE @ 350°F:
Orientation: Longitudinal
Location: ¼ T

ID	UTS,psi	YS, .2%psi	%EL	%RA	Dia. In.	G/Len.
1	97,700	81,200	22.4	74.4	0.502	2.000

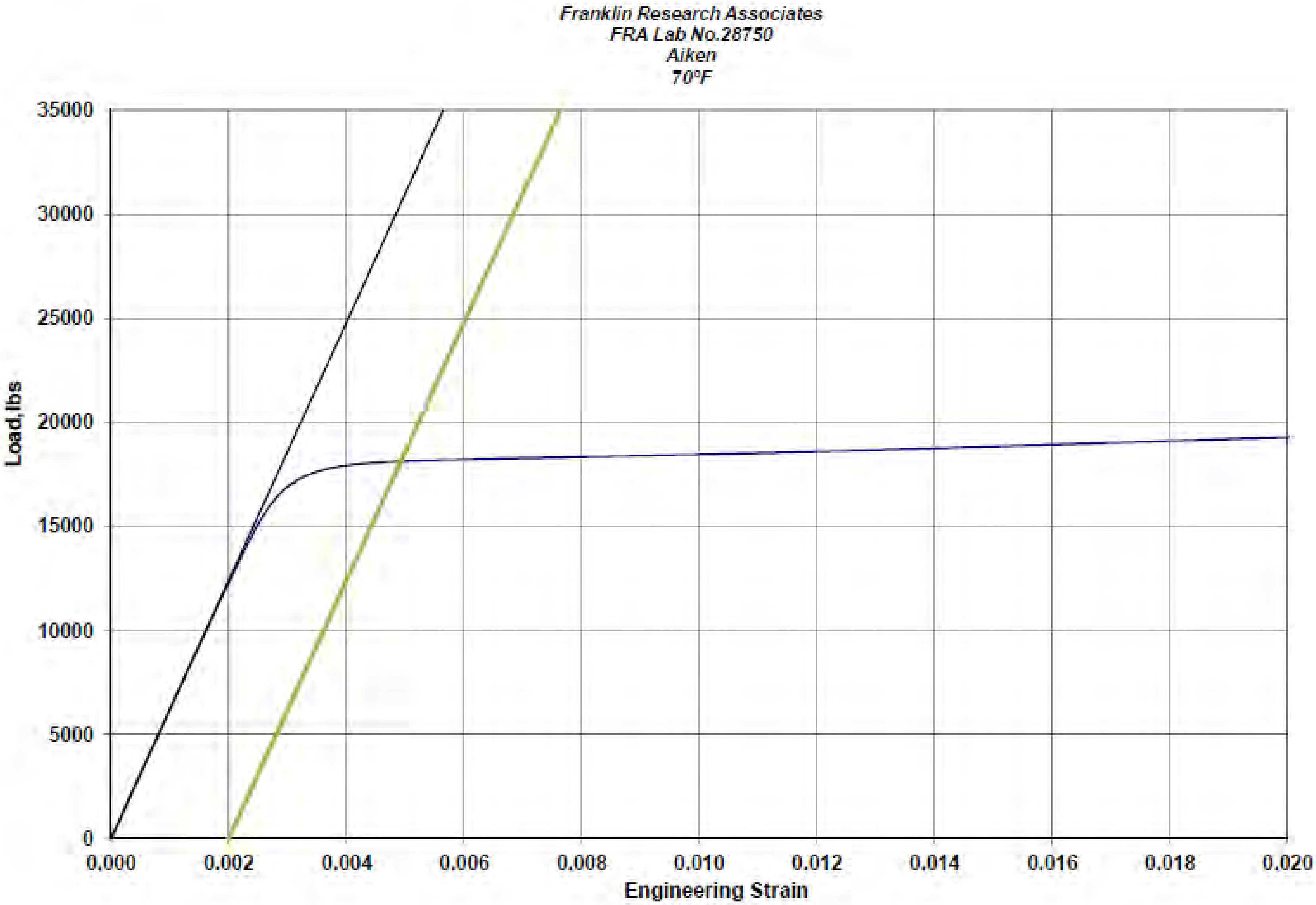
Henry J Malik
Manager - Laboratory Operations
ISO 9001:2008 Certificate Number 800467

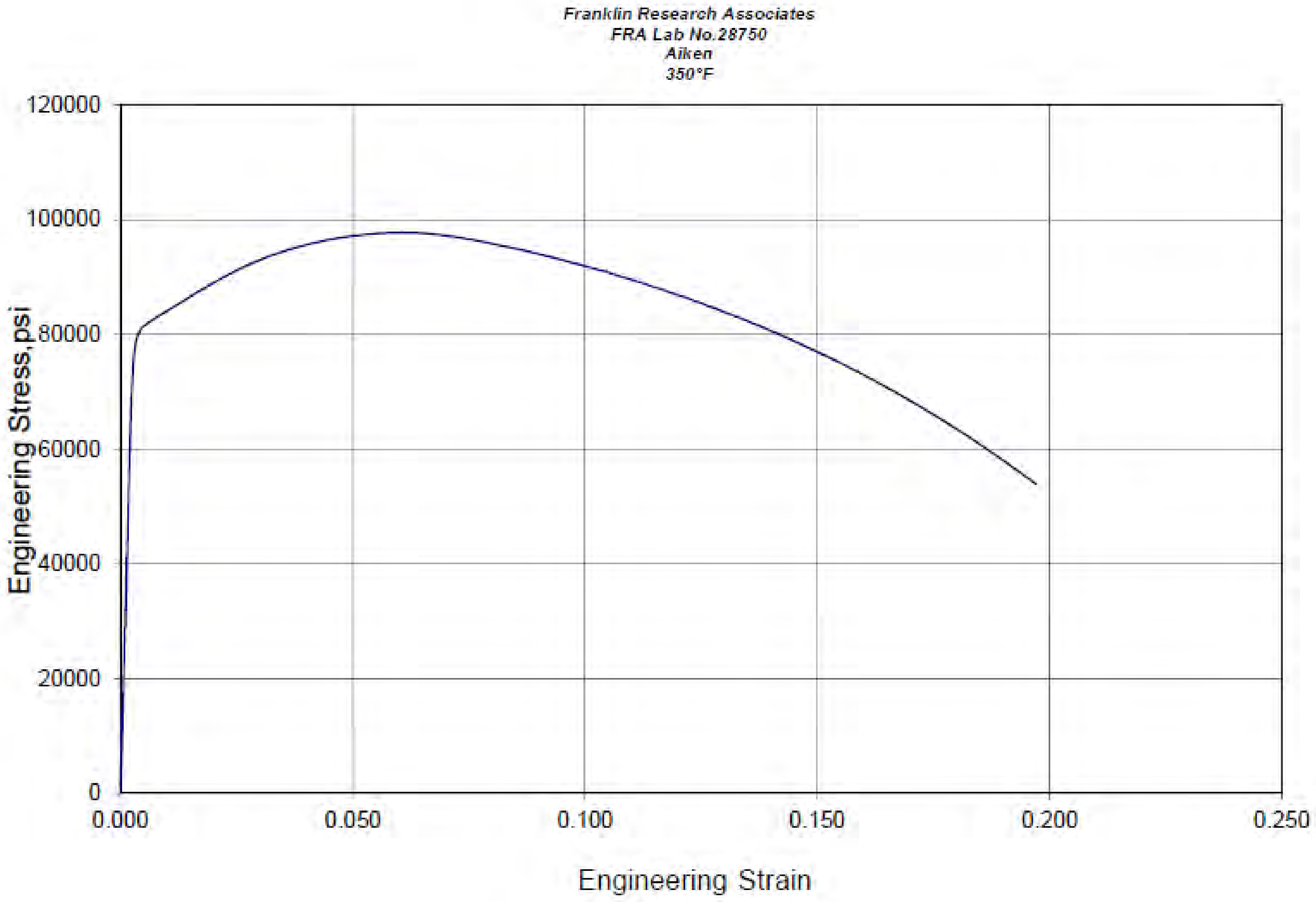
Franklin Research Associates
FRA Lab No.28750
Aiken
70°F



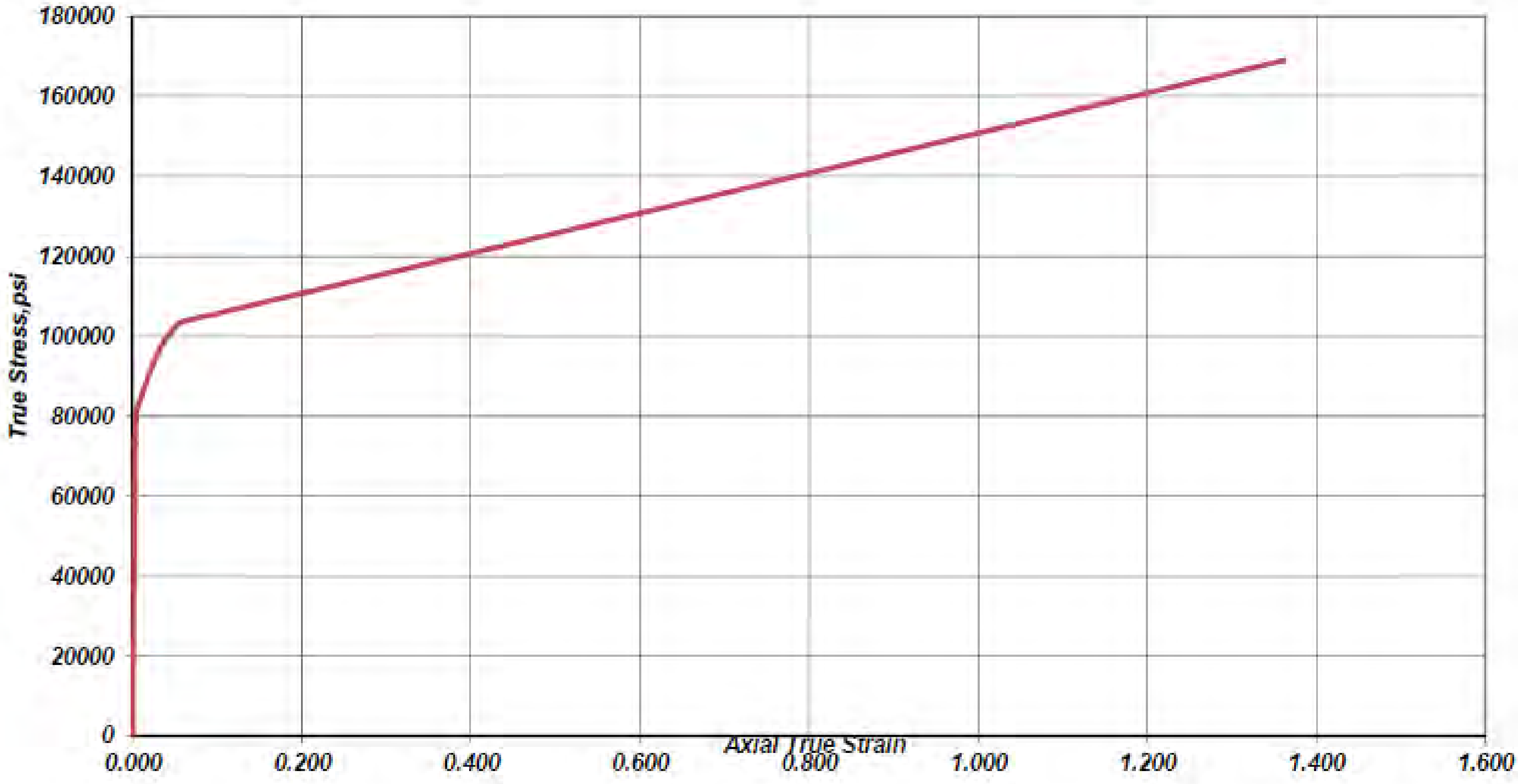


Franklin Research Associates
FRA Lab No. 28750
Aiken
70°F

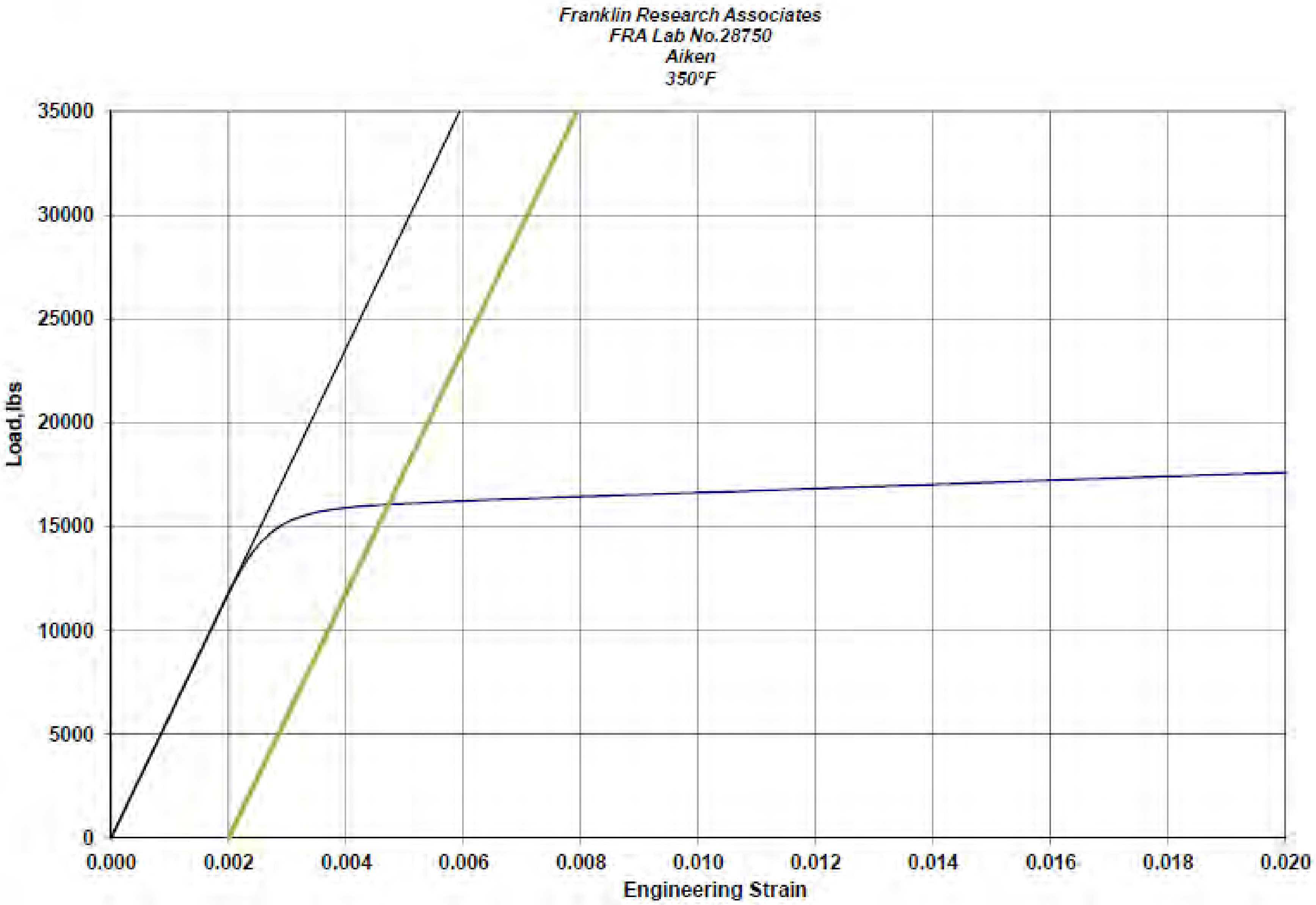

Franklin Research Associates
FRA Lab No.28750
Aiken
70°F
Load, lbs
35000
30000
25000
20000
15000
10000
5000
0
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
Engineering Strain



Franklin Research Associates
FRA Lab No.28750
Aiken
350°F



Franklin Research Associates
FRA Lab No.28750
Aiken
350°F



Franklin Research Associates
FRA Lab No.28750
Aiken
350°F
Load,lbs
35000
30000
25000
20000
15000
10000
5000
0
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
Engineering Strain

	NORMALIZE CYCLE		AUTENITIZE CYCLE					TEMPER CYCLE		Test Material	MECHANICAL PROPERTIES						IMPACT TEST												
					COOLANT																								
MAT	Temp	Hrs	Temp	Hrs	Type	Start	Fin	Temp	Hrs	TST-SIZE	YS	UTS	Elg	RA	HBW		ORIENT	LOC	TEMP	C-1	C-2	C-3	AVG	LE1	LE2	LE3	S1	S2	S3
F22	1750	3	1725	2.25	water	66	74	1250	4	Prolongation	88,700	106,000	21.6	67.3	223	223	T	T4	-75	51	56	44	50	32	40	27	60	60	60
F22	1750	2.25	1725	2.75	water	85	91	1225	4	Prolongation	86,600	104,800	21.2	68.6	235	235	L	T4	-75	69	63	56	63	37	37	32	40	40	30
F22	1750	2	1725	2.5	water	90	96	1225	4.5	Prolongation	90,500	108,500	20.6	72.8	235	235	L	T4	-75	110	76	113	100	60	38	58	100	80	100
F22	1750	2	1725	3	water	96	109	1225	5.25	Prolongation	85,600	102,600	20.3	71.2	229	229	L	T4	-75	109	73	98	93	62	42	55	85	70	80
F22	1750	2.25	1725	2.25	water	98	109	1225	4.25	Prolongation	94,270	110,999	20.4	69.0	235	235	L	T4	-75	61	97	76	78	35	54	39	80	85	85
F22	1750	2	1725	2	water	73	78	1225	4.25	Prolongation	87,479	104,634	21.5	76.1	229	229	L	T4	-75	117	100	133	117	73	60	69	100	80	100
F22	1750	2	1725	3.75	water	62	66	1225	4	Prolongation	87,699	104,202	21.7	75.1	229	229	L	T4	-75	64	44	50	53	39	25	32	30	10	20
F22	1750	2	1725	2	water	66	76	1225	4.25	Prolongation	90,569	106,430	21.8	73.9	229	229	L	T4	-75	37	72	71	60	21	41	42	20	60	60
F22	1750	2	1725	2	water	85	90	1225	4	Prolongation	91,319	108,338	19.7	69.6	235	235	L	T4	-4	100	99	86	95	59	62	51	100	100	100
F22	1750	2.25	1725	2	water	81	87	1225	5	Prolongation	98,400	114,500	22.2	73.4	235	235	L	T4	-75	137	94	66	99	67	48	31	100	90	60
F22	1750	3	1725	2.25	water	50	63	1250	4	Prolongation	87,100	104,100	22.7	73.7	217	217	L	T4	-75	110	79	118	102	67	50	71	55	50	70
F22	1750	3	1725	2.25	water	50	63	1250	4	Prolongation	87,400	104,900	21.4	71.5	217	217	T	T4	-75	81	95	102	93	46	56	61	70	75	70
F22	1750	3	1725	2.25	water	50	63	1250	4	Prolongation	87,100	104,100	22.7	73.7	217	217	L	T4	-75	110	79	118	102	67	50	71	55	50	70
F22	1750	6	1725	7.25	water	70	77	1250	10	4X8X12	86,279	105,546	22.2	74.1	221	221	L	T4	-75F	102	88	101	97	70	57	68	85	70	80
F22	1750	9.25	1700	9.75	water	65	69	1235	12.5	Prolongation	86,925	105,520	23.3	72.9	223	223	L	T4	-50F	119	111	113	114	80	71	76	100	80	100
F22	1750	9.25	1700	9.75	water	65	69	1235	12.5	Prolongation	89,491	106,962	23.3	75.0	225	225	L	T4	-50F	133	139	118	130	79	84	70	100	100	80
F22	1750	7.25	1700	7.5	water	46	61	1235	11.5	Prolongation	81,719	100,506	24.6	73.2	210	210	L	T4	-50F	120	113	145	126	74	74	87	80	80	100
F22	1750	7.25	1700	7.5	water	46	61	1235	11.5	Prolongation	81,739	99,970	24.1	69.4	212	212	L	T4	-50F	68	95	67	77	53	71	49	80	85	45
F22	1750	7.25	1700	12.5	water	79	90	1220	15.75	4X4X8	83,301	101,743	24.9	76.4	219	219	L	T4	-0F	119	119	146	128	78	76	89	100	100	100
F22	1750	6	1700	7.5	water	81	93	1230	10.5	Prolongation	89,151	108,722	22.3	72.3	234	234	L	T4	-50F	82	72	93	82	58	52	66	50	45	65
F22	1750	9.25	1700	9.5	water	67	90	1230	12.5	Prolongation	81,248	99,978	22.7	66.6	215	215	L	T4	-50F	101	50	108	86	71	36	71	60	45	70
F22	1750	7	1725	7	water	78	78	1220	10.5	Prolongation	90,160	107,628	23.5	72.7	230	230	L	T4	0F	133	136	143	137	76	84	88	100	100	100
F22	1750	5	1700	4.5	water	76	81	1220	6.75	4X4X8	88,514	105,929	24.1	73.9	228	228	L	T4	-50F	84	86	123	98	60	58	76	70	70	100
F22	1750	5	1700	4.5	water	76	81	1220	6.75	4X4X8	81,933	98,072	24.3	78.9	215	215	L	T4	-50F	190	203	205	199	88	96	95	100	100	100
F22	1750	4	1700	4.5	water	81	86	1230	6.5	4X4X8	84,859	102,368	24.3	72.1	224	224	L	T4	-50F	105	111	122	113	74	77	79	85	85	100
F22	1750	4	1725	4.5	water	80	91	1230	6.5	4X4X8	90,850	106,953	23.3	71.4	229	229	L	T4	-50F	126	122	113	120	85	81	75	100	100	100
F22	1750	6	1725	6.5	water	69	75	1230	10.5	Prolongation	84,223	103,826	22.7	69.3	219	219	L	T4	-50F	47	67	83	66	33	48	56	40	60	85
F22	1750	6.25	1725	6.25	water	74	75	1220	10.25	4X4X8	88,201	105,449	24.4	76.0	226	226	L	T4	-50F	145	151	145	147	87	94	86	100	100	100
F22	1750	7	1725	7	water	72	74	1240	12.25	4X4X8	85,685	103,876	25.4	76.0	228	228	L	T4	-50F	126	116	137	126	82	77	86	100	100	100
F22	1750	7	1725	7	water	72	74	1240	12.25	4X4X8	85,798	103,762	25.5	74.8	222	222	L	T4	-50F	151	142	152	148	86	84	87	100	100	100
F22	1750	3	1725	5	water	74	76	1220	8	4X4X8	85,170	103,171	24.0	72.8	218	218	L	T4	-50F	54	104	95	84	43	70	64	60	100	90
F22	1750	3	1725	5	water	74	76	1220	8	4X4X8	85,661	101,720	23.4	67.6	216	216	L	T4	-50F	83	68	62	71	58	50	45	55	50	50
F22	1750	3	1725	5	water	74	76	1220	8	4X4X8	90,467	107,824	22.5	71.1	231	231	L	T4	-50F	114	120	92	109	71	77	63	100	100	70
F22	1750	3	1725	5	water	74	76	1220	8	4X4X8	87,316	103,417	24.6	75.0	226	226	L	T4	-50F	152	106	169	142	88	75	94	100	80	100
F22	1750	4	1725	5.5	water	69	70	1250	8	4X4X8	92,211	108,236	18.6	48.1	232	232	L	T4	-50F	36	33	39	36	28	24	28	40	40	50
F22	1750	4	1700	5.5	water	70	91	1220	9.25	4X4X8	82,476	100,699	21.1	62.3	218	218	L	T4	-50F	36	44	51	44	26	34	37	40	50	55
F22	1750	4	1700	5.5	water	70	91	1220	9.25	4X4X8	85,427	103,255	24.0	72.1	223	223	L	T4	-50F	87	48	93	76	59	37	60	70	45	70
F22	1750	4	1700	5.5	water	70	91	1220	9.25	4X4X8	83,431	102,536	25.1	76.4	222	222	L	T4	-50F	148	131	132	137	89	84	82	100	100	100
F22	1750	5.75	1700	5.5	water	70	91	1220	9.25	Prolongation	90,938	109,668	23.0	71.6	236	236	L	T4	-0F	130	134	140	135	86	87	89	100	100	100
F22	1750	5.75	1700	5.5	water	70	91	1220	9.25	Prolongation	90,938	109,668	23.0	71.6	236	236	L	T4	-0F	130	134	140	135	86	87	89	100	100	100
F22	1750	5	1700	5.5	water	72	85	1220	10.5	4X4X8	88,858	106,799	23.8	73.4	228	228	L	T4	-50F	159	145	152	152	91	91	86	100	100	100
F22	1750	5.25	1700	5.5	water	72	85	1220	10.5	4X4X8	85,326	103,071	23.9	72.4	219	219	L	T4	-50F	105	114	112	110	72	77	72	100	100	100
F22	1750	4	1700	5.5	water	70	91	1220	9.25	4X4X8	85,500	103,113	23.3	73.0	224	224	L	T4	-50F	128	142	120	130	87	86	79	100	100	85
F22	1750	4	1700	5.5	water	70	91	1220	9.25	Prolongation	92,147	109,984	23.3	76.6	237	237	L	T4	-50F	175	171	140	162	94	97	88	100	100	100
F22	1750	3	1700	5	water	64	69	1220	7	4X4X8	94,700	110,300	22.6	69.2	237	237	L	T4	-50F	108	118	111	112	62	72	70	80	100	100
F22	1750	5.75	1700	4.75	water	67	80	1220	9.75	Prolongation	88,200	105,600	22.8	73.0	229	230	L	T4	0F	159	169	176	168	86	93	NB	100	100	NB
F22	1750	8.5	1700	4.5	water	73	83	1220	7	4X4X8	95,500	110,700	23.6	69.5	236	237	L	T4	-50F	132	135	128	132	71	77	69	100	100	100
F22	1750	8.5	1700	4.5	water	73	83	1220	7	4X4X8	91,500	107,200	21.0	61.4	226	231	L	T4	-50F	82	77	93	84	54	45	60	75	70	85
F22	1750	6.25	1700	7.5	water	72	79	1220	12	Prolongation	94,100	111,400	21.3	65.6	237	237	T	T4	-50F	25	50	87	54	20	28	53	25	50	80
F22	1750	6.25	1700	7.5	water	72	79	1220	12	Prolongation	94,100	111,400	21.3	65.6	237	237	T	T4	-50F	25	50	87	54	20	28	53	25	50	80
F22	1750	9	1700	6.5	water	77	86	1220	10	4X4X8	87,000	104,700	24.0	70.5	222	224	L	T4	-50F	136	123	142	134	74	69	84	100	100	100
F22	1750	4	1700	5.5	water	70	91	1220	9.25	4X4X8	85,427	103,255	24.0	72.1	223	223	L	T4	-50F	87	48	93	76	59	37	60	70	45	70
F22	1725	5.5	1675	5.5	water	72	80	1220	10.5	Prolongation	90,200	108,600	22.3	70.9	229	229	L	T4	-50F	95	98	98	97	60	63	63	65	65	65
F22	1750	6	1700	6.5	water	61	63	1220	10.5	Prolongation	90,900	108,400	25.2	75.5	232	235	L	T4	-50F	131	136	138	135	79	81	82	100	100	100
F22	1750	4	1700	5	water	63	75	1220	7	4X4X8	88,899	107,004	22.9	69.5	222	222	L	T4	-50F	117	113	112	114	77	80	78	100	100	100
F22	1750	7	1700	6.5	water	57	63	1220	14.75	Prolongation	85,900	104,800	16.8	36.9	223	219	T	T4	-50F	17	24	60	34	17	19	41	34	40	65
F22	1750	3	1700	5	water	66	78	1220	8.5	4X4X8	90,800	108,100	24.4	70.3	226	230	L	T4	-50F	136	146	126	136	75	81	71	100	100	100
F22	1750	4.5	1700	5	water	63	75	1220	7	4X4X8	95,460	112,730	24.0	75.0	237	237	L	T4	-50F	149	144	145	146	92	91	91	100	100	100
F22	1750	6.5	1700	5	water	75	85	1230	10	4X4X8	86,300	102,800	23.6	75.0	218	218	L	T4	-50F	140	133	134	136	86	73	74	100	100	100
F22	1750	5	1700	5	water	66	78	1220	8.5	Prolongation	95,100	96,800	24.0	75.0	235	235	L	T4	-50F	126	116	122	121	76	70	74	100	100	100
F22	1750	5	1725	5.75	water	81	82	1220	10.5	Prolongation	87,600	105,600	20.4	60.8	226	234	T	T4	-50F	31	83	59	58	21	55	41	35	75	65
F22	1750	3.75	1700	4.5	water	78	81	1240	6.5	Prolongation	93,270	111,408	23.0	75.7	236	236	L	T4	-50F	143	132	136	137	88	75	80	100	100	100
F22	1750	4.75	1700	4.5	water	65	70	1230	6.5	4X4X8	93,025	110,320	24.3	73.3	234	234	L	T4	-50F	120	130	132	127	71	74	78	100	100	100
F22	1750	3.25	1700	4.5	water	63	70	1230	5	Prolongation	87,374	106,868	24.1	74.5	232	232	L	T4	-50F	125	139	153	139	71	79	85	100	100	100
F22	1750	4	1700	5	water	70	77	1230	10	4X4X8	89,299	107,316	23.6	70.8	228	228	L	T4	-50F	119	118	126	121	77	80	82	100	100	100
F22	1750	4	1700	5	water	70	77	1230	10	4X4X8	95,337	112,578	24.3	74.2	236	236	L	T4	-50F	123	116	126	122	76	73	81	100	100	100
F22	1750	3	1700	4	water	72	78	1230	9.25	Prolongation	91,179	109,267	24.1	74.3	232	231	L	T4	-50F	134	133	133	133	77	78	78	100	100	100
F22	1750	7.75	1700	7.75	water	67	71	1230	11.5	Prolongation	91,000	109,600	23.0	69.3	232	232	L	T4	0F	127	139	121	129	81	88	82	100	100	90
F22	1750	5.25	1700	5	water	67	75	1230	8	Prolongation	95,000	112,900	23.0	72.5	235	234	L	T4	-50F	153	164	170	162	76	81	85	100	100	100
F22	1750	4	1700	5	water	67	75	1230	8	Prolongation	90,457	107,723	21.8	66.0	228	228	L	T4	-50F	48	47	35	43	32	32	25	40	35	20
F22	1750	7.25	1700	5.5	water	69	75	1220	10.5	4X4X8	94,776	112,873	23.4	75.8	237	237	L	T4	-50F	137	142	142	140	85	86	89	100	100	100
F22	1750	6.5	1700	6.5	water	70	75	1230	10.5	4X4X8	84,400	102,229	24.7	74.5	214	214	L	T4	-50F	122	124	114	120	87	87	83	100	100	100
F22	1750	7.25	1700	6.5	water	70	75	1230	10.5	4X4X8	89,536	107,887	23.5	72.6	231	231	L	T4	-50F	135	135	147	139	80	86	92	100	100	100
F22	1750	6	1700	9.5	water	74	79	1225	10.5	4X4X8	92,214	110,790	23.9	69.7	235	237	L	T4	-50F	130	120	115	122	85	81	77	100	100	100
F22	1750	6.25	1700	6.5	water	79	84	1230	10.75	4X4X8	87,427	108,655	24.1	73.8	235	235	L	T4	-50F	127	121	103	117	81	67	65	100	100	100
F22	1750	7.25	1700	6.5	water	70	75	1230	10.5	4X4X8	89,536	107,887	23.5	72.6	231	231	L	T4	-50F	135	135	147	139	80	86	92	100	100	100
F22	1750	5	1700	5.5	water	72	85	1220	10.5	4X4X8	84,601	102,572	24.7	50.8	215	215	L	T4	-50F	148	148	154	150	90	90	97	100	100	100
F22	1750	6.25	1700	6	water	73	80	1220	11	4X4X8	91,234	109,280	22.7	70.2	236	236	L	T4	-50F	126	127	117	123	78	76	76	100	100	100
F22	1750	5.25	1700	5	water	67	75	1230	8	Prolongation	95,000	112,900	23.0	72.5	235	234	L	T4	-50F	153	164	170	162	76	81	85	100	100	100
F22	1750	6	1700	6	water	73	80	1220	11	4X4X8	88,183	106,980	23.6	71.6	229	229	L	T4	-50F	110	125	130	122	70	79	84	100	100	100
F22	1750	4	1700	6	water	73	80	1220	11	Prolongation	92,100	109,600	21.6	68.8	236	232	L	T4	0F	145	143	132	140	87	84	78	100	100	100
F22	1750	2.5	1725	2.25	water	76	86	1225	4	4X8X12	90,683	108,176	20.9	65.2	232	232	L	T4	-75F	41	24	27	31	28	18	20	20	15	15
F22	1750	7	1725	7	water	71	80	1250	10.5	4X8X12	80,122	98,855	24.0	71.7	211	211	L	T4	-75F	79	56	83	73	59	40	65	60	30	60
F22	1750	7	1725	7	water	73	82	1250	10.25	4X8X12	82,859	101,243	24.3	74.6	222	222	L	T4	-75F	38	50	36	41	28	38	29	20	25	20

F22	1750	7.25	1725	7.25	water	68	79	1250	10	4X8X12	84,497	102,194	23.1	68.8	218	218	L	T4	-75F	80	74	85	80	59	58	63	55	55	60
F22	1750	8	1725	7	water	72	81	1250	10	4X8X12	82,333	100,558	23.6	71.4	214	214	L	T4	-75F	40	47	47	45	56	40	38	35	35	40
F22	1750	7	1725	7	water	63	71	1250	10	4X8X12	85,766	103,862	24.1	73.4	222	222	L	T4	-75F	103	102	84	96	74	71	63	85	80	65
F22	1750	7	1725	8.5	water	67	74	1250	11	4X8X12	86,129	103,915	22.2	70.6	218	218	L	T4	-75F	35	42	47	41	29	30	34	20	25	25
F22	1750	5.25	1700	5.5	water	70	91	1220	9.25	Prolongation	89,655	106,387	23.8	75.0	228	228	L	T4	-50F	172	154	157	161	100	82	87	100	100	100
F22	1750	5.25	1700	5.5	water	72	85	1220	10.5	Prolongation	92,800	111,900	22.7	72.7	232	231	L	T4	-50F	159	123	128	137		68	69		80	80
F22	1750	5	1700	5.5	water	73	79	1220	9	Prolongation	85,311	102,240	24.1	76.2	218	218	L	T4	-50F	157	164	140	154	89	96	81	100	80	80
F22	1750	7.75	1700	7.75	water	67	71	1230	11.5	Prolongation	89,545	108,072	24.6	75.5	225	225	L	T4	-50F	134	127	124	128	86	82	75	100	100	100
F22	1750	5	1700	5.5	water	71	75	1230	9	Prolongation	87,134	106,247	23.0	74.2	225	225	L	T4	-50F	128	138	133	133	76	79	80	100	100	100
F22	1750	7.75	1700	7.75	water	67	71	1230	11.5	Prolongation	89,545	108,072	24.6	75.5	225	225	L	T4	-50F	134	127	124	128	86	82	75	100	100	100
F22	1750	7.75	1700	7.75	water	67	71	1230	11.5	Prolongation	89,545	108,072	24.6	75.5	225	225	L	T4	-50F	134	127	124	128	86	82	75	100	100	100

Appendix G - Evaluation of Pressure Rating Methods Recommended by API RP 17TR8

Peer Review Comment Responses

Prepared by

ARGONNE SAGES HPHT PROJECT TEAM

June 27, 2017

Disclaimer

This report was prepared by Argonne National Laboratory (ANL) under contract to the Department of Energy (DOE) through an inter-agency agreement between the Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE) and the DOE. The opinions, findings, conclusions, and recommendations expressed in the report are those of the authors and they do not necessarily reflect the views or policies of BSEE.

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Argonne Project Team Response to Peer-Review Comments

Introduction and Background

This document is a response to peer-review comments of the Argonne report that addressed a trial application of API 17TR8 (first edition), a design guideline for high-pressure, high-temperature subsea equipment. The Argonne project and peer review[1] was funded by the Bureau of Safety and Environmental Enforcement (BSEE) at Argonne National Laboratory (Argonne). This project began in mid-2015 with the objective of applying relatively recent API guidelines and conducting instrumented physical tests to failure in a controlled environment.

The API document, 17TR8, incorporated the latest oil and gas industry thinking, including the use of ASME Section VIII, Division 3, methodology for high-pressure, high-temperature subsea equipment design. Specifically, this methodology includes elastic-plastic finite element analyses (FEA) for rated working pressures in excess of 15,000 psi. The technical report combines this analysis approach with other API guidance, but such combined guidance has not been validated fully in the public domain. To this end, Argonne conducted and reported the physical design, build, and test to failure of one typical component as one step toward validation.

Argonne contracted with Aiken Engineering to design, analyze, fabricate, and test a 3.25-inch bore component made according to regular practices used in the oil and gas industry. To be representative of typical subsea components and hardware, the tested hardware (of which two were made) had a flanged tubular section that transitioned to a cross-bored square cross section of the type that might occur in a valve. These components were ASTM A182 F-22, as are commonly used in the industry for such applications (although unclad). The final components were pressure-tested to failure, which occurred as expected in the tubular sections. The pressure testing was compared to pretest FEA predictions based on an analyst's interpretation of the API 17TR8 guidance and was presented in a technical report to BSEE. The subsequent peer review of this Argonne deliverable was conducted, directed, and overseen solely by BSEE staff.

Technical reports delivered to BSEE are subject to peer review in accordance with established agency policy. For the Argonne 17TR8 report, BSEE contracted with an organization to administer this process. The process began with the solicitation of technical reviewer candidates and concluded with a final peer-review report that compiled reviewer comments. That peer-review report contains a wide range of comments that are addressed in this present document.

Many reviewers' comments are specific to reported details and the scope of the Argonne project. Concurrently, several comments are peripheral to the actual scope of work undertaken for the BSEE-funded project. The latter include points about API 17TR8 and other standards, the intent of the ASME Boiler and Pressure Vessel Code (BPVC), and general topics associated with designing and building subsea components. Because many of these points are part of the motivation for the BSEE project and provide specific suggestions for future discussion and

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[1] Summary Report for the External Peer Review of *Evaluation of Pressure-Rating Methods Recommended by API RP 17TR8,* Prepared by ExDyna under BSEE Contract Number: BPA E14PA00008, Task Order Number: E17PB00021,(Task Order 9), May 12, 1917.

projects, they have been included as part of Argonne’s responses. The second section of this report addresses subjects in the peer review that are relevant to the project scope. The subcategories are the materials, design, and geometry of test bodies; FEA; burst tests; and miscellaneous subjects. The next response category is restated conclusions based on peer-review comments. This document concludes with noted responses beyond the review charges.

Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)

Opinions and Expanding Scope of Current Argonne Study

Among peer reviewers' comments, there are numerous opinions about the methodology of the Argonne study and the contents of the report. In some instances, there are contradictions among the reviewers. Generally, these contradicting opinions are pertinent to some parts of API 17TR8 and the incorporation of certain ASME Section VIII paragraphs. Several comments could enhance the Argonne study, provide beneficial information, and reduce uncertainties; however, an extension of the Argonne study is not a consideration at this time. Nevertheless, there is merit to recognizing these suggestions and opinions, as they have considerable relevance to defining and debating future validation and confirmation efforts. The Argonne team concurs with most of the subjects in this group.

Literature Review

The Argonne team concurs that a comprehensive, narrated technical review of validation literature with a detailed bibliography should be part of any technical report such as API 17TR8. The Argonne team understands that a complete package of such information was not available for public consumption despite previous requests for such information. As a package, such information could be useful to understand and communicate the basis and data of the study. Such a review could have explained the following:

- adopting the ASME 1.8 factor for subsea equipment when prior API guidelines and industry practice had been closer to 2.1.
- depending on fracture mechanics and crack-growth technology as a basis to offset the added conservatism associated with a 2.1 factor.
- improving clarity and intent about design factors being mean failure values rather than minimums below two standard deviations.
- removing technical doubts and uncertainties that exist because subsea situations differ from pressure-vessel designs.

Finally, such an information package (beyond the informative citations provided by a reviewer in the peer-review comments) could also aid analysts unaffiliated with the proceedings leading to API 17TR8 in applying guidance more consistent with intent.

Since only portions of the ASME BPVC are guidelines in 17TR8, the Argonne team does not agree that, because the BPVC Section VIII has been validated over many decades, 17TR8 is validated too. Validation is not necessarily transferable when a standard is modified by any other standard, at least not until a thorough analysis of the literature (and/or in conjunction with appropriate testing) has occurred for the entirety of the new situation. The API recognizes and accommodates this partial adoption of ASME BPVC in API 17TR8 Section 4.2.1.4, which reads as follows:

"Traditionally, the standard practice is to rely on the ASME BPVC to provide design guidance when the equipment's functional requirements go beyond the defined boundaries of the API specifications/standards. However, the problem then arises as to "how much of the ASME

BPVC does one follow"; 1) exact to the "letter" 2) use portions of the code that are applicable to the particular design or 3) following a parallel path using the ASME BPVC methods, but develop another set of design margins applicable to oilfield applications. Oilfield equipment are of complex geometry, far from simple cylindrical pressure vessel or piping union design. They are typically subjected to a variety of extreme external loading conditions and they are not explicitly addressed in ASME BPVC. This leads the equipment designer to rely on sound engineering practices and judgment, accompanied by unique validation prototype testing programs."

It is very likely that a thorough literature review, as suggested by the peer-reviewer comments, could not only further clarify the boundaries of the BPVC Section VIII applicability, but also lead to greater design consistency and assurances. Section 4.2.1.4 also helps explain why differences of opinion exist between BSEE project analysis and the methods a peer reviewer may have preferred. Sound engineering practice and judgment to one person may not be the same to another.

A fundamental premise of the Argonne study (as noted on page 6 of the project report) was to apply API 17TR8, First Edition[2], principles—including related guidance contained in specific normative references—as they existed in fully approved form at the onset of the BSEE-sponsored project. These principles specifically include:

- API 6A[3]/6X[4]/17D[5];
- ASME Division 2: 2013 Part 5 by Linear-Elastic FEA;
- ASME Division 2: 2013 Part 5 by Elastic-Plastic FEA; and
- ASME Division 3: 2013 Part KD by Elastic-Plastic FEA.

The Argonne report did discuss the evolution of particular standards and the relative impacts of differences on pressure-based design ratings. These comparisons were not intended to be a validation literature review, but rather a simple industry history providing a basis for comparisons with trial application of the 17TR8 guidance (through collapse pressure determination using FEA modeling). Ideally, a thorough literature review would not only quantify proposed design margins, but fully justify any departure from historical success. This appears to not have been done for the First Edition of 17TR8 and has not been made available to interested users.

ASME BPVC Is Guidance

The Argonne team agrees with identified limitations and cautions regarding the use of ASME BPVC methods in API 17TR8 for design verification and assessment. The ASME BPVC is not a design handbook. While there is a degree of specificity in API 17TR8, there is also considerable latitude on design verification of high-pressure, high-temperature (HPHT) subsea equipment applications. The normal expectation is that not all designers will follow exactly the same practices. The obvious goal is to assure that, when following verification guidelines, the resulting

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[2] High-Pressure, High-Temperature Design Guidelines, API Technical Report 17TR8, First Edition, February 2015.
[3] API 6A, Specification for Wellhead and Christmas Tree Equipment, Twentieth Edition, October, 2010.
[4] API Standard 6X, Design Calculation for Pressure-Containing Equipment, First Edition, March 2014.
[5] API Specification 17D, Design and Operation of Subsea Production Systems-Subsea Wellhead and Tree Equipment, Second Edition 2011.

components are not prone to failure in service. This not only protects the environment, but also helps assure safe operations, including life safety.

Non-Pressure-Related Failure Modes

Obviously, a subsea component or even a portion of a component can have many failure modes other than pressure alone. However, pressure often (but not always) drives at least part of the design and remains a prominent factor in the manufacturing acceptance process. As a research-oriented project rather than a project intended to produce a production component, the scope of the BSEE-sponsored project never intended to explore other failure modes or to apply both forces and moments in an elevated temperature environment. To assure project objectives would be accomplished, informally, the Argonne team did look at non-pressure-related failure modes and agrees that exploring other failure modes and testing in other conditions would contribute significantly to the validation process. Failure modes and loading combinations other than pressure should be a consideration for future validation projects.

ASME BPVC Validation

The ASME BPVC has existed for decades and has been validated when all of a particular section and division are applied (Section VIII, Division 2 or Division 3 in this context). The Argonne team agrees that the BPVC is useful for analytical verification of subsea components. However, as discussed above, API 17TR8 does not adopt the entirety of either division for a variety of reasons, including complex geometry. Again, the ASME code is **not** a handbook of design, and thus the designer and analyst have an obligation to apply "*sound engineering practices and judgment*" to the situation at hand.

Aside from geometry differences (between pressure vessels and subsea equipment), the Argonne team believes other important differences also impact how much one can rely on BPVC methods for a particular subsea situation. These differences include the following:

- Subsea components do not have pressure-relief valves to limit maximum pressure loading. This difference could compromise the containment boundary in the subsea situation.
- Most pressure vessels are subject to in-service inspection. Many subsea components are not adequately accessible or retrievable for such inspections.
- There is not necessarily close parity between the forms of materials used for component manufacture. For example, subsea equipment bodies are forgings, while large pressure vessels tend to be combinations of rolled plates welded together. Fasteners in both applications are based on bar stock.
- Usually, temporal pressure vessel load and operating conditions are relatively easy to quantify compared to the subsea environment, where conditions for a particular well can vary greatly and unexpectedly from forecasts.

The materials for test articles of the BSEE-sponsored project were a rich chemistry F-22 forging that substantially exceeded the project's material specification (specified minimum yield of 75 ksi with actual yield in excess of 90 ksi). This material is substantially different from the listed ASME BPVC material and may not fall within the technical limitations of ASME methods for alternate materials.

Performance of Burst Test Is Expensive and Dangerous

The peer review includes several statements that burst tests of subsea equipment are impractical and unsafe. One example of this statement is given in comments on page 83 of the peer review. The Argonne study is evidence that this is not a correct statement. Two test bodies were tested to failure in a safe and practical manner, and the results were valuable. There is no doubt that burst tests must be properly planned, and adequate projectile containment structures must be provided. All major subsea equipment manufacturers have test bunkers designed to contain projectiles that might occur from bursts. Damage to the test bunker, if used, can be prevented by enclosing the test component in a simple and inexpensive fabricated containment that absorbs most or all of the released energy. The Argonne burst tests were conducted in an open, controlled-access area with containment and observing personnel isolated in a shielded area some distance from the test.

Statistical Relevance

The Argonne team wholly agrees; results from one or two tests are not statistically significant if one is seeking to quantify values that effectively establish and quantify safety margins. At the same time, one or a few full-scale tests provide far more confidence than no test results. Scaled tests can contribute, but there are nearly always scaling questions that are difficult to quantify beyond a reasonable doubt. The Argonne team believes the least uncertainty of any test outcome occurs when test articles have close similarity to a production version. This includes test materials being full scale, manufactured with identical processes and materials as the production item, and tested in representative conditions to the extent practical.

The Argonne team recognizes that full-scale testing to a statistically valid level can be very costly and time consuming. However, since there is considerable validation value derived from any number of full-scale tests (of an article prepared in accordance with commonly accepted industry practices and conventions), such testing is useful and advisable to validate a new or revised standard. This is particularly relevant when that standard relies upon excerpts from other standards or departs significantly from historical norms. The Argonne team's understanding is that there was no physical, testing-based validation information in the public domain for a subsea component prepared according to the guidelines of the First Edition of API 17TR8.

Standards Released Subsequent to BSEE Project Start

As explained above, the project finite element analyses and component fabrication were based on standards specifically called out in API 17TR8, First Edition. The particular guideline is somewhat unique in that normative references are to a particular version, yet many API standards endorse the "latest version" of anything listed without a date or version. In addition to normative references, API 17TR8 provides a bibliography of some references without dates, versions, or guidance on use. One such example the Argonne team found is API Specification 20B (Specification for Open Die Forgings for the Petroleum and Natural Gas Industries). This standard is listed, but is not cited specifically in the main text of the technical report (First Edition of 20E is dated August, 2012, and the latest is the second edition dated February, 2017). For such a situation, are this specification and others a requirement, guidance, or merely optional information? If the specification's content is important, then this specification and any others should be incorporated into the 17TR8 text where applicable. Potentially, this can become part of the next revision of API 17TR8.

Forged Products (the forging supplier for the BSEE project) regularly provides large and small forgings to the oil and gas industry and has the infrastructure and quality system associated with both versions of 20E. Additional, nonproprietary details of Forged Products heat treatment and forging work are provided as requested and are consistent with what would normally be publicly released.

Another concern of the reviewers pertained to the version of the AMSE BPVC, since 17TR8 references the 2013 edition. This revision was considered in the study, even though the 2015 edition was current at the time the study was performed. Again, a driving consideration was to apply API 17TR8 as it was written.

The original release of API 17TR8 is also the current release. A revision is in progress, and prelease information indicates that there will be additional requirements for materials and other aspects of HPHT equipment. The additional requirements in the revised TR8 were not considered in the Argonne study, and no responses are provided regarding new requirements.

Collapse Pressure and Strain Limit

Evaluation of strain limit (API 17 TR8, Fig. 1- Div. 3: KD-232) is beyond the scope of the Argonne project and would not have altered the comparisons reported. The Argonne team agrees this would be done as part of a full analysis of a production component designed in accordance with API 17TR8. Such a full analysis would similarly consider different failure modes, ratcheting, hydro-test, and fracture mechanics. The Argonne team’s work focused on comparing global plastic-collapse predictions with physical testing as a step to validate 17TR8.

Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project)

Materials

Forging Reduction at Burst Region

For the valve bodies, Forged Products first forged the raw material (Heat AH450) to bloom, then reduced to a shaft that had a 16” diameter, was 51.60” long in the center, and had two identical square blocks at both ends (19.20” square by 27.20” long). Both the throat area and the single prolongation are from the middle section of the forging (shaft) that had experienced tremendous cross-section reduction (calculated to be around 12:1). For forgings, this amount of reduction will result in fine-grain structures before rough machining and heat-treating. The mechanical test results for the prolongation verified the strength of the materials in this area.

Heat-Treat Quenching and Grain Structure at Burst Region

The throat section is around 20” long, and the failure location during the burst testing was somewhere between 5” to 25” away from the prolongation piece. The heat-treat shop (Lone Star Heat-Treating Corp.) quenched the parts with the prolongation section facing the water jet, such that water flow was facilitated through the inside diameter. This area (flange/prolongation) received the most agitation and therefore experienced the most hardening. It takes less than 60 seconds for quenching thus the entire forging should be a bainitic microstructure. If some soft phases like pearlite were going to form (which is unlikely) due to the fast quench, it would be in the middle of the thick sections (end block) rather than the pipe section. Both the prolongation and thick sections should have high strengths and fully transformed bainite. For completeness, the quality assurance (QA)-verified heat treatment performed is summarized in the table below:

Process	Temperature (ºF)	Time (hrs) at Temp	Cooling Method
Normalized	1750	6.0	Air cooled
Hardened	1700	6.0	Water 71–73ºF
Tempered	1230	10.0	Water cooled

Material Properties from Prolongation

Material property verification tests were performed in accordance with ASTM A370. These tests were performed on test specimens taken from the prolongation. Longitudinal test specimens (parallel to the primary grain-flow direction) were obtained such that the tensile specimen gauge sections were at least ¼ T (where T is the thickness) and no less than 25 mm from the heat-treated surface. Charpy V-notch impact test specimens were also tested in the longitudinal direction. The specified material properties were as follows:

Material Property	**Required Value by API 6A PSL**
Yield strength (0.2% offset)	**3** 75,000 psi min
Ultimate tensile strength	95,000 psi min
Reduction of Area	35% min
Elongation in 2”	18% min
Brinell hardness	197–237 after finish machining 40
Charpy V-notch* @ 0^{o}F	ft-lbs (min ave of 3 specimens) 30
Charpy V-notch* @ 0^{o}F	ft-lbs (min single value)

* Full-sized specimens (10 x 10 mm)

Mechanical properties are expected to be the same or slightly lower in thicker sections and the same or slightly higher in thinner sections. Forged Products simulated the heat-treat and quench operations and compared them to Jominy end-quench tests. The hardenability results and tensile strength projections were consistent across the entire cross sections of the test pieces. Based on Forged Products’ considerable experience with similar F22 heats, the tensile properties in the thinner section, where the intentional burst failure occurred, would be expected to be similar or slightly higher than those obtained from testing of the prolongation.

Post Burst Testing Material Examination

Posttest material investigations included optical metallography, a scanning electron microscopy examination. The objectives of this work were to:

1) investigate the microstructures of the material following the burst failure; and

2) determine if the burst failures originated at preexisting defects.

Samples were taken from three locations of the throat portions of both valve bodies. These locations were: at the burst, 180 degrees from the burst in the circumferential direction, and lastly at the flanged end farthest away from the burst. These tests were conducted at a third-party laboratory in Houston, TX, (Exova) that has considerable experience with oil and gas materials. Summaries of these investigations are noted here:

Metallographic samples were prepared for three orthogonal planes for the three sampling locations. This investigation showed that the grain-size average results varied between ASTM grain size 6 and 7. Microstructures were determined by Exova to be tempered martensite but there is uncertainty about this determination.[6] (Note: The forge shop had determined the structure was Bainite and there was no physical explanation likely to have caused any such structure change.) The “At Burst” locations showed elongated grain structures, as would be expected from plastically deformed material.

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[6] The differences between Bainite and Martensite are subtle. An experienced third-party metallurgist could not positively determine the structure based on the available information but believes the post-test structure was most likely Bainite. Additional investigation might be more conclusive.

Examination for Preexisting Defects

Electron microscope examination of the fracture surfaces found no evidence of preexisting machining or material defects. Dimple rupture was noted at 400X and 1500X magnification examinations of the fracture faces.

Post-Failure Metallurgical Examination

The peer review includes queries about whether metallurgical examinations of the material at the rupture locations should have been performed. For example, on page 76 of the peer review, a reviewer makes the following statement:

"…..a metallurgical evaluation of the failed components should be conducted."

Although the data obtained from these examinations would be useful, post-failure examinations were beyond the scope of the study, which encompassed only determining whether there were preexisting flaws.

Design and Geometry of Test Bodies

Shapes of Test Bodies

The peer review includes comments about the shapes of the test bodies from the standpoint that the flanges and thick body sections served no purpose other than to resist pressure. For example, on page 79 of the peer review, one reviewer states the following:

"The thick body section with intersecting bores did not contribute any useful information regarding the proof test, in that the design was adjusted to assure the failure would occur in the neck region."

This is a true statement. The test bodies were designed so that plastic collapse would occur in the neck section and not in the thick section with cross bores or in the flanges. The thick section with cross-bores was included to represent test body materials that had experienced a wide range of elastic and plastic strains. Moreover, the values of strains throughout the test bodies were known from results of the FEA solutions. This provides metallurgists with material that has been exposed to known values of elastic and plastic strains. Material with this strain history could be useful in future studies.

Flanges, Bolts, and Seals

The peer review included several criticisms of the flanges, bolts, and seals. More than one reviewer criticized these components because they did not meet the ASME codes or API standards. For example, on page 60, a reviewer makes the following statement:

"The flanges used in this situation are standard size 20 ksi flanges based on Table B.43 of API 6A for 20 ksi rated working pressures. The analysis does show that the flanges meet the requirements of global collapse at these pressures. However, it is likely that the sizes and numbers of bolts used might not meet the requirements of ASME Section VIII-2."

Criticisms of the flanges, bolts, and seals because they did not meet ASME codes or for any other reason are unwarranted. Flange evaluation was not an objective or concern of this study.

The only purpose of the flanges was to provide a safe, non-failing means of connecting blinds to the four openings of the test bodies. There was no requirement that the Argonne study flanges meet the ASME codes or any other code for that matter.

Flanges have been extensively evaluated in countless studies since the 1930s. The flanges were included in the designs to provide removable blind closures for the internal bores. They were designed not to rupture or leak before burst of the cylindrical neck sections in the test bodies. In fact, the bolts would not meet either API or ASME standards, and they would absolutely not meet all NACE MR0175 requirements. The bolts successfully performed the functions for which they were designed.

FEA

Independent FEA

Page 81 in the peer review summarizes comments by one reviewer about an independent FEA that was performed for the large neck body. The collapse pressure from the independent FEA was 72,251 psi, as compared to a collapse pressure of 72,850 psi from the Argonne FEA. The difference between the two collapse pressures was only 0.82%, which is insignificant.

The results of the independent FEA validate the accuracy of the Argonne FEA for the large neck body. Since the input (other than dimensions) and methodologies of the FEA for the small neck body were identical to those of the large neck body, it is reasonable to assume that validation of the small neck body FEA would occur if an independent FEA were performed.

The preceding two paragraphs, in essence, validate the accuracy of the methodology, assumptions, and input of the Argonne FEAs. Queries about these elements of the Argonne FEAs should have little to no impact on analytical results. Even so, responses to the peer-review queries about the FEAs are provided in the following paragraphs.

Mesh Sensitivity

A query on page 78 of the peer review stated that no documentation of the mesh sensitivity studies were included in the report. This is a correct statement. However, it is not common practice in stress reports to document anything but the results of the mesh sensitivity study. Section 6.1 in the Argonne report states that the FEA solutions of two different mesh densities for both test bodies produce collapse pressures within 1% of each other. The adequacy of the mesh densities are also validated by the results of the independent FEA of the large test body.

UY Displacement Constraint

Page 67 of the peer review states that the Argonne report does not describe the UY displacement constraints in the FEA models. The FEA models have no cut planes normal to the y-axis, and all loads in the Y direction are in static equilibrium. This means that a UY constraint is not necessary other than to prevent drift in the Y direction due to computer round-off errors. To prevent drift, a single node in each model was constrained in the Y direction. The location of the node was not important. A listing of reaction forces from solutions of the FEAs showed that reaction forces in the Y direction were virtually zero. This result is confirmed by stress and displacement plots in Appendix B1 for the large neck body and Appendix B2 for the small neck body. If improper Y direction constraints were applied, hot spots would have appeared in the plots.

Model Dimensions

The original intent of the study was to use the as-built dimensions of the two test bodies. The first solutions of the two FEA models occurred before the test bodies were manufactured. This step was to validate the designs of the test bodies and to confirm that plastic collapse would occur in the neck sections. Obviously, as-built dimensions were not available before the test bodies were manufactured, so nominal dimensions were used for these models. After the two test bodies were manufactured, the as-built dimensions became available. These are listed in Appendix F of the Argonne report. The actual outside and inside diameter dimensions in the critical sections where failure occurred were within 0.50% of the nominal dimensions. Rebuilding and solving the FEA models with as-built dimensions would produce virtually identical collapse pressures. For this reason, all FEA solutions were performed with the nominal dimensions.

Elastic-Plastic Material Properties

There were several queries in the peer review regarding the elastic-plastic material properties used in the FEA solutions. The models used the true stress/true strain values that were obtained from a tensile test by Franklin Research Associates in Houston. The tensile test specimen was taken at a ¼ T location from the 12 x 2.25 x 6 qualification test coupon (QTC) provided by Forged Products. A plot of the true stress/true strain data is provided on page F-36 of the Argonne report. Additional information about the tensile test is provided on page F-35 of the report.

Von Mises Flow Rule

The peer review included several queries about the elastic-plastic material model used in the FEA solutions. As required in Divisions 2 and 3, “the von Mises yield function and associated flow rule” were utilized in the FEA models.[7]

Load-Displacement Curves

Page 80 of the peer review states that load-displacement curves from the FEA solutions were not provided in the Argonne report and that they would provide insight into the development of plastic hinges. Load-displacement curves were not included in the report because they would not serve any useful purpose during performance of the FEA or evaluation of the results. Load-displacement curves provide the FEA analyst with an indication of when plastic collapse is about to occur. This information would not be useful for this particular situation.

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[7] For clarification with regard to API 6a and API 6X: API 6A uses stress intensity for ratings based on the ASME methods. The allowable stress intensity is 2/3 the yield strength at the rated internal pressure. As an alternate 6A allows the use of von Mises stress at the bore and at the hydrostatic test pressure of 1.5 x the internal pressure. The allowable von Mises stress at the bore is the yield strength. The FEA analyst’s experience is that usually the von Mises stress method will produce lower pressure ratings for 20 ksi equipment. API 6X allows the use of either stress intensity or von Mises stress based on the ASME methods with a 2/3 Sy allowable stress.

FEA Solutions to Plastic Collapse

Page 64 includes the following criticism by a reviewer about the iterative solution methods used in the Argonne study:

"The report indicates that it is a requirement, when using elastic-plastic evaluation, to determine the maximum pressure rating for a component and then apply the design margin to it. This is an incorrect statement."

This statement by the reviewer is not correct based on Paragraph 5.2.4.1 of ASME, Division 2 that states the following:

"Protection against plastic collapse is evaluated by determining the plastic collapse load of the component using an elastic-plastic stress analysis. The allowable load on the component is established by applying a design factor to the calculated plastic collapse load."

Clearly, ASME states that the elastic-plastic solution should be performed until elastic-plastic collapse occurs.

Even so, both the method used in the Argonne study per ASME and the method suggested by one reviewer are acceptable and will provide correct results. However, the method used in Argonne study was precisely as specified in Paragraph 5.2.4.1 of ASME, Division 2.

Inaccurately Modeled Components

The peer review included several criticisms that the blind, bolts, nuts, and seals were not included in the FEA models. Reviewers' concern was that disregarding these components may have affected the accuracy of the results. For example, on page 57 of the peer review, one reviewer states the following:

"The FEA models did not include all components of the assembly which was subjected to burst, such as the flange bolting, ring gasket, and blind flanges. These may not influence the results, but not including them raises the question of accuracy in the modeling."

As previously stated, the only important results of the Argonne study were the plastic collapse pressures of the two test bodies. Both test bodies collapsed in the neck section at locations far enough away from the flanges that inaccurate modeling of the flanges did not affect the burst pressures. The method of modeling the flange components provided statically equivalent loads at the flanged ends of the test bodies. Saint Venant's principle teaches that results far enough removed from statically equivalent features produce results that are the same as if accurate features were modeled. Figure B1.17 for the large neck test body and Figure B2.17 for the small neck test body unquestionably demonstrate that failure locations are far enough removed from the flanges. The stresses and strains in the neck sections, where burst occurred, were constant along the lengths near the locations of burst. They would not be constant along the lengths of the neck sections if end effects existed.

Burst Tests

Purpose of Strain Gages

The peer review includes numerous statements and queries about the strain gage results and how they could have or should have been used. Although remarks about strain gages by the peer reviewers are useful, no replies to these remarks are included in this response to the peer review. The reason is that the strain gage data was not a vital or necessary element for the conclusions or results of the Argonne study. Strain gages were applied to the test bodies simply to generate data that might be useful to BSEE or others. For example, BSEE might use the strain gage data from the differential pressure tests to study the effects of differential pressure.

One use of the strain gage data was to provide a visual indication about strain behavior as internal pressure increased during the burst tests. Although this provided a warning as to when burst was going to occur, it was certainly not essential to know during the burst test.

The strain gage data was also used to validate the accuracy of the FEA models at lower pressures when strains in the cylindrical neck section were linear with pressure. This validation is described in Section 6.4 of the Argonne report. As shown in Appendix D of the report, calculated strains were within 4% of measured values. Model validation using the strain gage data was not done because it was required, but because the data was available. Stresses and strains in the cylindrical neck section could be accurately validated using simple strength-of-materials calculations.

Several strain gages separated from the test vessels during hydro-testing, and even more were lost as pressure increased to failure. Strain gages characteristically fail at high strains. There are other strain-measurement methods, but there are also practical limitations to using these when performing a test to failure inside a safety containment shield.

Only Two Burst Tests Performed

The peer review includes numerous comments, queries, and questions about the accuracy of the conclusions since they are based on only two burst tests. For example, on page 58 of the peer review, one reviewer makes the following statement:

“The two component evaluations conducted are insufficient in number to demonstrate that the analytically predicted collapse pressure vs the proof test provide a statistical distribution range of data.”

It is obviously true that two data points are not a large enough sampling to perform statistical analysis. However, API 17TR8 does not include references to test data that would justify their methodology and acceptance criteria. As stated previously, the two test results from the Argonne study may not be statistically significant, but they clearly show that elastic-plastic FEA may not be conservative in all cases and for all equipment. The results of the Argonne study surely indicate that more tests to failure should be performed and compared with elastic-plastic FEA results. This is especially the case for more complex equipment with multibody contacts and moving components, which are common in HPHT subsea equipment.

Pressure Ratings by Hydro-test

On page 65 in the peer review, a reviewer correctly states that pressure rating by hydro-test using Division 3 rules should not be based on pressure, but the pressure when strain at the OD is 2%. Review of the FEA results from the neck section of the two test bodies at burst pressure shows that strains on the OD were greater than 2%. The net effect is that the Division 3 pressure ratings based on burst will be less than those stated in the Argonne report and by API criteria. This reinforces the statements on page 28 of the Argonne report that pressure ratings based on Division 3 hydro-test procedures produce ratings less than those from elastic-plastic FEA with a 1.8 load factor.

Proof Testing Contradiction

A comparison of burst pressure is useful to physically quantify the accuracy of analytical methods independent of whether API, ASME, or any other guidance prohibits or requires a test to failure for design validation. The Argonne team is not suggesting that components must be validated this way. However, since there is apparently a conflict between ASME guidelines and API (as identified by the peer reviewers), this matter should be reconciled by the appropriate technical committees.

Miscellaneous

Least Conservative Pressure Rating

On page 75 of the peer review, a reviewer makes the following statement about the Argonne report:

“One statement in Section 9.1 on page 24 states that ‘the least conservative pressure ratings were determined by ASME: VIII-3 elastic-plastic analysis.’ This is not correct. Table 9.2 shows that the least conservative margin calculated is 1.74 based on linear-elastic analysis by ASME Section VIII…”

The reviewer improperly quoted the sentence from the Argonne report. The following is the actual sentence from the report:

“”For all test components but the small neck test body, the least conservative pressure ratings were determined by Division 3 elastic-plastic analysis.”

The criticism of the Argonne report by the reviewer is not deserved.

Histogram Load Sequence

One reviewer makes the following statement on page 85 of the peer review:

“It’s possible to review the load histogram and evaluate a worst-case loading sequence for fatigue analysis. There can also be multiple load sequences run to verify a worst case.”

Fatigue load histograms of environmentally induced loads on HPHT subsea equipment must be statistically defined because of the random nature of these loads. Fatigue load histograms can consist of several hundred load bins with various combinations of tension, bending moment, and shear. Fatigue textbooks and even ASME, Division 3, state that the sequence of load application has a significant effect on fracture mechanics calculations.

Developing a sequence of loads that will produce conservative predictions of crack growth by fracture mechanics will not be so simple and may be impractical. Furthermore, validation that a load sequence produces conservative fracture mechanics calculations will not be a simple task. The sequence of environmental loads on subsea equipment should be carefully evaluated and reported by experts in both fracture mechanics and in environmental loads that are applied to subsea equipment.

Elastic-Plastic FEA as an Allowable Method by API

On page 75 of the peer review, one reviewer states that the statement in the Argonne report that elastic-plastic FEA was not allowed prior to 2015 is misleading. The reason given by that reviewer was that BSEE was reviewing analysis by elastic-plastic methods prior to 2015. The intent of the statement in the Argonne report was that API did not explicitly allow elastic-plastic FEA prior to 2015. Publication of API 17TR8 was the first API document related to subsea equipment that allowed elastic-plastic FEA.

Comparison of Subsea Equipment and Pressure Vessels

A reviewer in page 56 of the peer review states that it is a misconception that subsea equipment is unique and completely different from other equipment that contains internal pressure, operates at high temperatures, and is exposed to a corrosive environment and subjected to highly cyclical loads. Text in API 17TR8 does not support the “misconception” asserted by the reviewer. As stated previously, the following statement is in Section 4.2.1.4 in API 17TR8:

> “….. Oilfield equipment are of complex geometry, far from a simple cylindrical pressure vessel or piping union design. They are typically subjected to a variety of extreme external loading conditions and they are not explicitly addressed in ASME BPVC…..”

Section 4.3 in API 17TR8 provides additional statements that subsea equipment is exposed to loads different from those included in the ASME BPVC.

Linear-Elastic as a “Gold Standard”

On page 82 of the peer review, a reviewer makes the following statement:

“It would seem that the linear-elastic methods are being used as a ‘gold standard’ which the newer, more rigorous modern methods are being held to.”

This is an incorrect statement. The Argonne study did not conclude or state that the “newer, more rigorous modern methods” adopted in API 17TR8 should produce the same load ratings as those from linear-elastic analysis. Historically, the subsea industry has rated subsea equipment using linear-elastic analysis. Furthermore, subsea equipment rated by this method has operated successfully for several decades. The Argonne study simply pointed out that load ratings from some more modern methods are higher and thereby less conservative. Since equipment based on more modern methods has not been validated by extensive successful operation, it must be validated by engineering studies or load tests.

Numerical Analysis Compared to Test Results

On page 74 of the peer review, Richard Biel states the following:

“The report draws a false conclusion from Table 6.1 that the numerical analysis should exactly match the results of the physical test.”

This was not a conclusion of the report. It would be unfounded to make this conclusion when comparing any analysis results with test results. Theoretical results from scientific and engineering studies rarely match test results exactly.

Plastic Collapse and Ultimate Tensile Strength

A comment by a reviewer on page 63 of the peer review states that it is a gross simplification that the elastic-plastic analysis is solely based on tensile strength, as is stated in the Argonne report. It is true that yield strength and other variables do affect the plastic collapse load from an elastic-plastic analysis. However, the ultimate tensile strength is the most dominant material property that controls the burst pressure. Simple engineering studies will confirm this is true. Therefore, it is not a “gross simplification” to state that the burst pressure is predominately controlled by the tensile strength.

No FMECA

Page 68 in the peer review includes a statement by one reviewer that a FMECA should have been performed to identify all failure modes. As a part of the design process, an informal FMECA was performed to identify all possible modes of failure and to assure that failure would occur in the neck sections of the two test bodies. Since the Argonne study was a research project and not a design project, the FMECA was not included in the report.

“Design Margin” Term

The Argonne report uses the terms *margin of safety* and *factor-of-safety* when comparing load ratings to failure loads. Two reviewers, both from the pressure-vessel industry, strongly state that the Argonne report should use the term *design margin* rather than the terms *factor-of-safety* or *margin of safety*. *Design margin* is the term used in the pressure-vessel industry. However, different industries use different terms when describing the margin between operating loads and failure loads. For example, *stress utilization* is the most common term to describe this margin in the subsea industry.

Restated Conclusions Based on Peer-Review Comments

10.0 Conclusions

The following are the important conclusions of the Argonne study. These conclusions are based on results of the elastic-plastic FEA and hydro-tests that were performed as part of this study. The conclusions apply to HPHT subsea equipment rated for 20 ksi or less. No consideration has been given to equipment rated for pressures greater than 20 ksi. However, there is no apparent reason that these conclusions would not apply to equipment rated for pressures higher than 20 ksi.

These conclusions were marginally revised after the consideration of peer-review comments. The majority of the revisions are in the discussion section after each conclusion. These revisions were made to clarify a few misunderstandings that were evident from the peer-review comments. The content of the conclusions themselves has not substantially changed.

The Division 3 elastic-plastic method is not recommended for HPHT subsea equipment as published with a 1.8 design load factor until supplementary validation is performed.

ASME, Division 3, allows a 1.8 load factor for calculating load ratings based on elastic-plastic FEA. This is lower than the 2.4 load factor allowed by ASME, Division 2. The Argonne study shows that the equivalent load factor for existing subsea equipment is about 2.1 for simple shapes. Decades of successful operating experience show that the equivalent load factor of 2.1 has produced safe, reliable subsea equipment.

Pressure-vessel experts working with ASME have determined that a 1.8 load factor is suitable for pressure vessels designed and manufactured in accordance with the rules in Division 3. The Argonne study did not consider pressure vessels and does not question the use of a 1.8 load factor for Division 3 pressure vessels.

Nonetheless, just because a 1.8 load factor is suitable for pressure vessels does not mean it is suitable for HPHT subsea equipment. Many important characteristics of HPHT subsea equipment are significantly different from pressure vessels, as acknowledged in the following quote from Section 4.2.1.4 in TR8:

> *"….Oilfield equipment are of complex geometry, far from a simple cylindrical pressure vessel or piping union design. They are typically subjected to a variety of extreme external loading conditions and they are not explicitly addressed in ASME BPVC……"*

Another important consideration is that TR8 does not require that all the rules and requirements in Division 3 be used. TR8 adopts only a small part of Division 3.

A 1.8 load factor may produce HPHT equipment that is reliable and safe for subsea operation. However, TR8 does not provide any references validating that a 1.8 load factor is suitable for HPHT subsea equipment. Until scientific studies or tests are offered that validate the suitability of a 1.8 load factor for HPHT subsea equipment, it is recommended that a larger load factor be used for HPHT subsea equipment.

The Division 3 elastic-plastic method with a design load factor of 2.1 is recommended to calculate load ratings for HPHT subsea equipment.

This recommendation is based on the results of the Argonne study and the validation data currently available in the public domain. If scientific studies or tests exist in the public domain that validate a 1.8 load factor, then it is recommended that the TR8 committee publish a paper presenting this work so that it can be peer-reviewed. If the TR8 committee cannot do this, then the committee should commission appropriate scientific studies or tests validating that a 1.8 load factor is adequate for HPHT subsea equipment.

A Division 3 analysis with a design load factor of 1.8 is acceptable if the factor is applied to results of a load test, and validation is provided that demonstrates the additional requirements in TR8 and Division 3 sufficiently reduce the risk of failure.

Paragraph KD-1254 in Division 3 provides a procedure for rating equipment based on a proof test. This confirms that a proof test to failure is acceptable by Division 3 as a means to pressure-rate equipment.

The design load factor in Division 2 is 2.4, which is 33% greater than the design load factor of 1.8 in Division 3. ASME and TR8 state that this reduction in the margin of safety is validated by additional requirements, such as fracture mechanics in Division 3. HPHT subsea equipment in general has more complex shapes, more multibody contacts of components, and different materials as compared to pressure vessels. Before a load rating for HPHT subsea equipment is determined by dividing the test loads by a design load factor of 1.8, the user should confirm that the reduction in margin of safety has been validated.

For a Division 2 linear-elastic analysis, it is recommended that stress intensities are compared with allowable stresses and not von Mises stresses until supplementary validation is performed.

The Division 2 linear-elastic method is an acceptable method in TR8 to rate HPHT subsea equipment for pressures of 20 ksi or less. Division 2 allows that von Mises stresses be compared with allowable stresses, whereas API historically has compared stress intensities with allowable stresses.

The Argonne study revealed that the use of von Mises stresses allows higher pressure ratings for subsea equipment. Since subsea equipment has historically been rated using linear-elastic analysis with stress intensity, the design margins based on von Mises stresses will be lower than the design margins of historically successful equipment. The safety of reduced design margins based on the use of von Mises stresses should be investigated before the subsea industry makes this change. Until this issue is investigated, it is recommended that the HPHT subsea industry continue using stress intensities.

Note that this is not a question about the accuracy of von Mises stress, but about the safety of reduced margins of safety. Scientific studies and tests have confirmed that von Mises stress is a more accurate predictor of yield than stress intensity. Stress intensity is always greater than or equal to von Mises stress.

It is recommended that the subsea industry compare collapse pressures from FEA with burst pressures from hydro-tests for a variety of subsea equipment.

For numerous subsea components, the subsea industry should compare the collapse pressures from elastic-plastic FEA with the actual burst pressures from hydro-tests. This is necessary to validate the accuracy of collapse pressures by FEA. The reason for this recommendation is that the Argonne study showed that collapse pressures from FEA were higher than burst pressures for the two test bodies that were evaluated in this study.

This is an especially concerning outcome for subsea equipment because the two test bodies in this study were simple shapes. Many subsea components have much more complex geometries, and many have geometries with multibody contacts. It is possible that more complex shapes with multibody contacts will be even less conservative than the simple shapes evaluated in this study.

The subsea industry should confirm that performing the fracture mechanics analysis required by Division 3 justifies reduction of the design load factor to 1.8.

Reduction of the design margin based on performance of fracture mechanics may not be suitable for HPHT subsea equipment. The following are two important reasons this is true:

1. Division 3 justifies the reduction of the design load factor based on the requirement of fracture mechanics analysis. The purpose of a fracture mechanics analysis is to ensure that defects do not propagate to the critical crack size and cause a rapid, brittle failure. This may not be a critical failure mode for subsea equipment. TR8 requires that all pressure-containing components meet the material requirements in API 6A and NACE MR0175. Material that meets the requirements of these two codes will be ductile, have high impact strengths, and have high fracture toughness. Materials with these properties are not susceptible to brittle failures. Operating history confirms that subsea equipment made of materials that meet these requirements are not susceptible to brittle fractures. A reduced design margin should not be justified by requiring an analysis to prevent brittle failure if brittle fracture has historically not been a problem and is not expected to be a problem in the future.
2. To perform a fracture mechanics analysis, Division 3 requires a load histogram with loads in the same sequence that they will be applied in service. This is usually easy for the pressure vessels for which Division 3 was written. However, developing a load histogram with loads in the proper sequence may not be practical or perhaps even possible for HPHT subsea equipment. The reason is that the highly cyclic loads on subsea equipment capable of causing fatigue cracks are randomly applied by the environment. This means that load histograms for subsea equipment must be statistically defined in load bins with a percent occurrence time for each load bin. The sequence of application is random and unpredictable. It may be possible to convert a statistically based load histogram into a conservative sequence. However, this has not been demonstrated in a published and peer-reviewed format. This should be done before subsea equipment design margins are reduced based on fracture mechanics analysis.

Comments Outside of Peer Review Charge

One reviewer chose to go beyond the charge questions provided as guidance for the peer reviewers. Specifically this reviewer commented on the competence of the performer. There are no Argonne project team responses to these comments.

Appendix A- Cross Tabulation of Responses to Peer-Review Report Text as Tabulated in Section 4.2[8]

The following table tabulates peer review comments with the responses provided in the foregoing text. When paragraphs appear on two pages, that paragraph is referenced as one paragraph for comment tabulation purposes.

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
	56	1	DP[9]	None needed	
	56	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Opinions and Expanding Scope of Current Argonne Study
	56	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
	56	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Comparison of Subsea Equipment and Pressure Vessels
	56	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
	56	5	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Least Conservative Pressure Rating
	56	5	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Linear-Elastic as a “Gold Standard”

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[8] Section 4.2 is peer-reviewer comments arranged by charge questions. These comments appear on pages 56-87 inclusive.

[9] Reviewer Key: DP = Dan Peters, PB = Paul Bunch, and RB = Richard Bihl.

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
	56	5	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
	56	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Only Two Burst Tests Performed
	56	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	No FMECA
	56	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Least Conservative Pressure Rating
	56	6	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Collapse Pressure and Strain Limit
	57	1	PB	Introduction and Background	Introduction and Background
	57	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
	57	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Inaccurately Modeled Components
	57	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
	57	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
	57	3	PB	None needed	
	58	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project)-Materials	Materials

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
	58	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
	58	3	PB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
	58	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Plastic Collapse and Ultimate Tensile Strength
	58	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Pressure Ratings by Hydro-test
	58	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Only Two Burst Tests Performed
	58	4	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
	58	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Performance of Burst Test Is Expensive and Dangerous
	58	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
	59	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
	59	2	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
	59	3	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
	59	4	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term
	59	5	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) –FEA	Independent FEA
	59	6	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) –FEA	FEA Solutions to Plastic Collapse
	59	6	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
	60	1	RB	Comments Outside of Peer Review Charge	Comments Outside of Peer Review Charge
	60	1	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term
1.1.1	60	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
1.1.1	60	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
1.1.1	60	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Opinions and Expanding Scope of Current Argonne Study
1.1.1	60	5	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.1	60	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Standards Released Subsequent to BSEE Project Start

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.1	60	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.1	61	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Standards Released Subsequent to BSEE Project Start
1.1.1	61	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.1	61	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
1.1.1	61	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.1	61	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.1	61	5	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.2	62	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term
1.1.2	62	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.2	62	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Linear-Elastic as a “Gold Standard”
1.1.2	63	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.2	63	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.2	63	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.2	63	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Plastic Collapse and Ultimate Tensile Strength
1.1.2	63	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.2	63	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.2	63	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.2	64	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Standards Released Subsequent to BSEE Project Start
1.1.2	64	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Von Mises Flow Rule
1.1.2	64	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Pressure Ratings by Hydro-test
1.1.2	64	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Plastic Collapse and Ultimate Tensile Strength
1.1.2	64	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.2	64	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Pressure Ratings by Hydro-test
1.1.2	64	2	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.3	64	3	DP	None needed	
1.1.3	64	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	FEA Solutions to Plastic Collapse
1.1.3	64	5	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.3	65	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Pressure Ratings by Hydro-test
1.1.3	65	2	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.3	65	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.3	65	4	RB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
1.1.3	65	4	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.4	66	1	DP	None needed	
1.1.4	66	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Model Dimensions

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.4	66	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Forging Reduction at Burst Region
1.1.4	66	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Heat-Treat Quenching and Grain Structure at Burst Region
1.1.4	66	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.4	66	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
1.1.4	67	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.4	67	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	UY Displacement Constraint
1.1.4	67	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Von Mises Flow Rule
1.1.4	67	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
1.1.4	67	5	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
1.1.4	67	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Model Dimensions

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.4	67	7	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.5	67	8	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.5	67	8	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.5	68	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
1.1.5	68	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Von Mises Flow Rule
1.1.5	68	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	No FMECA
1.1.5	68	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
1.1.5	69	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Inaccurately Modeled Components
1.1.5	68	2	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.5	68	2	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Least Conservative Pressure Rating
1.1.6	68	3	PB	None needed	

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
1.1.6	68	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.6	69	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.6	69	5	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Heat-Treat Quenching and Grain Structure at Burst Region
1.1.6	70	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.6	70	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Post Burst Testing Material Examination
1.1.6	70	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Standards Released Subsequent to BSEE Project Start
1.1.6	70	2	PB	Forged Products Table in Report	
1.1.6	70	3	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.6	70	4	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.7	70	5	DP	None needed	
1.1.7	71	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Post-Failure Metallurgical Examination
1.1.7	71	2	DP	No welding on test articles	

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1.1.7	71	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Forging Reduction at Burst Region
1.1.7	71	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Heat-Treat Quenching and Grain Structure at Burst Region
1.1.7	71	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Examination for Preexisting Defects
1.1.7	71	5	PB	None needed	
1.1.7	71	6	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Forging Reduction at Burst Region
1.1.7	71	6	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Heat-Treat Quenching and Grain Structure at Burst Region
1.1.8	72	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
1.1.8	72	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.8	72	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.8	72	3	DP	None needed	
1.1.8	72	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.8	72	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review

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1.1.8	72	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
1.1.8	73	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
1.1.8	73	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.8	73	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Heat-Treat Quenching and Grain Structure at Burst Region
1.1.8	73	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
1.1.8	73	3	PB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
1.1.8	73	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
1.1.8	73	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.8	74	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.8	74	2	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Numerical Analysis Compared to Test Results
1.1.9	74	3	DP	None needed	
1.1.9	74	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Elastic-Plastic FEA as an Allowable Method by API

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1.1.9	75	1	DP	None needed	
1.1.9	75	2	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.9	75	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Least Conservative Pressure Rating
1.1.9	75	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.9	75	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.9	75	5	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Elastic-Plastic FEA as an Allowable Method by API
1.1.9	76	1	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
1.1.9	75	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.9	76	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
1.1.9	76	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
1.1.9	76	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Histogram Load Sequence
1.1.9	76	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review

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1.1.9	76	3	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Comparison of Subsea Equipment and Pressure Vessels
1.1.9	76	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Examination for Preexisting Defects
1.1.9	76	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Post-Failure Metallurgical Examination
1.1.9	77	1	PB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
1.1.9	77	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
1.1.9	77	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.9	77	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
1.1.9	77	2	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
1.1.9	77	2	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
1.1.9	77	2	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
2.2.1	77	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes

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2.2.1	77	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
2.2.1	78	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
2.2.1	78	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
2.2.1	78	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Mesh Sensitivity
2.2.1	78	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
2.2.1	78	4	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Independent FEA
2.2.1	78	4	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
2.2.2	79	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Mesh Sensitivity
2.2.2	79	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Shapes of Test Bodies
2.2.2	79	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
2.2.2	79	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
2.2.2	79	4	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Independent FEA
2.2.2	79	5	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
2.2.2	79	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Shapes of Test Bodies
2.2.2	79	6	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Histogram Load Sequence
2.2.2	79	7	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Model Dimensions
2.2.2	80	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
2.2.2	80	2	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Independent FEA
2.2.2	80	2	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
2.2.2	80	3	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Load-Displacement Curves

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2.2.2	80	4	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
3	80	5	DP	None needed	
3	81	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
3	81	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
3	81	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Von Mises Flow Rule
3	81	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Independent FEA
3	81	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Design and Geometry of Test Bodies	Flanges, Bolts, and Seals
3	81	5	RB	None needed	
4	82	1	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
4	82	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Linear-Elastic as a “Gold Standard”
4	82	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
4	82	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Independent FEA

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4	82	5	RB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
3	82	5	RB	Comments Outside of Peer Review Charge	Comments Outside of Peer Review Charge
5	83	1	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Linear-Elastic as a “Gold Standard”
5	83	2	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term
5	83	3	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Performance of Burst Test Is Expensive and Dangerous
5	83	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
5	83	3	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Comparison of Subsea Equipment and Pressure Vessels
5	83	4	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Proof Testing Contradiction
5	83	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Performance of Burst Test Is Expensive and Dangerous
5	84	1	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Burst Tests	Purpose of Strain Gages
5	84	2	PB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
5	84	3	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review

Peer Review Report Subsection	Peer Review Report Page	Peer Review Report Paragraph	Peer Reviewer	Response Report Heading with Subsection as Applicable	Response Report Subsection
6	84	4	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
6	84	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
6	84	4	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
6	84	5	DP	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Comparison of Subsea Equipment and Pressure Vessels
6	84	5	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
6	84	6	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
6	85	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
6	85	1	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
6	85	2	PB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	Histogram Load Sequence
6	85	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
6	85	4	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes

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6	85	5	RB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
7	86	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
7	86	2	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
7	86	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
7	86	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
7	86	4	PB	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
7	86	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Performance of Burst Test Is Expensive and Dangerous
7	86	6	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance
7	86	6	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
8	87	1	DP	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Non-pressure-Related Failure Modes
8	87	2	DP	Restated Conclusions Based on Peer-Review Comments	Restated Conclusions Based on Peer-Review Comments
8	87	3	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Statistical Relevance

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8	87	4	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
8	87	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
8	87	5	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	Literature Review
8	87	6	PB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Validation
8	87	7	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -FEA	Elastic-Plastic Material Properties
8	87	7	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Materials	Material Properties from Prolongation
8	87	7	RB	Argonne Project Team Responses (Not Directly Relevant to BSEE/Argonne Project Scope)	ASME BPVC Is Guidance
8	87	8	RB	Argonne Project Team Responses (Directly Relevant to BSEE/Argonne Project) -Miscellaneous	“Design Margin” Term