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February 23, 2018

Director Scott Angelle
Bureau of Safety and Environmental Enforcement
U.S. Department of the Interior
1849 C Street, NW
Washington, DC 20240

RE: ANL Peer Review Draft Report (December 1, 2016) entitled "Evaluation of Pressure Rating Methods Recommended by API 17TR8"

Dear Director Angelle:

API and our members appreciate the time you and your staff have taken to discuss design, development and use of high-pressure high-temperature (HPHT) equipment and the application of the API 17TR8, "High-Pressure High-Temperature Design Guidelines." Our collaboration and mutual commitment to safety will continue to enable the safe and efficient development of HPHT resources on the OCS.

As you know, we have some concerns regarding the ANL Peer Review Draft Report (December 1, 2016) entitled "Evaluation of Pressure Rating Methods Recommended by API 17TR8" (ANL draft report). Our chief concern is the new recommended design factor or load resistance factor design to be used in lieu of the factors in the published ASME Codes and other long-established API and other industry standards for the design and manufacturing of oilfield equipment.

Per our discussion, attached is the detailed report from the API 45-member Task Group (TG) under the Committee on Standardization of Oilfield Equipment and Materials. The TG members represented a cross-section of industry and subject matter experts in the design, development and use of HPHT equipment and the application of the API 17TR8, "High-Pressure High-Temperature Design Guidelines." The TG was charged with reviewing the ANL draft report and recommending potential revisions and clarifications. During the review, the TG engaged BSEE and ANL to the extent possible to better understand the methodology and data presented in the ANL draft report.

We believe this detailed information along with the peer review of the ANL draft report, and the proceedings of the OOC November 2017 HPHT Workshop should be evaluated alongside the ANL draft report. Finally, API and the Offshore Operators Committee are reviewing the BSEE process and guidance on submitting a Conceptual Plan and Deepwater Operations Plan to obtain BSEE approval to implement a HPHT project.

Again, API appreciates the time you and your staff have spent on this topic and we look forward to continued engagement and cooperation between API and BSEE to enable the safe and efficient development of resources on the OCS. Please feel free to contact me at 202-682-8159, or miller@api.org with any questions.

Sincerely,

Attachment

cc: Doug Morris, Chief Office of Offshore Regulatory Programs
Michael Pittman, Chief, Risk Assessment and Analysis Branch, Office of Offshore Regulatory Programs
Lars Herbst, GOM Regional Director
Russell Hoshman, Technical Advisor for Regional Field Operations

API CSOEM Multi-Subcommittee Task Group
Technical Response

to

Argonne National Laboratory Draft Report on

Evaluation of Pressure Rating Methods Recommended by API RP 17TR8

dated December 1, 2016

February 15, 2018

API CSOEM Multi-Subcommittee Task Group
Technical Response to Argonne National Laboratory Draft Report on
Evaluation of Pressure Rating Methods Recommended by API RP 17TR8

Table of Contents

1. EXECUTIVE SUMMARY

The API Task Group (API TG) acknowledges the value in the data provided by the Argonne National Laboratory (ANL) draft Report on *Evaluation of Pressure Rating Methods Recommended by API RP 17TR8,* dated December 1, 2016. The burst test results are consistent with other industry studies for ASME Section VIII, Division 3 (refer to Susumu TERADA, P.E. - PROPOSAL OF NEW EQUATIONS FOR CYLINDRICAL AND SPHERICAL SHELL OF ASME SECTION VIII DIVISION 3 FOR HIGH PRESSURE VESSELS; Proceeding of ICPVT-12, September 2009).

However, the API TG does not support the ANL draft report's findings, conclusions and recommendations. The API TG points out several gaps in the draft report's material property qualification, which lead to inaccurate finite element analysis prediction of the global plastic collapse pressures as compared to the burst test results. The API TG also points out that the load resistance factor design values listed in the ASME Section VIII, Division 2 and Division 3, remain valid with industry design practices. The API TG respectfully recommends that the ANL draft report be retracted and reworked, addressing the gaps in material properties cited in this draft report.

API Technical Report 17TR8 *High-Pressure High-Temperature Design Guidelines* (API 17TR8), is a technical report intended to provide industry guidance for the high-pressure high-temperature (HPHT) equipment design process. This document, like other standards, draws on the principles of sound engineering practices. Use of API 17TR8 and other API documents is intended to supplement sound engineering practice.

The ANL draft report noted the use of API 17TR8 for the basis of the study; therefore, the API TG assessed ANL's conformance to the integrated process defined in API 17TR8. The API 17TR8 integrated process and its guiding principles consist of design (verification and validation), material qualification and manufacturing quality. As stated in the introduction of API 17TR8, it is not a standalone document; it must be used in combination with other applicable codes and standards that are relevant to the design of HPHT equipment and support API 17TR8 guiding principles. The API TG performed a detailed technical assessment of the ANL draft report and the specific conclusions and recommendations provided in the ANL draft report.

Gaps were identified in the material qualification process for the appropriate tensile properties used in the finite element analysis for the calculation of the plastic collapse pressures. Specifically, to correlate the material properties to the longitudinal burst direction, the transverse tensile properties (yield strength and ultimate tensile strength) should have been determined. The ANL draft report focused only on the global plastic collapse design load factor, which is one of five (5) potential failure modes identified for HPHT equipment design. All failure modes require verification of integrity. Additionally, any one of these failure modes can be the governing design criteria for the equipment design. The ANL did not perform the study in accordance with API 17TR8 for the calculations of the equipment pressure ratings.

The API TG does not believe all of the conclusions in the draft report are substantiated by data. Specifically, material properties acquired from the prolongation plan are likely not representative of the properties closer to the center of the forgings where the neck is located (location of burst). The API TG sought and received some clarification on ANL's process on material qualification and some evidence to support the ANL claims that the material qualifications were performed adequately. Additionally, the API TG believes engineering practices and requirements based on recognized industry standards were not applied correctly.

It is also important to recognize that the design factors associated with the load resistance factor design (LRFD) methodology for global plastic collapse in ASME Section VIII, Division 2 (ASME VIII-2) or ASME Section VIII, Division 3 (ASME VIII-3) are derived from industry statistical averages. The conclusions of the ANL draft report were based on the use of two (2) data points, which is not sufficient to support their conclusions and recommendations.

2. API TASK GROUP CONCLUSIONS

API CSOEM Multi-Subcommittee Task Group has completed the review of the Argonne National Laboratory Draft Report on *Evaluation of Pressure Rating Methods Recommended by API RP 17TR8,* dated December 1, 2016. The API TG recognizes the value in the data provided by the ANL draft report. Nevertheless, the API TG cannot endorse the ANL draft report due to lack of technical justifications and data to support the findings and conclusions of the draft report.

The ANL draft report focused on the comparisons of the hydrotest burst pressure to the theoretical plastic collapse pressure. The API TG observed deficiencies in the material qualification associated with the finite element analysis for the calculation of the collapse pressure. These deficiencies cast doubt on the validity of these calculations. Contrary to the comprehensive and integrated approach of API 17TR8, the ANL draft report advocates HPHT equipment design and validation through proof-test to failure (burst pressure), which is prohibited by ASME Section VIII Division 3. Proof-test to failure for equipment design, in general, is impractical from the perspective of adequate statistical sampling size and the inherent risks.

The API Task Group conclusions are listed below:

1. There is insufficient data to justify changing the ASME Section VIII Division 2 or Section VIII Division 3 load resistance factor design (LRFD) factors as currently stated in API 17TR8 "High-Pressure High-Temperature Design Guidelines." Conclusions of the ANL draft report were based on the use of only two data points. Previous publications such as Susumu Terada, P.E. – Proposal of New Equations for Cylindrical and Spherical Shell of ASME Section VIII Division 3 for High Pressure Vessels; Proceeding of ASME ICPVT-12, September 2009 and OTC-27605-MS, Design Margins for Normal, Extreme and Survival HPHT Application – OTC 2017 were based on 145 data points and 50 data points respectively. These two publications also indicated that a 7% discrepancy between FEA and actual test results to failure is acceptable and does not justify the suggestion for a change of ASME factors.
2. The methodology outlined in the ANL draft report did not conform to recognized oil and gas industry standards and documents. Specifically, the ANL work did not conform to API 17TR8, "High-Pressure High-Temperature Design Guidelines" and other industry standards used in the design, development, and manufacture of HPHT equipment.
3. API 17TR8, "High-Pressure High-Temperature Design Guidelines" should continue to be applied as written to the design of high-pressure, high-temperature subsea equipment including the use of ASME standard LRFD factors of 2.4 for ASME Section VIII, Division 2 and 1.8 for ASME Section VIII, Division 3.
4. The ANL draft report should be revised to account for the large quantity of tests and industry experience that were utilized to support the ASME standards.

3. BACKGROUND

High-pressure high-temperature environment (HPHT) is defined by 30 CFR §250.804 as a maximum shut-in tubing pressure greater than 15,000 psi (15 ksi) and/or greater than 350°F at the mudline. To develop these HPHT reservoirs, there is a need for 20,000 psi (20 ksi) rated subsea equipment to be developed, suitable for the anticipated reservoir pressure.

Traditionally, a broad range of pressure-containing oilfield equipment design is based on the definitions and formulae found in API 6A and API 6X. There is limited guidance available on the use of 20 ksi rated working pressure (RWP) equipment based on API 6A in production conditions above 15 ksi. For high-pressure high-temperature equipment, $\geq$ 20 ksi and $\geq$ 350°F, additional considerations for design (verification and validation), material and quality (manufacturing practices) should be applied to meet the design principles, materials and manufacturing practices for subsea equipment with such pressure ratings. These are guiding principles to HPHT equipment design.

In March 2013, API published its first document to address technical challenges and considerations to HPHT equipment design with API Technical Report 1PER15K-1, *Protocol for Verification and Validation of High-pressure High-temperature Equipment.* API 1PER15K-1 takes a system-level approach to the review of the entire well system exposed to HPHT conditions; however, this document does not offer analysis tools or design processes for the verification or validation of specific hardware.

Subsequently, API Subcommittee 17 (SC17) formed a task group to develop design guidelines for the verification and validation of specific subsea oil field hardware: API Technical Report 17TR8 *High-Pressure High-Temperature Design Guidelines* (API 17TR8). The first edition was published in February 2015. API 17TR8 outlines an integrated process and its guiding principles consist of design (verification and validation), material and quality. API 17TR8 is not a standalone document (as stated in the Introduction of API 17TR8). It must be used in combination with other applicable codes and standards, which are relevant to HPHT equipment design and in support of API 17TR8 guiding principles; design, materials, and quality.

In addition to API SC17, other API SCs (SC19 and SC16) also pursued the development of requirements for HPHT equipment design, and they also used similar guiding principles of design (verification and validation), materials, and quality, which are in addition to the requirements of the governing API standards. HPHT is an evolving technology advancement for the oil and natural gas industry. The API achieves continuous improvement of API standards by ensuring subject matter experts use a standard development process to incorporate lessons learned into the API standards. To supplement API design processes, the API traditionally employs ASME engineering practices as the design analysis tools for pressure-containing equipment, modifying or adapting their application for subsea/offshore conditions, as necessary. This inter-dependent practice remains with the various API standards and documents on HPHT equipment design.

The analysis method traditionally used in the current API product specifications (e.g., API 6A, API 17D) is based upon the design practices of applying the thin-wall/linear-elastic analysis method of ASME VIII-2 with a design margin based on the material's specified minimum yield strength (SMYS), typically 2/3 x SMYS, for the allowable stress design (ASD). These existing industry practices have resulted in successful, field proven equipment. Nonetheless, HPHT applications are subject to increased design pressures and design temperatures, resulting in either higher stresses and strains in pressure-containing components, or thicker-wall components. Therefore, thick-wall design methods are typically needed.

Thick-wall designs may present substantial difficulties in material manufacturing; it is usually more difficult to maintain uniform material properties throughout the wall sections of manufactured equipment (through-wall material properties). Additionally, when deciding whether to use the linear-analysis or the elastic-plastic analysis method in HPHT equipment design, consideration for the engineering principles of thin-wall design ($R/t > 4$ or $OD/ID < 1.25$) and thick-wall design ($R/t \leq 4$ or $OD/ID \geq 1.25$) must be applied. ASME VIII-2 and ASME VIII-3 limit the use of the linear-elastic analysis method to thin-wall design, as this analysis method may result in non-conservative designs for thick-wall components because the implicit linear stress distribution used in the stress-classification procedures does not accurately represent the nonlinear stress distribution associated with thick-wall sections. These are the main driving forces for the adoption of the thick-wall/elastic-plastic analysis method with respective LRFD factors from ASME VIII-2 and ASME VIII-3, where the design margin is based on the material minimum specified ultimate tensile strength (UTS) and provides an accurate prediction of the material stress-strain condition. The design methodology of ASME VIII-3 can further result in design products that are manageable in terms of weight and size, but it comes with the trade-off of more rigorous analysis, validation, additional material testing and material quality, and quality assurance. These practices were adopted into API 17TR8 for HPHT equipment design.

The ANL Draft Report on *Evaluation of Pressure Rating Methods Recommended by API RP 17TR8*, challenges various aspects of API 17TR8. The draft report:

- Challenges ASME VIII-3 elastic-plastic analysis and its load resistance factor design (LRFD);
- Challenges the elastic-plastic analysis methodology (ASME VIII-2 and ASME VIII-3) applied to subsea equipment design;

- Proposes a new LRFD design load factor for ASME VIII-2/ASME VIII-3; and
- Advocates the use of proof-test to failure of actual equipment to support the existing ASME VIII-3 LRFD design factor.

The ANL draft report was contracted by the Bureau of Safety and Environmental Enforcement (BSEE) of the Department of the Interior, and it was supported by Aiken Engineering, Southwest Research Laboratory and various technical experts.

The API Committee on Standardization of Oilfield Equipment and Materials (CSOEM) recognized that the ANL draft report could have an impact on various API standards, therefore, API CSOEM authorized the formation of the API TG to review and prepare the technical response to the ANL draft report. Considering that the ANL draft report may affect various API Subcommittees (SC), this task group included representations from:

1. API SC6 – Valves and Wellhead Equipment;
2. API SC16 – Drilling Well Control Equipment;
3. API SC17 – Subsea Production System;
4. API SC19 – Completion Equipment (governance of API 14A, API 11D1); and
5. API SC21 – Materials.

Additionally, the American Society of Mechanical Engineers (ASME) members also collaborated in the API TG. The API TG members are listed in **APPENDIX A.**

4. API TASK GROUP PROCESS

The API TG commenced the technical review process with the initial meeting held on January 30, 2017 and defined the strategy for the technical responses to the ANL draft report. At this meeting, two (2) main tasks for the development of the API TG technical response were defined: the technical review of ANL draft report and the post-study material evaluation.

A subsequent task group meeting was held on March 22, 2017, to discuss the collective comments, findings and observations about the ANL draft report. The details of the technical review, the assessments and the API TG's observations of each task and its sub-tasks are provided in this API TG report.

4.1 TECHNICAL REVIEW of ANL DRAFT REPORT

A general plan was defined by the API TG for the technical review of the ANL draft report. The API TG used a top-down, tier-level approach correlating to the stated scope of the ANL draft report. The review consists of:

1. A general assessment of the ANL application of API 17TR8: Since the ANL reported the use of API 17TR8 as the basis of the study, it is important to assess conformance to the integrated design process outlined in this industry HPHT design guideline.
2. A detailed technical review of the ANL draft report: The API TG members performed the detailed review of the ANL draft report. Their findings and inquiries were submitted and collated into this API TG report. Findings and inquiries are categorized into appropriate disciplines: 1) Material; 2) Design; analysis/FEA; 3) Validation testing; and 4) General.
3. Specific API TG comments to each of the ANL's conclusions and recommendations.

The detailed processes for the API TG's technical review and observations are provided in Section 5.

4.2 POST-STUDY MATERIAL EVALUATION

In the preliminary review of the ANL draft report, the API TG identified gaps in the appropriate tensile properties pertinent to the study and as input parameters into the finite element analysis performed, e.g. the transverse tensile property was not addressed. In response to API TG identification of these gaps, the ANL representatives approached API TG Materials Team to determine the feasibility of material testing using the post-mortem test bodies. The API TG Materials Team agreed that this was an expedited way to incorporate the appropriate tensile properties for the test bodies design analysis. API CSOEM authorized direct engagement with the ANL representative for the execution of this task.

The details of this initiative are contained in the correspondence between the API TG Materials Team and the BSEE/ANL team. The correspondences, as well as the API TG observations about the post-test material evaluation efforts are provided in Section 6**.** This initiative concluded without any further material testing, due to inadequate material remaining, as advised by BSEE.

5. TECHNICAL REVIEW OF ARGONNE NATIONAL LABORATORY DRAFT REPORT

5.1 ANL EXECUTION OF THE STUDY

The ANL Draft Report on *Evaluation of Pressure Rating Methods Recommended by API 17TR8,* dated December 1, 2016, is posted on the BSEE website (www.bsee.gov). As stated in the ANL draft report, the purpose of the 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. The methodology of this study is summarized below, as stated in the draft report;

- *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 ANL designed two (2) components for this study; the Large Neck and the Small Neck. These components were designed and analyzed by finite element analysis (FEA) and hydrostatically tested to determine the actual burst (rupture) pressure for the components. These burst pressures were subsequently compared to the theoretical plastic collapse pressures calculated from the FEAs of the two (2) test components.

5.1.1 MATERIAL QUALIFICATION

The material specification used for this study is stated to be ASTM A182 F22, low-alloy steel, typically used in subsea application. In subsea application, this material specification is subjected to various material processing procedures to achieve its desired form (forging), and mechanical/tensile properties. These procedures typically include hot-working requirements, heat treatment process, quenching, tempering, etc., and they are specified in detail in a material processing specification (MPS) or the forging processing plan.

For the ANL study, the specified mechanical/tensile properties as stated in ANL draft report Appendix A2 Section 11.0 Mechanical Properties, are:

- Ultimate tensile strength (UTS) minimum 95,000 psi

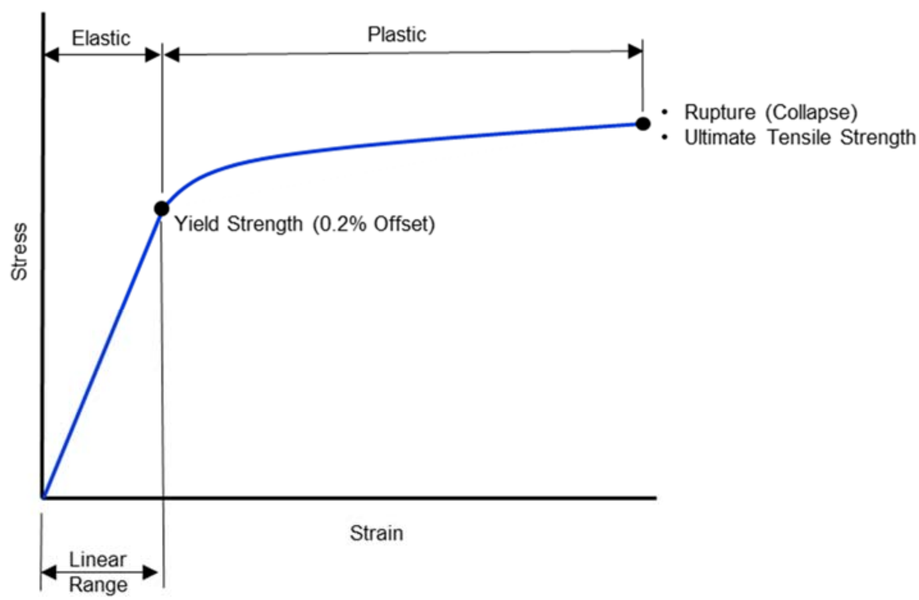
- Yield strength (YS) minimum 75,000 psi
- Reduction area minimum 35%
- Elongation in 2 in. minimum 18%
- Brinell Hardness 197 – 237 HB after finish machining

The tensile properties were determined by material testing of qualification test coupon (QTC) specimens taken from a prolongation taken from the flanged-end of the forging. This process is also typically referred to as the material qualification. The ANL's prolongation plan consisted of a hollow QTC with one material test report reported for the tensile properties representative of the two (2) forgings used as the test bodies.

5.1.2 DESIGN ANALYSIS

For the design analysis phase, ANL performed linear-elastic and elastic-plastic analysis through finite element (FE) modeling to calculate the theoretical plastic collapse pressures. The FEA used the material model of the specified minimum material properties and the actual material properties derived from the material qualification phase. The ASME methodology was used to develop the true stress-strain curve for the specified minimum material properties. A representative of a true stress-strain material curve is illustrated in Figure 1 below.

Figure 1 - Representative True Stress-Strain Material Curve



5.1.3 RESULTS OF THE STUDY

The ANL manufactured the test bodies and performed a hydrotest of the two (2) components to determine their burst pressures. The burst pressures were then compared to the theoretical plastic collapse pressures calculated from the elastic-plastic FEA. The burst pressures were also used to calculate test components maximum pressure rating.

These results and comparisons are summarized and presented in the applicable tables within the ANL draft report and they are provided below for reference.

5.1.3.1 Comparison of Burst and Plastic Collapse Pressures

ANL Draft Report Table 6.1 compared the burst pressures from the hydrotest with the collapse pressure from FEAs with the specified and actual material properties.

ANL Draft Report 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 Properties	-7.05%	-6.71%
Burst Pressure Compared to Plastic Collapse of Specified Material Properties	7.56%	8.30%

* Based on the higher values of the actual material property as reported from Forged Product Inc. and Franklyn Research and Associate.

Through the comparisons of the burst pressures to the calculated plastic collapse pressures, the ANL stated their challenges to API 17TR8 design methodology in the ANL draft report's findings and conclusions. The API TG identified gaps to the material qualification process for the actual material properties, discussed later in this report. Notably, the intention of the elastic-plastic LRFD methods is to ensure the design is adequate at the rated pressure and not that the predicted plastic collapse pressure exactly align with an actual burst pressure.

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

The calculated maximum pressure ratings for the test bodies are provided in Table 7.1 of the ANL draft report. For the proof-test maximum pressure ratings, the ANL applied the procedures of API 6A Section 4.3.3.5.1 and ASME VIII-3, KD-1254 to the burst-test pressures or the collapse pressure. For the elastic-plastic maximum pressure ratings, ANL divided the calculated plastic collapse pressures for the specified material properties by the respective elastic-plastic LRFD factors of ASME VIII-2 and ASME VIII-3.

In these comparisons, it is important to also consider the ANL study's scope of designing and manufacturing test bodies for 20 ksi operating pressure or 20 ksi rated working pressure with the calculated maximum pressure ratings by methodologies outlined in the draft report. This assessment will determine conformance to the study's objective.

In this regard, the API TG annotated, in brackets, Table 7.1 with the ratios of the calculated maximum pressure ratings to the 20 ksi rated working pressure to illustrate the margin of conformance to the ANL's scope of the study.

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

Test Body	Maximum Pressure Rating (psi)			
	API 6A Proof Test[1]	Division 3 Proof-Test[2]	Division 3 Elastic-Plastic[3]	Division 2 Elastic-Plastic[3]
Small Neck Body	20,934 **[1.05]**	24,173 **[1.21]**	26,584 **[1.33]**	19,938 **[0.997]**
Large Neck Body	27,641 **[1.38]**	31,918 **[1.60]**	34,861 **[1.74]**	26,146 **[1.31]**

[ ] = Maximum Pressure Rating / 20 ksi rated working pressure

API TG Notes to ANL Draft Report Table 7.1

The following notes refer to Table 7.1 and to the superscript numbers in the column headings.

1. ANL used the actual burst test pressures; however, API 6A Section 4.3.3.5 does not have provisions to accept the burst pressure as the hydrostatic test pressure applied in accordance with API 6A Section 4.3.3.5.3.2, Application of pressure. Additionally, API 6A Section 4.3.3.5.3 provides procedures for the calculation of the maximum allowable working pressure based on measured strain responses under the hydrostatic test conditions.
2. ANL used the actual burst test pressures; however, this is not in conformance with ASME VIII-3 Article KD-1212 where it prohibits test to destruction to determine the collapse pressure (burst pressure). Additionally, ASME VIII-3 Article KD-1253 provides procedures for determining collapse pressure based on measured strain responses under the hydrostatic test conditions. And finally, the calculations of maximum pressure rating for "Division 3 Proof-Test," require the use of actual material properties. However, API TG identified gaps in the material qualification process that was used to generate the data for the study (discussed later in this report).
3. The calculations are based on the specified minimum material properties.

It is observed from these results that the calculated maximum pressure ratings exceeded the study's scope of 20 ksi rated working pressure using API 6A, ASME VIII-2 and ASME VIII-3 methods for the Large Neck Body. The ASME VIII-2 elastic-plastic analysis resulted in a maximum pressure rating of 19,938 psi for the Small Neck Body, which is less than the study's objective of a 20 ksi rated working pressure. This nonconformance to the study's objective was not addressed in the ANL draft report. Furthermore, this appeared to be the basis of ANL Conclusion #3 for a reduced ASME VIII-2 LRFD design factor of "2.1" from the current "2.4." ANL should clarify the basis used for the proposed "2.1" elastic-plastic LRFD design factor for ASME VIII-2."

Regarding subsea practices, the selection of 20 ksi rated working pressure (RWP) equipment is based on an anticipated reservoir pressure of less than 20,000 psi. Therefore, this equipment is not expected to be exposed to an internal pressure that exceeds its rated working pressure based on the reservoir identified characteristics. These design loading requirements are identified in an equipment's functional specifications. These general guidance and considerations are outlined in the integrated processes of API 17TR8, and they should have been applied in the ANL study.

5.1.3.3 Ratio of Pressure Rating to Collapse Pressure by FEA

The ANL further calculated the "Ratio of Pressure Ratings to Collapse Pressure by FEA" and these ratios are denoted in the ANL Draft Report Table 9.1 as "Factor of Safety from Burst." For this exercise, the ANL divided the plastic collapse pressure by the maximum pressure rating, which resulted in the LRFD design factors that conformed to ASME VIII-2 and ASME VIII-3. This appears to be an alternate representation of Table 7.1, where the plastic collapse pressures were divided by the respective elastic-plastic LRFD factors of ASME VIII-2 and ASME VIII-3 to calculate the maximum pressure ratings. It is important for the API TG to assess the "Factor of Safety from Burst" in light of the ANL study's objective of 20 ksi rated working pressure.

The API TG has added annotations in brackets to Table 9.1 with the "Factor of Safety from Burst" based on the 20 ksi rated working pressure and the plastic collapse pressures. The annotated table is focused only on the elastic-plastic FEAs of the Large Neck Test Body and the Small Neck Test Body.

ANL Draft Report Table 9.1 - Ratio of Pressure Rating to Collapse Pressure by FEA

Description of Component	Plastic Collapse* (psi)	Factor of Safety from Burst By Elastic-Plastic FEA	
		Division 2	Division 3
Large Neck Test Body	62,750	2.40 **[3.13]**	1.80 **[3.13]**
Small Neck Test Body	47,850	2.40 **[2.39]**	1.80 **[2.39]**

Notes:

[ ] = Plastic Collapse Pressure / 20 ksi rated working pressure

* Based on the specified minimum material properties.

With consideration to the study's objective of 20 ksi rated working pressure, it is shown that the "Factor of Safety from Burst" exceeded the LRFD factor acceptance criteria as defined in ASME VIII-2 and ASME VIII-3 for the Large Neck Test Body.

For the Small Neck Test Body, the "Factor of Safety from Burst" exceeded the required LRFD design factor of ASME VIII-3; however, it does not conform to the LRFD design factor of ASME VIII-2. This observation is consistent with the nonconformance finding for calculated maximum pressure rating of 19,938 psi for the Small Neck Body (refer to Table 7.1 of the ANL draft report).

A similar exercise can be performed to determine the "Factor of Safety from Burst" based on the actual burst pressure to the ANL study's scope of 20 ksi rated working pressure. These factors should be compared to the LRFD acceptance criteria defined in ASME VIII-2 and ASME VIII-3. The API TG performed this assessment and it is provided in Figure 2 - Factor of Safety from Burst Test Pressures.

Figure 2 - Factor of Safety from Burst Test Pressures

Description of Component	Burst Test Pressure (psi)	"Factor of Safety from Burst" By Elastic-Plastic FEA	
		Division 2	Division 3
Large Neck Test Body	72,850	2.40 **[3.64]**	1.80 **[3.64]**
Small Neck Test Body	55,850	2.40 **[2.79]**	1.80 **[2.79]**

Note:

[ ] = Burst Test Pressure / 20 ksi rated working pressure

As shown above, the "Factor of Safety from Burst" based on the burst test pressures with the ANL study's scope of 20 ksi rated working pressure exceeded the LRFD acceptance criteria ASME VIII-2 and ASME VIII-3, for both test components.

5.1.3.4 API TG Observations

The ANL draft report noted that the Small Neck Test Body did not meet the requirements of ASME VIII-2 LRFD design factor, while the Large Neck Test Body complies with both ASME VIII-2 and ASME VIII-3 LRFD design factor; however, the ANL draft report did not address this nonconformance nor assessed whether the study objectives were met.

The ANL defined the study objective as a 20 ksi rated working pressure test body designed, manufactured and tested. The ANL deviated from the study's objective and focused its findings and conclusions based on the maximum pressure ratings calculated from the burst test pressures and the plastic collapse pressures from FEA. Equipment pressure rating, in accordance to typical API practice and specifically to API 17TR8, is designated as 15 ksi RWP, 20 ksi RWP or 25 ksi RWP, and it is not based on the maximum pressure ratings. In the assessments to the 20 ksi rated working pressure, the API TG offered the appropriate perspective in the applications of API 17TR8.

The ANL study did not use a 20 ksi rated working pressure to assess the differences between the burst pressures and the calculated plastic collapse pressures: ANL assessed these pressure differences against the calculated maximum pressure rating. Investigation of the data with consideration of the study's objective, knowledge of subsea application and sound engineering practices may have resulted in different findings and conclusions.

5.2 ANL APPLICATON OF API 17TR8

The ANL reported that the API 17TR8, *High-pressure High-temperature Design Guidelines,* was used for the basis of the study; therefore, it is important to assess the study's conformance to the integrated design process outlined in this document.

API 17TR8 outlines an integrated process and its guiding principles consist of design (verification and validation), material and quality. These processes are compiled into API 17TR8 Figure 1 – HPHT Design Flow Chart. The integrated process is a thorough and holistic approach to HPHT equipment design and is used to confirm that the equipment is fit-for-service in its intended environment and application. API 17TR8 is a technical report and is intended to provide industry guidance for the HPHT equipment design process. This document, like other industry standards, draws on the principles of sound engineering practices. Use of API 17TR8 and API standards is intended to supplement sound engineering practice.

As stated in the introduction, API 17TR8 is not a standalone document, it must be used in combination with other applicable codes and standards, which are relevant to HPHT equipment design and in support of API 17TR8 guiding principles. It is important to recognize that HPHT equipment design is an integrated process consisting of 1) design, 2) material and 3) quality, requiring a multi-disciplinary, collaborative effort between equipment designers and end-users, metallurgical engineers and quality control/quality assurance experts.

5.2.1 API 17TR8 INTEGRATED PROCESS

The following section is an analysis and summary of the ANL conformance to the integrated process of API 17TR8. The process is described, and then key observations of ANL conformance to these processes are given.

5.2.1.1 Develop an equipment functional specification

The API 17TR8 starts with the development of the equipment functional specification that includes the requirements to:

1. Identify equipment design parameters, including pressure rating (i.e., 15 ksi RWP, 20 ksi RWP, 25 ksi RWP, etc.) and temperature rating;
2. Identify applicable loadings (i.e., external loads, cyclic loads, etc.).

In this process, the ANL identified the subject test bodies' maximum operating pressure as 20,000 psi at 70°F. This can be considered as the equipment design rating: pressure and temperature. As stated in the draft report, the calculations for the study were performed at the design pressure of 26,000 psi to accommodate loads other than internal pressure, e.g., external loads. The API TG notes that the addition of 6,000 psi to the design pressure or 130% of the design load for the consideration of external loads is not an accurate application of external loads in standard subsea equipment design practice. The application of an additional 6,000 psi would result in an equivalent pressure-end load (tension) and would not be comparable to the bending and/or torsional loads. Detailed design parameters and a loading histogram can be developed for subsea equipment design, and they are typically derived through a global riser analysis.

The API TG believes that the ANL work did not develop an adequate equipment functional specification.

5.2.1.2 Identify failure modes

Risk analysis, specifically, failure modes, effects and criticality analysis (FMECA) is a useful tool to identify the equipment's potential failure modes with the resulting hazards mitigated appropriately. An additional objective of a FMECA is to identify any additional validation testing requirements associated with the equipment's functional specification and above the requirements specified in current API 6A/API 17D. The FMECA is the foundation of the design verification, material validation and validation testing programs.

The FMECA would have identified the differences between pressure load and external loads, as observed in Section 5.2.1.1 above. The ANL process did include a quasi-FMECA by acknowledging that the internal pressure will rupture the neck region of the test bodies; however, appropriate mitigation measures for this failure mode were not implemented.

The ANL process did not perform the appropriate risk analysis and/or FMECA or implement risk mitigation measures for the test bodies.

5.2.1.3 Perform material qualification

A critical aspect to HPHT equipment design is the material qualification process. This process is provided in API 17TR8 1st Edition Section 6 and Annex B, and in API 17TR8 2nd Edition - Annex D, Material Characterization Protocols. A thorough understanding of the material properties and true stress-strain data are essential to evaluating the test body using the elastic-plastic finite element analysis of ASME. Notably, this element is the most significant gap in the ANL study for the following reasons:

1. Material properties acquired from the prolongation plan are likely not representative of the properties closer to the center of the forgings where the neck is located (location of burst). The ANL's prolongation plan and test specimens' locations are discussed in Section 5.3 of this report.
2. The tensile properties (yield strength, ultimate tensile strength) were acquired only in the longitudinal direction for input into the finite element analysis. Based on the burst direction where the hoop stress is the governing factor, tensile properties in the transverse direction are pertinent to the ANL study; however, these properties were not acquired in the material qualification program.
3. The appropriate API standard for the material qualification referenced in API 17TR8 1st Edition is API Specification 20B - *Open Die-Shaped Forgings for Use in the Petroleum and Natural Gas Industry*, 1st Edition April 2013. This standard requires tensile properties in longitudinal and transverse directions for thorough understanding of the forging's anticipated anisotropic material properties (refer to Section 4.3.5, Mechanical Testing, of API Spec 20B). Normal quality assurance practice is to assess that these tensile properties meet the material specified minimum requirements. Subsequently, sound engineering practice applies the material's specified minimum tensile properties to the equipment design process. Specific to the ANL work, the lower of the tensile property values from the transverse and longitudinal directions should have been used as the input material model to the FEA for the calculations of the plastic collapse pressures for the test bodies.
4. The API TG noted that there is only one (1) set of tensile properties reported when there were (2) forgings used in the study. The prolongation plan as well as the forging processing plan will have significant impact on the tensile properties used for the design analysis of the test bodies. The forging processing plan or manufacturing procedure specification should have been included in the draft report as it is critical to the validity of the material properties used in the FEA analysis.

Thorough characterization of material properties is necessary for accurate elastic-plastic analysis in equipment design with API 17TR8. As stated above, only longitudinal tensile properties were available and used in the design analysis of the ANL draft report. The uncertainties related to the material properties results in uncertainty in the appropriate theoretical plastic collapse pressures for the test bodies.

The ANL study calculated the equipment pressure rating based on incomplete and potentially inappropriate tensile properties.

5.2.1.4 Define the acceptance criteria

The appropriate industry design standards are to be identified for the equipment design, e.g., API 6A/API 17D, ASME VIII-2, ASME VIII-3, etc. It is important to note that API 17TR8 serves as the design guideline or design process that directs the equipment designer to various recognized industry codes and standards for specific disciplines, i.e., design analysis, material qualification, quality, etc.

The ANL defined API 6A, ASME VIII-2 and ASME VIII-3 as the industry standards for the study. Additionally, Table 7.1 of the ANL draft report summarizes the applications of these industry standards to the calculations of the test bodies' maximum pressure rating.

The API TG affirms that the ANL defined the acceptance criteria for the study.

5.2.1.5 Perform design verification

The objective for design verification is to confirm that the HPHT equipment design complies with its functional specifications and serviceability criteria, and the equipment has adequate protection against failure modes identified for HPHT equipment. Typical failure modes identified for HPHT equipment are:

1. Global plastic collapse: capability of pressure-containment under loads (pressure, temperature, external loads);
2. Local strain limit damage: structural discontinuities exhibiting local plastic strain;
3. Ratcheting: incremental cyclic growth;
4. Plastic collapse under the hydrostatic test conditions: capability of pressure-containment under hydrostatic test pressure;
5. Fatigue: estimated equipment life, based on applied cyclic loads.

In the design verification process, API 17TR8 emphasizes the importance of a holistic design verification process with the appropriate material properties to assess adequate protection against failure modes. In addition to the global plastic collapse verification, API 17TR8 specifies design verification for other identified failure modes in HPHT equipment design, which include local strain limit damage, ratcheting, plastic collapse under hydrostatic test condition and fatigue assessment (as required).

The ANL study focused on the global plastic collapse design load factor, which is only one of five (5) potential failure modes identified for HPHT equipment design. Any one of these failure modes can be the governing design criteria for the equipment design.

The ANL did not perform the study in accordance with API 17TR8 for the calculations of the equipment failure modes.

5.2.1.6 Perform validation testing

The design validation process is performed to demonstrate that the equipment maintains the mechanical integrity and functionality/operability relative to its functional specifications. The output from the FMECA process would identify a validation testing program associated with the equipment's performance requirements, based on identified failure modes. The validation testing program may include validation of materials used for the equipment design and validation of the design method.

As outlined in Section 5.2.1.3, the ANL study did not perform a FMECA to identify the test body's failure modes and carry out the appropriate material validation/qualification process for the material specification used in the study.

The ANL study performed proof-test on two (2) test bodies to determine the burst pressure (or rupture) by hydrotest. Strain-gauging data for the validation of the FEA was reported up to the hydrotest pressure of 30 ksi (1.5 x RWP); however, this is limited to the elastic region (linear range) of the material model. The data is summarized below at the location of interest, the neck:

- Large Neck Test Body: ± 2.4% (refer to ANL Draft Report Appendix D, Table D1.1).
- Small Neck Test Body: ± 3.3% – 3.6% (refer to ANL Draft Report Appendix D, Table D1.2).

The ANL study further progressed the hydrotest to the test body's burst pressure; however, strain-gauging data were not reported up to the burst pressures (Large Neck = 67,959 psi; Small Neck = 51,469 psi) or in the plastic region of the material model, from the onset of yielding up to the burst/collapse pressure. Figure 6.4 and Figure 6.5 of the ANL draft report show that the strain gauge is mounted on the test body during the burst test, however, the strain reading was not collected. Subsequently, the actual burst pressures were compared to the theoretical collapse pressure leading towards the calculations of the test body pressure rating.

Note: Refer to Figure 1 – Representative True Stress-Strain Material Curve, for illustration of the relationship between the linear range and the plastic region on a material model curve.

API 6A and ASME VIII-3 provide proof-test procedures to calculate equipment maximum pressure ratings, based on measured strain responses under the hydrotest condition. The ANL should have used the proof-test procedures to determine the test body pressure ratings.

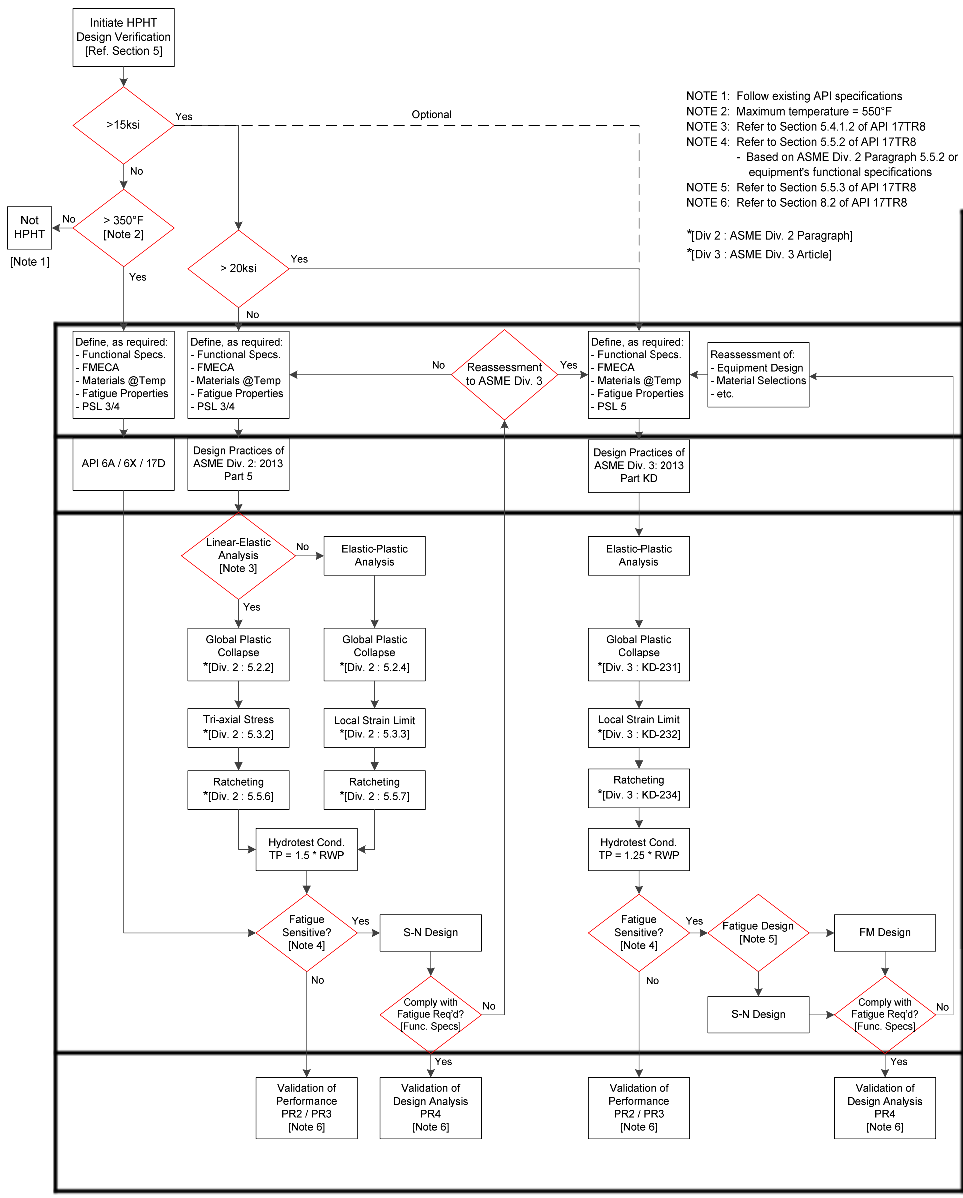
The ANL performed proof-test to failure for the validation of the test body pressure rating, by comparing the burst test pressure to the calculated plastic collapse pressure. This practice is explicitly prohibited by ASME VIII-3. Proof-test to failure is not an appropriate or suitable approach to equipment design due to the inherent risks to safety, personnel and equipment.

The ANL did not perform the validation testing program in accordance with API 17TR8.

5.2.2 OBSERVATIONS TO ANL APPLICATON OF API 17TR8

As discussed in Section 5.2.1 above and illustrated in Figure 3 – Conformity Assessment to API 17TR8 Integrated Process: HPHT Design Flow Chart, the ANL did not deploy the integrated process in their application of API 17TR8 for the study. API 17TR8 specifies an integrated process for HPHT equipment design that requires thorough assessment of the equipment functional requirement, material qualification, design verification for adequate protection against potential failure modes and validation testing. These processes must be adhered to for demonstration of the equipment's fit-for-service in HPHT application. The ANL did not perform the study in accordance with API 17TR8 nor did it use the document's holistic approach for the calculations of the test body pressure rating.

Figure 3 – Conformity Assessment to API 17TR8 Integrated Process
HPHT Design Flow Chart



Legend: Conformity Assessment Dashboard

○ Conform to the API 17TR8 Process

● Nonconformance to the API 17TR8 Process

Conformity Dashboard	API 17TR8 Integrated Process
●	• Develop an equipment functional specification • Identify failure modes • Perform material qualification
○	• Define acceptance criteria (design standard) ▪ API 6A/17D, ASME VIII-2 and ASME VIII-3
●	• Perform design verification (with appropriate material properties) in accordance with design standard ▪ Global plastic collapse ▪ Local strain limit damage ▪ Ratcheting ▪ Plastic collapse under hydrostatic condition ▪ Fatigue analysis (as required)
●	• Perform validation testing ▪ Validation of FEA: Strain-gauge data only up to hydrotest pressure of 30 ksi ▪ Proof test to failure

5.3 DETAILED TECHNCIAL REVIEW

The API TG performed a detailed review of the ANL draft report. Throughout the technical review process, the API TG noted findings and the areas where additional clarifications to ANL's execution of the study of API 17TR8 were required. Only highlights from the review are presented below and a complete list of the technical issues is found in **APPENDIX B.**

The task group categorized their findings and observations into four (4) disciplines; 1) Material, 2) Design Analysis/FEA, 3) Validation Testing and 4) General. These findings included those from the Post-Study Material Evaluation initiative, are discussed in Section 6.

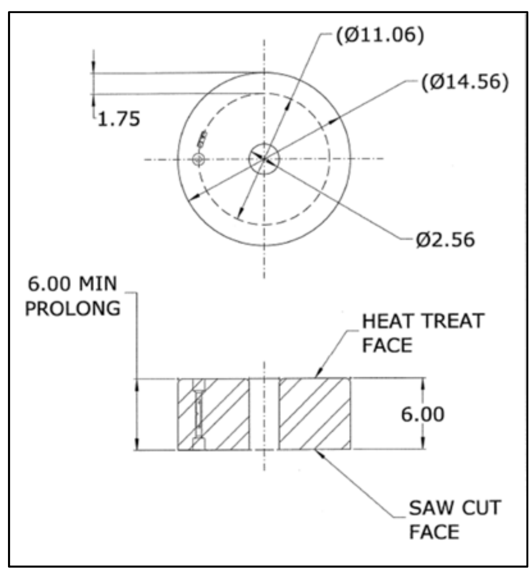
5.3.1 FINDINGS AND OBSERVATIONS IN DETAILED TECHNICAL REVIEW

The detailed technical review of the ANL draft report allowed the API TG to make the following observations and findings in each discipline:

5.3.1.1 Materials

1. Material qualification for the appropriate tensile properties was not fully performed. The transverse tensile properties are pertinent to this study, as they would correspond to the longitudinal burst direction where the hoop stress is the dominant criteria. The draft report only reported tensile properties in the longitudinal direction.
2. The appropriate API standard was not used in the material qualification process. The ANL applied API 6A PSL3 in their material qualification process. The applicable API standard for material qualification for the application of API 17TR8 is API Spec 20B, *Open Die-Shaped Forgings for Use in the Petroleum and Natural Gas Industry*, 1st Edition April 2013, and the requirements for longitudinal and transverse tensile properties are specified therein for thorough understanding of forging material properties.
3. In accordance with ANL's Appendix A2 Section 11.0, Mechanical Properties "…*test specimens gauge length as taken from the prolongation is at least 1/4T and no less than 25mm from any heat-treated surface where T is the thickness.*"

   As illustrated in ANL's Description of Prolongation (refer to **APPENDIX D**), the prolongation is clearly shown as a hollow QTC, pictured below. Additionally, the Test Layout diagram indicates that the test specimens are taken at 1/4T from the outside diameter (heat treated surface).



In this regard, API TG advises that this does not conform to the requirements of API 6A, specifically to the test specimen location as specified in Section 5.7.4.1, Material qualification/Tensile and impact specimens, where:

> "*Test specimens shall be removed from the QTC such that their longitudinal centreline axis is wholly within the centre core 1/4T envelope for a solid QTC or within 3 mm (1/8 in) of the mid-thickness of the thickest section of a hollow QTC (see Figure 3)*."

4. Correlation of material properties between the prolongation specimens and the area of interest, the neck, was not included in the draft report. With a reported 12:1 cross-section reduction ratio in the neck region, the material is expected to be anisotropic where differences in tensile properties are expected between the longitudinal and transverse directions, as well as between the QTC prolongation and the neck region.
5. The ANL pre-determined the failure mode of the test body as "*Internal pressure will rupture the neck at this location before failure occurs at any other location*" (refer to the second paragraph on p13 of the ANL draft report). This should warrant the need for the material properties' correlation to the location of interest (the neck) in addition to tensile properties in the transverse direction, correlated to longitudinal burst direction. The correlation plan of material properties for the location of interest, the neck, should have been included in the study.

5.3.1.2 Design Analysis/FEA

1. With reference to Table 9.2 and Table 9.3 in the ANL draft report, the API TG noted that the API internal pressure rating did not include the hydrostatic test pressure condition, which can be the governing criteria for API 6A linear-elastic analysis; however, the hydrostatic test condition was not considered in the recommended LRFD factor. Further, it appears that in the ANL-recommended "2.1" LRFD factor, the ANL attempted to match the load ratings of the API 6A linear-elastic analysis method (linear analysis) to those of the ASME VIII-2 or ASME VIII-3 elastic-plastic analysis method (non-linear analysis).
2. Using the information in the ANL draft report, the API TG was not able to derive the "2.1" LRFD design factor that the ANL recommended for ASME VIII-2. The ANL-recommended "2.1" LRFD design factor for ASME VIII-2 does not appear to be based on the test data but rather on the draft report's subjective conclusion that this adjusted LRFD should be in line with existing API 6A linear elastic design margins. And yet, a 7% deviation from the "1.8" LRFD factor would drive towards a LRFD of ~"1.93" not "2.1." Therefore, the recommended "2.1" design factor does not appear to be based on test results.
3. The API TG noted that there were two (2) sets of longitudinal tensile properties reported: Forged Product Inc. (YS=92,200 psi/ TS=111,100 psi) and Franklin Research Associates (YS=91,600 psi/ TS=108,700 psi). The FPI tensile properties (higher values) were used in the design analysis and not the Franklin Research Associates tensile properties (the lower values), which would have been the sound engineering practice for equipment design. No basis for using the higher values was provided in the ANL draft report.
4. The ANL draft report does not clearly give the rationale for the conclusion that stress intensities should be considered rather than von-Mises as specified in ASME VIII-2.

5.3.1.3 Validation Testing

1. ASME VIII-3 Article KD-12, specifically KD-1212, prohibits test to destruction (burst pressure) to determine the collapse pressure for the calculation of the maximum pressure rating.
2. Strain gauge data stopped at 30,000 psi or in the linear region of a material curve. Strain gauge data should have continued into the plastic region of the material curve, up until the strain gauges delaminated from the specimen, to determine the accuracy of the FEA-predicted behavior of the

test body once it initiated plastic deformation and up to the burst pressures: 51,469 psi (Small Neck) and 67,959 psi (Large Neck).

5.3.1.4 General

1. The burst pressures from the draft report are approximately 7% lower than the theoretical collapse pressure calculated from the elastic-plastic finite element analysis for both of the Small Neck and Large Neck test bodies, based on actual tensile properties. Nevertheless, the ANL did not perform due diligence in identifying the appropriate tensile properties as input parameters into the finite element analysis. The ANL made subsequent recommendations based on this comparison.
2. Based on the specified minimum tensile properties, yield strength and ultimate tensile strength, the burst pressures are approximately 7% higher than the FEA-calculated collapse pressures. In this regard, the ANL could have recommended using specified minimum tensile properties for FEA, which would have been consistent with sound engineering practice of using specified minimum material properties in equipment design analysis.
3. Establishing pressure rating by engineering analysis is not to predict the failure point of the component but to determine a safe limit to the operational conditions of the component using a combination of the estimated failure load and a design factor.
4. The ANL conclusion that the LRFD design factor should be “2.1” was reached using two (2) pressure vessel geometries (cylindrical geometry near the necks) with internal pressure only, without considering the appropriate external loads. Therefore, those limited FEA results are not sufficient to draw the ANL conclusion of the LRFD design factor of “2.1.”

The API TG has concerns with the ANL study and observed uncertainties in the execution of the study. These findings and observations by the API TG do not support the ANL draft report’s technical conclusions and recommendations. Revisions to the draft report that include specific and clear responses to the API TG inquiries and comments are requested to better understand the ANL perspective and its application of API 17TR8.

5.3.2 ASSESSMENT OF THE ANL DRAFT REPORT NARRATIVE

During its technical review of the ANL report, the API TG noted several unsupported statements, which in turn led to unsupported conclusions. The table below provides samples of such statements along with supported counterpoint from the API TG.

Narrative from the ANL Draft Report	Counterpoint with Supports
Prior to 2007, linear-elastic analysis was the only method accepted by API or ASME for verifying pressure ratings. [pg. 9]	Plastic analysis (or elastic-plastic analysis), in addition to linear-elastic, was available in: • ASME VIII-2 1998 Edition (Mandatory Appendix 4-136) • ASME VIII-3 1998 Edition (Article KD-240). The first publication of ASME VIII-3, 1995 Edition, initially provided plastic analysis methodology. ASME VIII-3 1998 Edition and onward are available on IHS.
Currently, API has not approved verification by elastic-plastic FEA. [pg. 9]	Plastic analysis (or elastic-plastic analysis) is available in these current API documents and standards: • API 6X – 1st Edition, March 2014 (covers API 6A/16A) • API 11D1 – 3rd Edition, April 2015 • API 14A – 12th Edition January 2015 • API 17D – 2nd Edition, May 2011 • API 17G – 2nd Edition, July 2006 • API 17TR7 – 1st Edition, April 2017 • API 17TR8 – 1st Edition, February 2015
Furthermore, for pressures above 20 ksi, TR8 requires that pressure ratings be set using only Division 3 elastic-plastic methods. [pg. 10]	API 17TR8 only provides recommendations to the design methodology of ASME VIII-2 or ASME VIII-3, based on equipment RWP (refer to Section 4.2.1.4 of API 17TR8). These are not mandatory requirements.
API still requires verification by the linear-elastic procedures set forth in the 2004 release of Division 2. [pg. 9]	Plastic analysis (or elastic-plastic analysis) is available in these current API documents and standards: • API 6X – 1st Edition, March 2014 (covers API 6A/16A) • API 14A – 12th Edition January 2015 • API 11D1 – 3rd Edition, April 2015 • API 17D – 2nd Edition, May 2011 • API 17G – 2nd Edition, May 2011 • API 17TR7 – 1st Edition, April 2017 This is in addition to the linear-elastic analysis procedures of ASME VIII-2, 2004 Edition. It should be noted that API 6X was published to address the referencing of the design methodology in the superseded 2004 Edition of ASME VIII-2.
The fifth procedure is pressure rating by proof test. This procedure is allowed in API 6A and Division 3. [pg. 18]	API 6A and ASME VIII-3 allow for calculations of pressure rating by proof-test and there are procedures specified therein, based on measured strain under the hydrostatic test condition. However, these standards do not advocate proof-test to failure/destruction to determine an equipment pressure rating. Additionally, ASME VIII-3 prohibits proof-test to failure/destruction to determine the collapse pressure.

Many codes concerning pressure ratings describe methods for determining pressure ratings based on hydrostatic proof test to failure. [pg. 20]	API 6A and ASME VIII-3, applicable to ANL study, do not have provisions for proof-test to failure for determining pressure rating. ASME VIII-3, Article KD-1212, Tests for Determination of Collapse Pressure CP, states "*Strain measurement tests may be used for the determination of the collapse pressure CP. Distortion measurement tests may be used for the determination of the CP if it can be clearly shown that the test setup and the instrumentation used will give valid results for the configuration on which the measurements are made. Brittle coating tests and tests to destruction shall not be used to determine the CP."*
Pressure rating based on linear-elastic FEA is allowable under API 6A and under ASME Division 2, but not under ASME Division 3". [pg. 19]	Currently, ASME VIII-3 2015 Edition provides the linear-elastic analysis method, limited to the diameter ratios (OD/ID) less than 1.25 (refer to KD-200(d)) or thin-wall design. Otherwise elastic-plastic analysis method shall be applied to the diameter ratios greater than 1.25 (refer to KD-200(c)) or thick-wall design. Similarly, ASME VIII-2 does not recommend the use of linear-elastic analysis for thick-wall designs. In accordance with ASME VIII-2 Paragraph 5.2.1.3: "*The use of elastic stress analysis combined with stress classification procedures to demonstrate structural integrity for heavy-wall (R/t $\leq$ 4) pressure containing components, especially around structural discontinuities, may produce non-conservative results and is not recommended. The reason for the non-conservatism is that the nonlinear stress distributions associated with heavy wall sections are not accurately represented by the implicit linear stress distribution utilized in the stress categorization and classification procedure. The misrepresentation of the stress distribution is enhanced if yielding occurs. For example, in cases where calculated peak stresses are above yield over a through thickness dimension which is more than five percent of the wall thickness, linear elastic analysis may give a non-conservative result. In these cases, the elastic-plastic stress analysis procedures in 5.2.3 or 5.2.4 shall be used*". These engineering principles guided API 17TR8 to recommend the use of elastic-plastic analysis method of ASME VIII-2 and ASME VIII-3 for high-pressure, thick-wall design, typically associated with HPHT equipment (refer to Figure 1 – HPHT Design Flow Chart and Section 5.4.1.3 of API 17TR8).

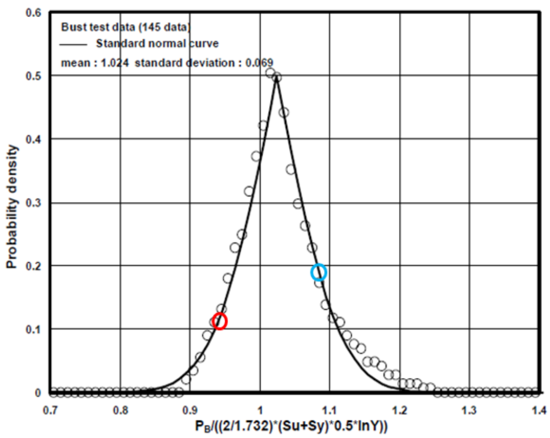
5.4 API TASK GROUP COMMENTS TO THE ANL's Draft CONCLUSIONS

The ANL draft report provided six (6) conclusions as the result of the study. As the final step of the top-down assessment of the technical review, the API TG commented on each of the ANL's draft conclusions. These are provided below:

1. **The Division 3 elastic-plastic method is not recommended for HPHT subsea equipment, as published with a 1.8 design load factor**
   a. This conclusion does not appear to be based on the test data but rather a subjective conclusion that use of ASME VIII-3 is not acceptable, as the ANL test data does not align with the conclusion that ASME VIII-3 and its LRFD of "1.8" is not sufficient.
   b. ASME VIII-3 design margin against plastic collapse is supported by the ASME technical publication; Susumu TERADA P.E. – ASME ICPVT-12, PROPOSAL OF NEW EQUATIONS

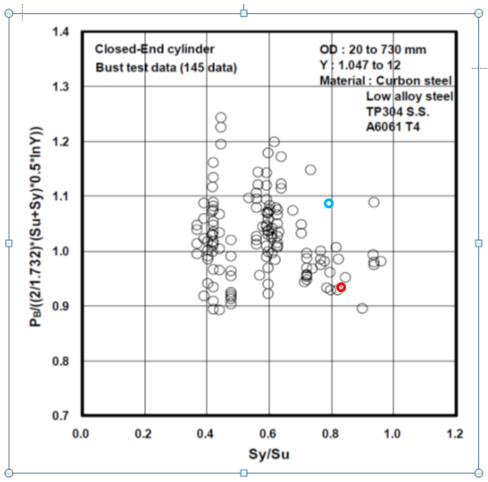
FOR CYLINDRICAL AND SPHERICAL SHELL OF ASME SECTION VIII DIVISION 3 FOR HIGH PRESSURE VESSELS - September 2009.

c. The ANL reported burst test pressures are within the statistical distribution of the aforementioned ASME-ICPVT technical publication in support of ASME VIII-3 LRFD design factor. The ANL's burst pressures are plotted in accordance with the parameters of this technical publication and are illustrated to be within the statistical distribution of burst test results (145 data points) performed in support of ASME VIII-3 design margin against collapse.



As specified materials, Sy/Su=0.79, Pb/FEA=1.08

Actual material properties, Sy/Su=0.83, Pb/FEA=0.94



As specified materials, Sy/Su=0.79, Pb/FEA=1.08

Actual material properties, Sy/Su=0.83, Pb/FEA=0.94

d. ASME VIII-3 design margin against plastic collapse is also supported by an OTC 2017 technical publication: OTC-27605-MS, Design Margins for Normal, Extreme and Survival HPHT Application: Andrew J. Grohmann, Jordan Selvey, and Scott Ellisor, Dril-Quip, Inc.

e. The ASME VIII-3 elastic-plastic method with the LRFD of "1.8" design factor should continue to be used for HPHT equipment design as it is additionally supported by technical publication referenced in 1.c) and 1.d) above.

f. ASME VIII-2 and ASME VIII-3 both use the identical elastic-plastic FEA methodology with different LRFD factors; however, the draft report only raised concerns on ASME VIII-3 methodology and its LRFD factor, when the observed difference in the collapse pressure by FEA and the burst test pressure is independent of the LRFD factor selected. Conversely, the observed difference would be applicable to both ASME VIII-2 and ASME VIII-3 criteria.

g. The API TG noted on Table 9.1 in the ANL draft report that the pressure rating of ASME VIII-2 elastic-plastic analysis is calculated to 19,938 psi, less than the expected pressure rating of 20,000 psi; however, this was not commented on in the ANL draft report.

2. A Division 3 analysis with a design load factor of 1.8 would be more justifiable if the factor is applied to the rupture pressure determined by a proof test to failure, and if justification is provided that demonstrates the additional requirements in Division 3 sufficiently reduce the risk of failure

a. ASME VIII-3 Article KD-12, specifically KD-1212, prohibits test to destruction (burst pressure) to determine the collapse pressure and subsequent derivation of pressure rating.

b. The procedures of ASME VIII-3 Article KD-12 and specifically, KD-1253 and KD-1254 were not followed to determine the collapse pressure of the component.

c. The proposed proof-test to failure to calculate pressure rating is impractical and inherently unsafe for the environment and human life for pressure ratings and equipment size associated with offshore HPHT equipment such as Christmas trees, wellheads, drill-through equipment, etc.

d. One proof-test or data point would not provide sufficient statistical sampling nor certainty in material quality. Relying on insufficient statistical sampling may result in erroneous ratings of equipment.

3. The Division 2 elastic-plastic method with a design load factor of 2.1 would be more in line with historically successful equipment to calculate load ratings for HPHT subsea equipment

a. The ANL draft report should provide appropriate technical justification or derivation for the proposed "2.1" LRFD design load factor for ASME VIII-2 elastic-plastic method. This conclusion was not clearly explained in the draft report.

b. With reference to Table 9.2 and Table 9.3 in the ANL draft report, the API TG noted that the API internal pressure rating did not include the hydrostatic test pressure condition, which is the governing criteria for API 6A linear-elastic analysis. This would change the proposed "2.1" factor to match the load ratings for API 6A methods to VIII-2 or VIII-3 methods.

c. This conclusion does not appear to be based on the test data but rather on a subjective conclusion that this adjusted LRFD should be in line with existing API 6A linear elastic design margins. A 7% deviation from "1.8" of ASME VIII-3 would drive towards a LRFD of ~"1.93" and not the proposed "2.1." Consequently, it appears that the proposed "2.1" is not based on test results.

4. For a Division 2 linear-elastic analysis, it is recommended that stress intensities, and not von Mises stresses, be compared with allowable stresses

a. Stress intensity has been typically used for linear-elastic analysis with the API allowable stress of 2/3 x SMYS and this remains appropriate.

b. Nevertheless, stress intensity in some cases (where shear and bending stresses dominate) may result in non-conservative results, as it involves utilizing only the maximum and minimum principal stresses. von Mises stress is a more accurate equivalent stress method, as it takes into account all principle stresses, and hence is recommended in ASME VIII-2 and API 17TR8.

5. It is recommended that the subsea industry consider comparing collapse pressures from FEA with burst pressures from hydrotest for a variety of subsea equipment

a. The proposed proof-test to failure for offshore equipment to calculate pressure rating is impractical and inherently unsafe for the environment and human life.

b. ASME VIII-3 Article KD-12, specifically KD-1212, prohibits test to destruction (burst pressure) to determine the collapse pressure for the calculation of pressure and subsequent derivation of maximum pressure rating.

c. If the ANL proceeds with further determination of collapse pressure based on hydrostatic test, strict adherence to ASME VIII-3 Article KD-12, specifically KD-1253 and KD-1254, is necessary.

6. For subsea equipment, the industry should verify that the additional fracture mechanics analysis and more rigorous material requirements in Division 3 justify a 33-percent reduction of the design load factor as compared to Division 2.

a. API 17TR8 2nd Edition – Annex D thoroughly addresses material characterization and qualification in environments specific for subsea application, which is the technical justification for the use of ASME VIII-3 fracture mechanics.

b. A subsea-equipment-loading histogram can typically be derived from a global riser analysis (GRA). This is standard practice in offshore application. As part of the design process, a conservative load sequencing based on the GRA or anticipated operational scenario can be developed for the fatigue assessment/ fracture mechanics analysis.

6. POST-STUDY MATERIAL EVALUATION

6.1 OBJECTIVES

The second task in the API TG technical review was to determine the feasibility of post-study material testing. The initial review of the ANL draft report showed that there are gaps in identifying the appropriate tensile properties, e.g., transverse tensile properties (yield strength and ultimate tensile strength), which are pertinent to the study and to the input material model into the finite element analysis for the calculation of the collapse pressure. The ANL draft report only reported the tensile properties in the longitudinal direction.

An ANL representative approached API TG Materials Team for potential guidance in material testing using the post-mortem test bodies. This was also determined to be an acceptable way to expedite resolution of the API TG concern that the appropriate tensile properties (transverse) correlate with the actual burst direction (longitudinal). API CSOEM authorized direct engagement with ANL to determine feasibility and execution of this task.

6.2 PROCESS

The material evaluation process involved discussions and interaction between the following entities:

- API TG Materials Team: Tim Haeberle (GE O&G), Pat Boster (SES), Paul Bunch (Cameron), Steven Shademan (Dril-Quip). Man Pham (APC - Facilitator)
- BSEE: Michael Pittman, Christy Lan, Candi Hudson
- ANL: Dan Frasier, Roy Lindley
- Aiken Engineering: Bill Aiken

The main objective of this task was to determine the feasibility of additional material testing on the post-mortem test bodies to address the gap in the draft report in regard to the appropriate tensile property for input parameters into the finite element analysis.

This initiative involved a series of teleconferences where participants discussed the objectives of the API TG Materials Team and exchanged information, focusing on the "Questions by Select API Material Team for ANL Draft Report" and "API Materials Team's Request for Data/Information."

Through the teleconferences, the API TG Materials Team was made aware that the post-mortem test bodies were located at Forged Product, Inc. Additionally, a box of QTC remnants was located at Aiken Engineering. This would have allowed for the post-test material testing to mitigate the gaps identified for the transverse tensile properties. The request was made to ANL to facilitate and arrange a meeting at Forged Product in order for the API TG Materials Team to: 1) review the forging processing plan, 2) examine the forging and QTC remnants, 3) assess the strain-hardening effects on these test bodies as portions of the component's material had gone through phase transformation (exceeding yield strength) in hydrotest and 4) to meet with the ANL's technical experts to gain a better understanding of the forging processing and material qualification process. However, this initiative concluded without results, as BSEE and ANL advised that there was not enough material remaining for testing.

Specific questions from the API Materials Team to BSEE/ANL/Aiken Engineering and their responses are contained in **APPENDIX C.**

6.3 OBSERVATIONS TO THE POST-TEST MATERIAL EVALUATION INITIATIVE

During the interactions between API Materials team and the BSEE/ANL team, the following findings were observed:

1. The ANL's justifications for the adequacy of the material qualification performed and for the adequacy of the material manufacturing process/forging processing plan to provide consistent properties between the prolongation and the neck area were based on the *opinions* of ANL's technical experts and were not substantiated by supporting data
2. The ANL did not apply the appropriate API standard for material qualification, which is API 20B. The ANL applied an outdated edition of the API standard for the material qualification process; API 6A – 19th Edition (February 2005 to April 2011). Furthermore, the ANL did not conform to the specific API 6A requirements for tensile specimen locations: Section 5.7.4.1, Material qualification/Tensile and impact specimens.

APPENDIX A: API MULTI-SUBCOMMITTEE TASK GROUP MEMBERS

The API Task Group members are listed below:

API Multi-Subcommittee Task Group for Technical Response to Argonne National Laboratory Draft Report - *Evaluation of Pressure Rating Methods Recommended by API RP 17TR8*			
First Name	**Last Name**	**Company**	**Email**
Man	Pham (Chair)	Anadarko	Man.Pham@anadarko.com
Brian	Skeels (Co-Chair)	TechnipFMC	brian.skeels@technipfmc.com
Jessie	Lin	ABS	jelin@eagle.org
Harish	Patel	ABS	hpatel@eagle.org
Jim	Raney	Anadarko	Jim.Raney@anadarko.com
Gregg	Walz	Anadarko	Gregg.Walz@anadarko.com
Dennis	Kaminski	Anadarko	Dennis.kaminski@anadarko.com
David	Miller	API	miller@api.org
Roland	Goodman	API	goodmanr@api.org
Holly	Hopkins	API	hopkinsh@api.org
Ed	Baniak	API	baniake@api.org
Shree	Krishna	Blade Energy	SKrishna@blade-energy.com
Jack	Soape	Blade Energy	JSoape@blade-energy.com
Austin	Freeman	BP	austin.freeman@bp.com
Cuesta	Jorge	BP	jorge.cuesta@bp.com
Paul	Bunch	Cameron - SLB	PBunch@cameron.slb.com
Greg	Kusinski	Chevron	gkusinski@chevron.com
Frank	Gallander	Chevron	FGallander@chevron.com
Matt	Vaclavik	Chevron	mvaclavik@chevron.com
Chris	McMillian	Chevron	Chris.McMillan@chevron.com
Chris	Kocurek	ConocoPhillips	Chris.Kocurek@conocophillips.com
Andrew	Grohmann	Dril-Quip	Andrew_Grohmann@dril-quip.com
Jim	Kaculi	Dril-Quip	Jim_Kaculi@dril-quip.com
Steve	Shademan	Dril-quip	steven_shademan@dril-quip.com
Jorge	Suarez	DNV	Jorge.A.Suarez@dnvgl.com
Bill	Cowan	ENI	bill.cowan@enipetroleum.com
Chris	Stewart	ENSCO	cstewart@enscoplc.com
Sterling	Lewis	ExxonMobil	sterling.f.lewis@exxonmobil.com
Tim	Haeberle	GE	tim.haeberle@ge.com
Rob	Hilts	Haliburton	rob.hilts@halliburton.com

Terapat	Apichartthabrut	Halliburton	terapat.apichartthbrut@halliburton.com
Parth	Pathak	OneSubsea - SLB	PPathak2@onesubsea.slb.com
Arshad	Bajvani	OneSubsea – SLB	ABajvani@onesubsea.slb.com
Tim	Bartlett	TechnipFMC	Tim.Bartlett@technipfmc.com
Kumarswamy	Karpanan	TechnipFMC	kumarswamy.karpanan@ technipfmc.com
Wayne	Mabry	Shell	wayne.mabry@shell.com
Terry	Cook	Shell	terry.cook@shell.com
Gong	Jung	Shell	gonghyun.jung@shell.com
Greg	Bailey	Shell	g.bailey@shell.com
Hari	Hariharan	Shell	hari.hariharan@shell.com
Pat	Boster	Stress Engineering Services	Pat.Boster@stress.com
John	Chappell	Stress Engineering Services	john.chappell@stress.com
George	Ross	Stress Engineering Services	george.ross@stress.com
Dan	Peters	Structural Integrity Associates	dpeters@Structint.com
Bud	Auvil	Structural Integrity Associates	bauvil@Structint.com

APPENDIX B: ADDITIONAL API TASK GROUP FINDINGS AND INQUIRIES TO THE ANL DRAFT REPORT

Additional findings and inquiries to the API TG detailed technical review are provided below:

API TG Findings and Inquiries	Category
1. ANL executed material qualification in accordance with API 6A PSL3, which is not comparable to the expected higher material quality for API 17TR8 – ASME VIII-3 equipment design (refer to Section 5.3.4 of API 17TR8). An example of elevated material quality requirement related to surface NDE acceptance criteria is provided below: | | **Surface NDE (MT)** | | ASME VIII-3 / PSL5 | 0.125" or by design | | API 6A PSL3 | 0.1875" |	Material
2. Material properties acquired from the prolongation may not be representative of the properties closer to the center of the forgings where the neck is located (location of burst). Details on the forging manufacturing procedure specification (MPS), specifically to the quenched and tempered processes, should be discussed in the draft report.	Material
3. The failure pressures from burst pressure tests are about 7% lower than those from elastic-plastic FEA for both the small neck and large neck test bodies. This difference may be due to the elastic plastic material model used in the FEA – the material test data may not match the material behavior near the failure location near the necks. The correlation of material properties at the neck (location of burst) with the prolongation properties as well as material properties used in the FEA should have been included in the draft report as they are critical to the validity of the material properties used in the FEA analysis.	Material
4. Since the elastic-plastic analysis governs by tensile strength, hardness readings (correlation with UTS) should have been measured with confirmation that the final test blocks had similar hardness to the tensile test coupon. The hardness readings on the final test blocks should have been performed for correlation to the UTS.	Material
5. Hardness distribution through the thickness should have been investigated to ensure adequate/high hardness at ID of the neck where potentially slow cooling would induce lower hardness reading. The hardness readings on the final test blocks should have been performed for correlation to the UTS.	Material
6. The lower the yield to ultimate strength, the smaller the Y/U ratio, means there is more strain hardening before plastic collapse failure (the material is tougher). HPHT designs typically require high yield to ultimate ratios in order to minimize size of equipment, which means there is limited strain hardening capability of the component.	Material
7. Uniformity of hardness around the failed cylinder is a concern due to horizontal heat treatment. It may induce inherent banana shaped (non-axisymmetric) or slack quenching. It would be helpful to have hardness around the cylinder and to understand why failure occurred at the specific location due to relatively low hardness at failed location. The hardness readings on the final test blocks should have been performed for correlation to the UTS.	Material

8. The draft report states that "if brittle fractures have not been a problem in the past" that they are "not expected to be a problem in the future" and that materials meeting the requirements of 17TR8 and NACE will be ductile and thus not susceptible to brittle fractures [p29]. There are concerns on several points with these assertions: a. Brittle fractures may not have been a problem for designs that meet current codes but changing design methodology introduces new failure modes that need to be accounted for. By going to a different design margin based on tensile strength (versus yield strength), brittle fracture can become a failure mode and should be assessed for equipment operating in higher temperature and pressure. Compliance with API 17TR8 and NACE does not assure that brittle fracture will not be a failure mode. The determination of brittle fracture is a combined evaluation of design analysis, material properties (with environmental effects) and NDE b. Impact testing is done at the lowest temperature of the equipment's temperature rating classification. This is to ensure that the material is above the temperature at which it transitions from being ductile to brittle, so that brittle fracture does not occur. However, even at temperatures above the transition temperature, if the crack is allowed to grow steadily until the critical crack size is reached, a fast and unstable fracture may still occur. This crack size must be determined for the environment in which the equipment is operating (this is a requirement of API 17TR8 materials that will be designed in accordance with VIII-3 methodology). It should be noted that API 17TR8 specifies assessment of environmental conditions (i.e., elevated temperature, reservoir conditions, etc.) effects on material properties.	Material
9. Section 6.3 "This means that pressure ratings calculated by analysis were greater than pressure ratings calculated by burst tests". However, there is no indication that the analysis took into account factors such as eccentricity of the test specimen bore with respect to its OD, misalignment of the bore, or other factors that could contribute to the actual burst point being lower than the calculated collapse point. Considerations should be made for these conditions.	Design analysis/ FEA
10. The dimensions of the test assembly and FE model should have been included in the draft report to identify identical measurements. The FE model may have used nominal dimensions, which may differ from the actual test assembly as measured dimensions?	Design analysis/ FEA
11. The change of LRFD from "1.8" to "2.1" will impact other LRFD dependent verifications applied to other failure criteria (e.g. local strain, hydrotest condition, etc.) as specified in Section 5 of API 17TR8 and Table KD-230.4 of ASME VIII-3. No recommendations were made for the ASME BPVC elastic-plastic analysis LRFD factors for global collapse criteria which includes thermal loads, local collapse criteria and hydrotest criteria. This may lead to improper evaluation and combination of LRFDs for the design verification of HPHT equipment designs.	Design analysis/ FEA
12. The criteria for FEA to determine the maximum load capacity was not stated. The maximum load capacity was used to compare the pressure test.	Design analysis/ FEA
13. It was not clear from the draft report whether the hydrotest as a loadstep was included in the FEA analysis.	Design analysis/ FEA
14. There was insufficient information in the ANL draft report regarding the finite element analysis modeling, boundary conditions, load, mesh sensitivity and results.	Design analysis/ FEA

15. The ANL draft report challenges the justification of ASME VIII-3 for having a lower load factor than ASME VIII-2 by using fracture mechanics for fatigue since time-based load history is not possible in subsea. The API TG believes a design load histogram can be developed from historical reservoir data (e.g. pressure and temperature). This histogram can then be used in fracture mechanics to calculate the estimated fatigue life of the equipment.	Design analysis/ FEA
16. The FEA modeling practices used by ANL in this draft report were not completely provided or were different from actual test conditions. Specific areas of consideration that could contribute to the discrepancy between the experimental and FEA results include: a. Applying bolt tension equal to the pressure end load as negative pressure to the bolt circles does not capture that some of the PEL (pressure-end load) will contribute to decompression of preloaded flange faces. b. The flange bolt holes appear to be neglected in the model and this will contribute to an increased stiffness of the flange. c. In the experimental set-ups, the bottom face of the block is constrained by the test plate. In the analysis, the block's bottom face was allowed to flex freely. d. In many respects, the effects of bolt preload seem to be neglected altogether. The effects of the top flange BX gasket and the mating blind flange were ignored in the analysis. e. Any difference between the FEA material model and the actual material will directly affect the result of a collapse analysis. Therefore, more data would need to be provided regarding the material models to see if non-conservative assumptions or modeling techniques contributed to the final, non-conservative, FEA results. f. A comparison should be made between a quarter symmetry model and half symmetry model.	Design analysis/ FEA
17. It is sound engineering practice to perform FEA with minimum specified material properties (e.g., yield strength, tensile strength). It is not typical to perform FEA with actual measured material properties for the calculation of the plastic collapse pressure. Dependent on the material manufacturing procedures, there may be variations for the tensile properties in the transverse and longitudinal directions. This is one reason why most design codes require the use of minimum specified material properties.	Design analysis/ FEA
18. The following is data that would help to further examine the relationship between the reported FEA and the reported experiments: a. Strain vs. Pressure on the pipe beyond the elastic region. Currently, the data stops at 30,000 psi. Data should expand beyond the linear region (as long as strain gages stay laminated) to determine how well FEA predicts behavior of the body once it contains plastic deformation. b. Additional details on the material model used in the FEA and how it compares to the material test data. How has the elastic-plastic stress-strain property been implemented in the analysis? What assumptions were made? etc. c. Details on the collapse mode and location of collapse experienced in the FEA model.	Design analysis/ FEA
19. The ANL draft report stated that "the internal pressure at the last converged solution is defined as the plastic collapse by ASME procedures". The last divergent solution is a numerical number not directly related to physical phenomenon. In fact, if this solution is used as the plastic collapse pressure, this pressure will be larger than the numerical predictions of rupture pressure. So, the observation the draft report made is expected, the logic to conclude that this makes ASME VIII-3 based pressure rating less conservative than the test results is not correct.	Design analysis/ FEA

<table>
<tr><td>

20. The ANL draft report stated in Section 6.0 "*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.*"

- The justification of the pressure rating analysis should not be to predict the failure point of the component, but to determine a safe limit to the operational conditions of the component using a combination of the estimated failure load and a design factor. As long as this rating consistently provides a safe limit to operating conditions, there is no need for the collapse pressure to "closely" agree with the actual burst pressure. This is clearly not a necessary condition for ASD methods (usually based on yield stress), as these methods are used to determine safe operational limits for equipment without determining the actual failure point of the equipment.

</td><td>Design analysis/ FEA</td></tr>
<tr><td>

21. Linear elastic FEA methods per API 6A and ASME Division 2 are different in allowable stress limits and stress intensity/von Mises stress. For example, here are 75 ksi F22 allowable stress limits:

a. API 6A: Allowable stress = 50 ksi (2/3 Sy); stress intensity

b. ASME VIII-2: Allowable stress = 39.6 ksi – minimum [Sy/1.5, Su/2.4] ASME Section II Part D Table 10-100), von Mises stress

</td><td>Design analysis/ FEA</td></tr>
<tr><td>

22. Further to the above, the maximum allowable stress for ASME VIII-2 linear-elastic analysis should be calculated as: min (YS/1.5, UTS/2.4) and not just YS/1.5. In this case, the UTS/2.4 would be the governing allowable stress criteria. The corrected API internal pressure ratings, based on the above, are provided below:

	Summary			
	Large Neck		Small Neck	
	ANL	Corrected	ANL	Corrected
API 6A, rating	29,551	28,268	23,825	20,465
ASME VIII-2, rating	34,091	26,989	27,483	22,427
Test Burst Pressure	62,750	62,750	47,850	47,850
Factor of Safety from Burst	2.12	2.22	2.01	2.34

</td><td>Design analysis/ FEA</td></tr>
<tr><td>23. The criteria for pressure test to determine the maximum load capacity; leak, bulge (unstable displacement), or visual crack opening at OD was not provided.</td><td>Validation testing</td></tr>
<tr><td>24. The ANL draft report did not state if the test assembly was inspected for cracks or defects before tests. The use of VIII-3 in API 17TR8 requires additional quality control and assurance related to material quality and properties, comparable to ASME VIII-3 Article KE-2. (see PSL5 of API 17TR8)</td><td>Validation testing</td></tr>
</table>

APPENDIX C: POST-TEST MATERIAL EVALUATION ENGAGEMENT

C.1 CORRESPONDENCE, DISCUSSION and TIMELINE

The timeline and discussions for the interactions between API TG Materials Team and BSEE/ANL are provided below. The objective of this engagement was to expedite the “Questions by select API Material Team for ANL Draft Report” and the requests by the API TG metallurgist for the post-study material evaluation initiative.

- 2/22/17: Teleconference
  - Attendees

    API: Man Pham

    BSEE: Michael Pittman
  - Discussion:

    Initial discussion was to plan for material evaluation on the post-mortem test bodies. The main objective of the material testing was to mitigate the gap identified as the appropriate tensile property for input parameters into the finite element analysis. It was observed that the burst direction was in the longitudinal direction in the cylindrical neck of the test bodies, therefore, the tensile properties (YS, UTS) in the transverse direction would have been pertinent to the study. However, the ANL draft report only reported the tensile properties in the longitudinal direction.

    BSEE is in receipt of the API TG Materials Team's questions and distributed to ANL and Aiken Engineering. These questions are basis of discussion amongst the API TG Materials Team, BSEE, ANL and Aiken Engineering representatives at the scheduled February 27th teleconference.

- 2/27/17: Teleconference
  - Attendees:

    API: Tim Haeberle, Pat Boster, Paul Bunch, Steven Shademan, Man Pham

    BSEE: Michael Pittman, Christy Lan, Candi Hudson,

    ANL: Dan Frasier, Roy Lindley

    Aiken: Bill Aiken
  - Discussion:

    API TG Materials Team discussed the objectives of the questions and the request for additional material testing, prolongation plan, forging processing plan and post-test evaluation performed to date.

    BSEE/ANL advised that the team were to review the questions and requests and would revert accordingly.

- 3/14/17: Teleconference
  - Attendees:

    API: Tim Haeberle, Pat Boster, Paul Bunch, Steven Shademan, Man Pham

    ANL Representative: Bruce Miglin
  - Discussion:

    Bruce Miglin advised that the cadaver test bodies were located at FPI (Forged Product, Inc.) and there is a box of remnants at Aiken Engineering.

    The discussion between Bruce M. and the API TG Materials Team involved the feasibility of additional testing API would like to have performed on the QTC remnants and the forging remnants.

It was tentatively agreed that this would meet would meet again, one week later (March 21) and would take inventory of remnants and assess the feasibility to perform additional material testing.

This discussion and proposal were to be carried forward to the wider BSEE/ANL teleconference, scheduled for March 15, 2017.

- 3/15/17: Teleconference
  - Attendees:

    API: Tim Haeberle, Pat Boster, Paul Bunch, Steven Shademan, Man Pham

    ANL: Roy Lindley, Dan Fraser

    BSEE: Michael Pittman, Christy Lan, Candi Hudson
  - Discussion:

    The discussion between BSEE/ANL and the API TG Materials Team involved the feasibility of additional testing API would like to have performed on the QTC remnants and the forging remnants.

    Requested ANL arrange for a meeting at Forged Products Inc., Houston to look at the manufacturing process plan, the forging remnants, and the QTC remnants

    Requested participation of Manuel Maligas (author of the material specification), Maurice Peltier and Lee White (forging processors).

- 3/24/17: email correspondences

BSEE replied, via email, to API TG Materials Team's correspondences of March 22, 2017 are provided in BSEE Final Correspondence, with the API's responses of March 28, 2017.

C.2 QUESTIONS BY SELECT API MATERIAL TEAM ON THE ANL DRAFT REPORT

API TG Materials Team was able to submit a set of questions and request for additional information to BSEE/ANL/Aiken Engineering for review and expedite.

The transcripts between the API TG Materials Team and the BSEE/ANL/Aiken Engineering team's dialogue to the questions are provided below. This interaction ended with the "Final BSEE Correspondence." (Refer to Appendix C.3)

ANL's responses are in red and API's responses are in blue:

1. In Section 5.3 "Material Properties of Components" second paragraph, "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 psi".

   Question: It is stated that these are actual properties. Is there any evidence that these properties represent the actual mechanical properties in the neck region at the location of failure? Specifically, representative of the hoop stress (circumferential) direction. This is related to the prolongation plan for forging.

   - Argonne Response (March 14, 2017)

Attachment 1 shows details of the prolongation and locations of the tensile test specimen. All details of the prolongation meet the requirements in the material specification and in API 6A (ANSI/API Specification 6A 20th Edition, October 2010).

The material specification was written by Manuel Maligas who has been writing material specifications for subsea forgings for more than 30 years. His opinion is that the tensile properties in the transverse direction will be approximately equal to those in the longitudinal direction.

The Forged Products metallurgist developed the heat treatment plan. His opinion is that the tensile properties in the neck region will be equal to or slightly greater than the tensile properties of the prolongation.

The stated intent of the study was to test bodies that were typical of large forgings that are currently used for large, high-pressure components in subsea operations. The following steps were taken to achieve this objective.

Material specification was written by a metallurgist with more than 40 years of experience writing specs for subsea forgings.

Forgings made by Forged Products, a company whose primary business is manufacturing large forgings for the subsea industry.

Heat treating was done by Lone Star Heat Treating, a company that has heat treated large forgings for the subsea industry for decades.

For the purpose of meeting the objective of the study, no special efforts were made to alter the tensile properties at the burst location to be different than what they would be using current manufacturing practices and API 6A requirements.

- API (March 22, 2017)

API Specification 6A Section 5.7.4.1 Paragraph 2 states, "*Test specimens shall be removed from the QTC such that their longitudinal centreline axis is wholly within the centre core 1/4T envelope for a solid QTC or within 3 mm (1/8 in) of the mid-thickness of the thickest section of a hollow QTC (see Figure 3)*". A prolongation QTC with a bore is considered a hollow QTC, and as specified above, the test specimens shall be removed from a locations within 3 mm (1/8 in) of the mid-thickness of the thickest section of a hollow QTC. However, the FPI drawing indicates the test specimens were removed from the 1/4T location on the OD side of the mid-thickness, so the test specimen removal was not in accordance with API Specification 6A, and the location used actually put the specimens closer to a quenched surface than specified by API Specification 6A.

The appropriate industry standard for material qualification to apply for forgings is API 20B, *Open Die-Shaped Forgings for Use in the Petroleum and Natural Gas Industry*, in application of API 17TR8. This API standard is referenced in API 17TR8 – 1st Edition, Bibliography.

Material qualification in accordance with API 6A PSL3 is not in compliance with API 17TR8. API 17TR8 elevated the material qualification and material quality to "PSL5" (refer to Section 5.3.4 of API 17TR8).

Note: ANL Attachment 1 - Description of Prolongation, is provided in **APPENDIX D.**

2. In Section 5.3 "Material Properties of Components" last paragraph. "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".

   Question: Was that true stress-strain curve adjusted to meet ASME criteria for perfectly plastic above ultimate strength?

- Argonne Response (March 14, 2017)

Yes, the procedures for true stress-strain material properties specified in ASME were followed. The tensile strength was limited to the true ultimate tensile strength. Attachment 2 shows the true stress strain test data provided by Franklyn Research and the stress-strain data in the ANSYS database.

  - API (March 22, 2017)

  Noted. ASME procedures were used to determine the true-stress true-strain material model.

  Note: ANL Attachment 2 – True Stress-Strain Data for Actual Material, is provided in **APPENDIX E.**

3. Low alloy steel forgings can be subject to reduced fracture toughness in the longitudinal direction as a result of segregation and banded microstructure.

   Question: What are the results of the microstructural examination for banding in the neck section?

- Argonne Response (March 14, 2017)

A *microstructural analysis was performed on three orthogonal planes at the burst location, 180 degrees from the burst, and in the thicker section away from the burst. Per this exam, the conclusion was: "Microstructure analysis showed the grain size average results varied between No.6 and No.7, consistent across both samples. Microstructure was observed as tempered martensite and at the burst locations showed elongated grain structures. This is consistent with normal expectations for such material.*

  - API (March 22, 2017)

  Request photographs to show banding or a lack of banding. The response did not address the banding which was the subject of the question.

4. In Section 5.1 (last bullet point), "Material Met all the Requirements of API 17TR8".

   Question: Did the ANL staff member who utilized the information in API 17TR8 realize that it is a Technical Report and it is to be used in conjunction with existing API specifications (see Normative References of API 17TR8).

- Argonne Response (March 14, 2017)

The material specification was written by Manuel Maligas, a Houston metallurgist who has been writing material specifications for subsea forgings for more than 30 years. The material specification for the test bodies is in Appendix A of the report. A review of the specification will confirm that the material meets the requirements of API 6A PSL3.

  - API (March 22, 2017):

  The appropriate material qualification standard to apply for forgings is API 20B, *Open Die-Shaped Forgings for Use in the Petroleum and Natural Gas Industry*, in API 17TR8 application. This API standard is referenced in API 17TR8 – 1st Edition, Bibliography.

  Material qualification in accordance with API 6A PSL3 is not in compliance with API 17TR8. API 17TR8 elevated the material qualification and material quality to "PSL5".

  An example of elevated material quality requirement related to non-destructive examination (NDE) acceptance criteria for surface indication/flaw is provided below:

Surface NDE (MT)

ASME VIII-3 / PSL5	0.125" or by design
API 6A PSL3	0.1875"

Additionally, ANL acquired material properties "…at least 1/4T and no less than 25mm from any heat treated surface where T is the thickness" (refer to Appendix A2 Section 11.0, Mechanical Properties). Please note that this does not comply with the requirements of API 6A Section 5.7.4.1 (Material qualification/Tensile and impact specimens), where "Test specimens shall be removed from the QTC such that their longitudinal centreline axis is wholly within the centre core 1/4T envelope for a solid QTC or within 3 mm (1/8 in) of the mid-thickness of the thickest section of a hollow QTC (see Figure 3).

ANL's used a hollow QTC – see photograph below from Attachment 1 – Description of Prolongation.

In regards to this photograph, are the yellow dots intended to represent the test specimen locations?

Note: ANL Attachment 1 – Description of Prolongation, is provided in **APPENDIX D.**

5. Appendix A2 (Material Specification), Section 5.0 (Heat Treatment), Bullet 2 "Forgings with Bores or Blind Holes Shall be Oriented to Allow for an Optimal Quench and to Minimize the Entrapment of Steam".

   Question: Can documentation be provided describing orientation in the quench tank with more complete description of the heat treatment process; i.e. sample orientation in furnace, thermocouple placement and quench tank circulation? Was this confirmed, by third-party?

   - Argonne Response (March 14, 2017):
   Attachment 3 provides additional information about the heat treatment process by Lone Star Heat Treating Co. (under contract and direction of Forged Products Inc.) including the orientation of the forging in the quench tank. Heat treatment was witnessed by Maurice Peltier and Manuel Maligas representing Aiken Engineering and Lee White representing Forged Products. An inspection report was not produced, but both Lee White and Manuel Maligas signed the heat treat chart.

     - API (March 22, 2017):
     Noted. FP Heat Treatment Information was provided (Attachment 3).

     Note: ANL Attachment 3 – Supplemental Data from Forged Products, is provided in **APPENDIX F.**

6. Appendix A2, section 10 "Material Qualification" end of first sentence "The QTC shall accompany the forged product through all heat treat cycle"

   Question: Was the QTC detached from the part prior to the heat treat cycle?

   - Argonne Response (March 14, 2017)
   Attachments 1 and 3 clearly show that the QTC was not detached prior to the heat treat cycle

     - API (March 22, 2017):
     Noted. FP Heat Treatment Information was provided (Attachment 3).

     Note: ANL Attachment 3 – Supplemental Data from Forged Products, is provided in **APPENDIX F.**

7. Appendix A2, Section 11, second paragraph "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 ¼ T and no less than 25mm from any heat-treated surface where T is the thickness"

   Question: Based on this section, the tensile tests and impact test specimens were not taken at the location specified by API 6A/API 17D for a hollow QTC. Please clarify.

   - Argonne Response (March 14, 2017)
   Awaiting additional information for full response.

     - API (March 22, 2017):
     See API comment to Item 1 and Item 4

8. Appendix A2, Section 4 "Hot Working Requirements", first bullet "The minimum forging reduction ratio shall be minimum of 4.0 to 1"

   Question: Was a microstructural analysis performed to verify that the dendritic structure had been completely broken down in the necked area and correlates to the structure of the mechanical test coupon?

   - Argonne Response (March 14, 2017)
   Yes, the dendritic structure was completely broken down as described in the Argonne response to Question 3. Attachment 3 includes a letter from the Forged Product's metallurgist, Mehdi Rahimi, stating that the cross-section reduction was 12 to 1 at the location of the burst.

     - API (March 22, 2017):
     ANL confirmed that there is no dendritic structure. However, with a 12:1 cross-section reduction ratio, it is expected to be anisotropic, e.g. transverse and longitudinal properties are not identical values

     Note: Attachment 3 – Supplemental Data from Forged Products, is provided in **APPENDIX F.**

9. Appendix A2, Section 11 "Mechanical Properties" "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 ¼ T and no less than 25mm from any heat-treated surface where T is the thickness"

   Question: Were mechanical properties (tensile and Charpy V-notch) taken in the circumferential (transverse) direction? Since ductile failure was in the longitudinal direction and hence driven by hoop stress.

   - Argonne Response (March 14, 2017)
   All Tensile tests were performed from specimen taken in the longitudinal direction.

     - API (March 22, 2017):
     Based on the stated 12:1 cross-section reduction ratio where the material is expected to be anisotropic (e.g. transverse and longitudinal properties are not identical values) and the burst direction is in the longitudinal direction (this is also pre-determine in ANL report, 2nd para on pg13), the transverse tensile properties are critical information to this study and analysis.

10. Appendix F1 (Material Documents from Forged Products, INC. Page F-3). In the chemical composition analysis, the PA carbon content (0.015 wt %) does not meet the carbon content range (0.10-0.15 wt %) indicated in the chemical composition table of Aiken Engineering Company material specification (Appendix A2, Section 2.0) for ASTM A182 F22 low alloy steel.

    Question: Is this a misprint, as the variance is one-order of magnitude?

    - Argonne Response (March 14, 2017)

    Yes, this is a typo. The actual carbon content is 0.15 wt % as was confirmed by a test report.

        - API: Noted. However, please provide the aforementioned test report

11. Appendix F “Miscellaneous Documents” Page F-34

    Question: Was there a third party witness and verification report created?

    - Argonne Response (March 14, 2017)

    The answer to this question is provided in the Argonne response to Question 5.

        - API: Noted.

API Materials Team’s Request for Data/Information

- Transverse tensile properties from prolongation QTC if available

    - API (March 22, 2017)

    Material task group is awaiting confirmation from ANL/Bruce Miglin on feasibility of transverse tensile property testing due to available materials remaining. API (March 22, 2017).

- Manufacturing Procedure Specification (MPS) for forgings used

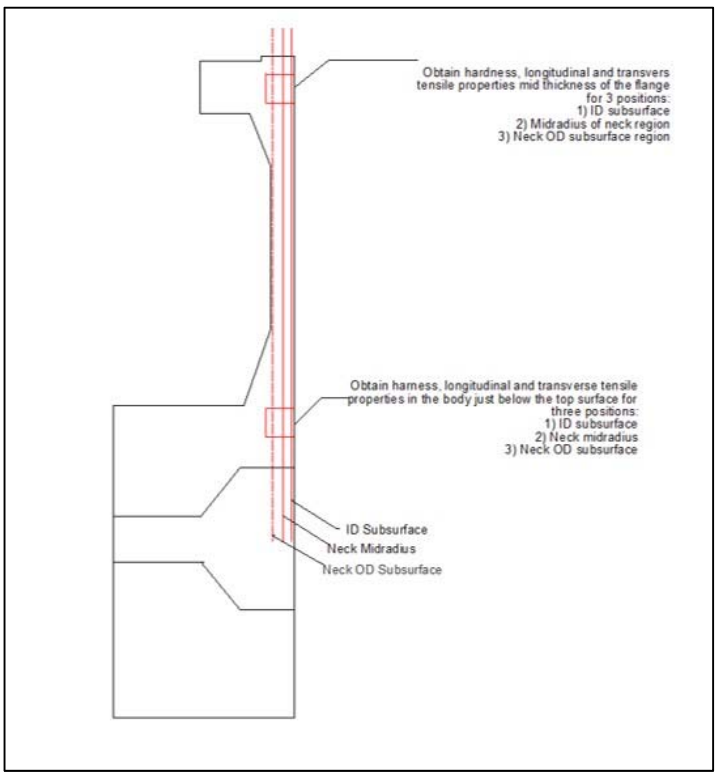
    - API (March 22, 2017)

    Typical elements to a MPS can be found in Section 5.3 and Section 5.4 of API 20B. They are, but not limited to:

        - the material specification;
        - the general process control variables and
        - size of starting material, cut weight and tolerances;
        - evaluation process used for incoming material and for determining cropped length of starting material;
        - hydrogen flake-control method (bake-out, slow cool, etc.), if applicable;
        - hot-working temperature range;
        - overall hot work ratio from starting material;
        - description of each forging operation, including general product configuration at the beginning and end of each
        - different type of hot work or forging operation and hot-work ratio for each step;
        - acceptable forging equipment for production;
        - inspection requirements;
        - NDE, if applicable
        - the heat treat parameters
        - furnace loading diagram, orientation and spacing of production parts;
        - heat treat times and temperatures for each processing cycle;
        - forging configuration and dimensions at time of heat treatment;
        - quenching medium and type of agitation (water/polymer, forced, horizontal; or vertical quench, ID/OD, etc.);

- quench medium start and finish temperature and transfer time to quench.

- Prolongation plan
    - API (March 22, 2017)
    ANL provided – Attachment 1
- 3rd Party verification report
    - API (March 22, 2017)
    ANL confirmed that 3rd Party Verification report is not available.
- Test Plan
  Metallography, Mechanical
    - API (March 22, 2017)
    Material task group is awaiting confirmation from ANL
- NDE
    - API (March 22, 2017)
    Ultrasonic Test reports: This will provide insight to material quality.
- Supplemental mechanical testing see attached Figure.
    - o Hardness, tensile and Charpy V-notch
    - API (March 22, 2017)
    Material task group is awaiting confirmation from ANL/Bruce Miglin on feasibility of supplemental mechanical testing due to available materials remaining.



C.3 FINAL CORRESPONDENCE WITH BSEE

The final interaction between the API TG Materials Team and BSEE/ANL to the questionnaire ended with BSEE's final email correspondence (March 28, 2017). The complete and final transcript to the post-test evaluation between the API TG Materials Team and BSEE are provided below. BSEE's dialogue (in red) with API TG's itemized responses (in blue) are provided below.

Thank you for taking the time to send your comments and clarifying remarks after the last telephone call we held together.

-Because the standards referenced in your email were not applicable at the time this project began, it would be helpful if you could re-couch your comments in light of the referenced standards in effect at the time of the ANL work began.

Please be advised the validity of API 6A 19th Edition was from February 2005 to April 2011, which would be invalid at time of ANL project.

For ANL project timeframe of 2015-2016, the applicable 6A would have been API 6A 20th Edition, published on October 2010, with the effective date of April 2011 to present. Therefore, the API TG Materials Team's referenced standards of API 20A 20th Edition and API 20B, referenced in 17TR8 1st Edition, would have been applicable to time of ANL project.

We have concerns with the premises and implications in our last teleconference and in this subsequent written clarification dated March 22, 2017. They are not generally aligned with the timing of the standards in force at the time of the project work. We recognize the industry is in the process of moving forward on tightening "quality and consistency" requirement in the new standards under development/released since this work, especially for forging. However, a most basic foundation of the project work was to not only follow appropriate standards but to adhere to generally accepted industry practices and use well established vendors that regularly serve the oil and gas industry.

Please be advised that the basis for HPHT equipment/technology development is applying design verification and validation processes that have been elevated from those in previous/existing API standards. In this regard, using only a standalone standard such as API 6A 19th Edition (referenced below, albeit the 19th Edition was invalid at time of ANL project) would not have appropriately captured the integrated design process for HPHT equipment outlined in API 17TR8.

Various API SCs have developed or ongoing development of its own HPHT requirements that addresses; design methodology, material characterization/qualification (forgings), risk assessment/FMEA/FMECA, QA/QC, etc. Samples of API HPHT standards are:

API PER 15K1: Protocol for Verification and Validation of High-pressure and High-temperature Equipment

SC17 TR8, HPHT Design Guidelines

SC19 TR1 (HPHT Design Guidelines), 11D1 (HPHT Annex), 14A (HPHT Annex)

SC16/ 16A Annex H – Extended Service Application (HPHT Service).

SC6/ 6A 21st Edition (significant changes to: PSL 4 to be more aligned with HPHT material and NDE requirements, validation for HPHT based on FMECA and reliability-based, etc.).

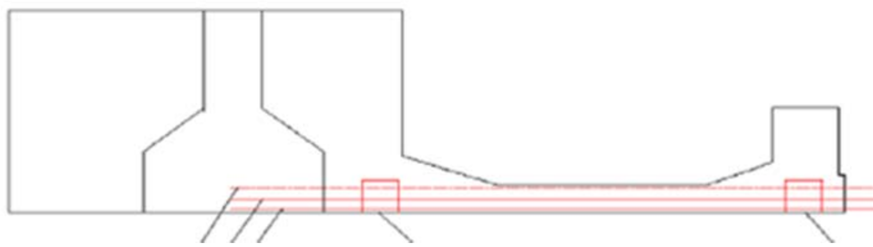
Further, there was considerable post-test materials analysis that are not normally associated with a production component.

We acknowledge that "post-test materials analysis would not be normally associated with a production component". However, the emphasis on the request for additional material analysis is to gather applicable data / material properties to support the design analysis and the failure mode (burst in longitudinal direction). The analysis and tests performed for this report were a research project and as such all pertinent information necessary in defining the results and conclusions should be obtained for completeness and accuracy.

Regrettably, there is not enough requisite remainder material for a sample from the neck area burst locations to perform the requested transverse test. Such a test is beyond the requirements of API 6A 19th edition (the standard in effect for this effort).

We acknowledge that the neck area at the burst location would not yield sufficient material and in addition to the phase transformation (strain-hardened) in this region, would not be valid material data.

However, the API TG Materials Team respectfully request an opportunity to proceed with review of the physical specimens as previously agreed upon in the last meeting. Specimens agreed as part of the physical inspection were: 1) those remnants from Aiken's office (some 35lbs of material, the prolongation) and 2) the actual test articles, the red boxes denoted in figure below:



Please be advised that the validity of API 6A 19th Edition was from February 2005 to April 2011, which would have been invalid at time of ANL project (2015).

The publication date for API 6A 20th Edition was October 2010, with the effective date of April 2011 to present. This Edition would have been applicable to ANL project start date (2015)

API 6A 19th edition was in effect at the time of design, manufacture and test to failure was the 19th edition. API specification 20B and 20C were not normative references in API 6A 19th edition.

Please be advised the validity of API 6A 19th Edition was from February 2005 to April 2011. For ANL project timeframe of 2015-2016, the applicable 6A would have been API 6A 20th Edition, published on October 2010, with the effective date of April 2011 to present.

It is correct that API 20B and 20C were not in the normative reference for API 6A 19th Edition. However, API 20B was published in April 2013 and would have been available for ANL project start time of 2015.

API RP 6HT is not in the normative references for 17TR8 but it is an applicable recommended practice for HPHT equipment heat treating procedures and is referenced in the ANL report Appendix A2 Material Specification

The version of 17TR8 in play at the time this project began was First edition, Feb 2015. API Specifications 20 B and 20 C were not normative references in that edition either.

API 17TR8 1st Edition has API 20B in the Bibliography. However, a critical element to 17TR8 integrated process is a FMECA to identify the failure mode (in this case, burst in the neck) and mitigate accordingly (in this case, tensile properties pertinent to the burst direction or transverse tensile properties)

With regard to the location of test samples, .25 T was in effect at the time. However, we had two independent, third party test samples taken, and despite the title on the report, one of those sets were in fact closer to .5 T. The requirement of the standard in effect was longitudinal only for .25 T. The quenched area was closer to the likelihood of a failure initiation point.

We respectfully disagree that the ".25T was in effect at the time".

The requirements for .5T (mid-thickness) in Section 5.7.4.1 in API 6A 19th Edition and API 6A 20th Edition did not change, in that "*Test specimens shall be removed from the QTC such that their longitudinal centreline axis is wholly within the centre core 1/4T envelope for a solid QTC or within 3 mm (1/8 in) of the mid-thickness of the thickest section of a hollow QTC (see Figure 3)*.

Future projects could include a transverse test to allow the possibility of further comparison.

The main objective for the request of transverse tensile properties is to correlate the material data pertinent to the burst direction. The ANL report made conclusions based on the calculated collapse pressure with tensile properties not correlated to the burst direction (failure mode). A critical element to 17TR8 integrated process is a FMECA to identify the failure mode (in this case, burst in the neck) and mitigate accordingly (in this case, tensile properties pertinent to the burst direction or transverse tensile properties

As mentioned in the earlier paragraph, the team desire to have an inspection of all remaining materials and test articles to gain a common understanding of the available material, opportunities and limitations. This teaming exercise will afford us to gain a common understanding of the exact status, options and possible paths forward as we share in this cooperative initiative to best characterize the material and the application of appropriate industry practices, BOD and mutual development of path forward

The API 17TR8 guideline document ballot versions' normative references are not in effect for the design, manufacture, and test to failure of the ANL devices.

Normative references do not necessarily define all HPHT design requirements. This is a good point and the reason why common industry practice leverages experienced engineers, accustomed with utilization of all most current and available standards and recommended practices available to the industry for a particular component. Rarely, if ever, does one single document cover all engineering considerations. Common to have peer reviews and gray beards to ensure we adopt best practices and avoid all available resources

The main objective for the request of transverse tensile properties is to correlate the material data pertinent to the burst direction. The ANL report made conclusions based on the calculated collapse pressure with tensile properties not correlated to the burst direction (failure mode). A critical element to 17TR8 integrated process is a FMECA to identify the failure mode (in this case, burst in the neck) and mitigate accordingly (in this case, tensile properties pertinent to the burst direction or transverse tensile properties

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If your team wants to offer potential comments on how all industry could be improved by applying the new normative references that should be addressed in position paper somewhere, which we might be inclined to assist in writing.

We have addressed these issues directly in the API 17TR8 2nd Edition – Annex D with detailed protocol procedures for material testing. Additionally, the upcoming OTC 2017 has an HPHT technical session scheduled for which the material characterizations (Annex D) and many other interesting HPHT topics will be presented.

To clear up a point we had a very detailed MPS formally approved by Aiken Engineering. These documents typically include proprietary cookbook methods that are not appropriate to place in a public report, or provide to the commenting group of metalurgists due to the conflict of interest for some of your team members in this set of comments. This would reduce the providers' ability to compete in the market place. We are evaluating whether a redacted version would be useful.

We certainly respect the confidential nature of companies and we will respect the preexisting guidelines set forth with BSEE, characteristic of such work endeavors.

Based upon your remarks, it appears that your team might be interested in seeing some sort of manufacture and test to the new standards and ballot 17TR8 procedures; perhaps a different material would be of interest. If so, I am willing to take up the discussion with our management. I understand that DrillQuip conducted a similar simplified test which showed a 7% difference between the modelling and actual failure for F22 very recently. I look forward to seeing their results written up.

We will advise on the progress of DeepStar Phase 2 – Validation of Design Analysis for which we have forwarded an initial slide pack.

DrilQuip is receptive to provide its ASME VIII-3 Burst Test research/presentation, via teleconference.

Additionally, we would request ANL/BSEE review the data provided in ICPVT paper by Susumu Terada, 2009 (attached), as related the 145 burst test samples used to support ASME VIII-3 LRFD factor.

I believe that companies who are firmly convinced of the benefit the recent changes in the ballot edition of 17TR8 and the 20th edition of API 6A will be applying those changes in their efforts. BSEE regulations have not caught up with these new developments in the industry's point of view.

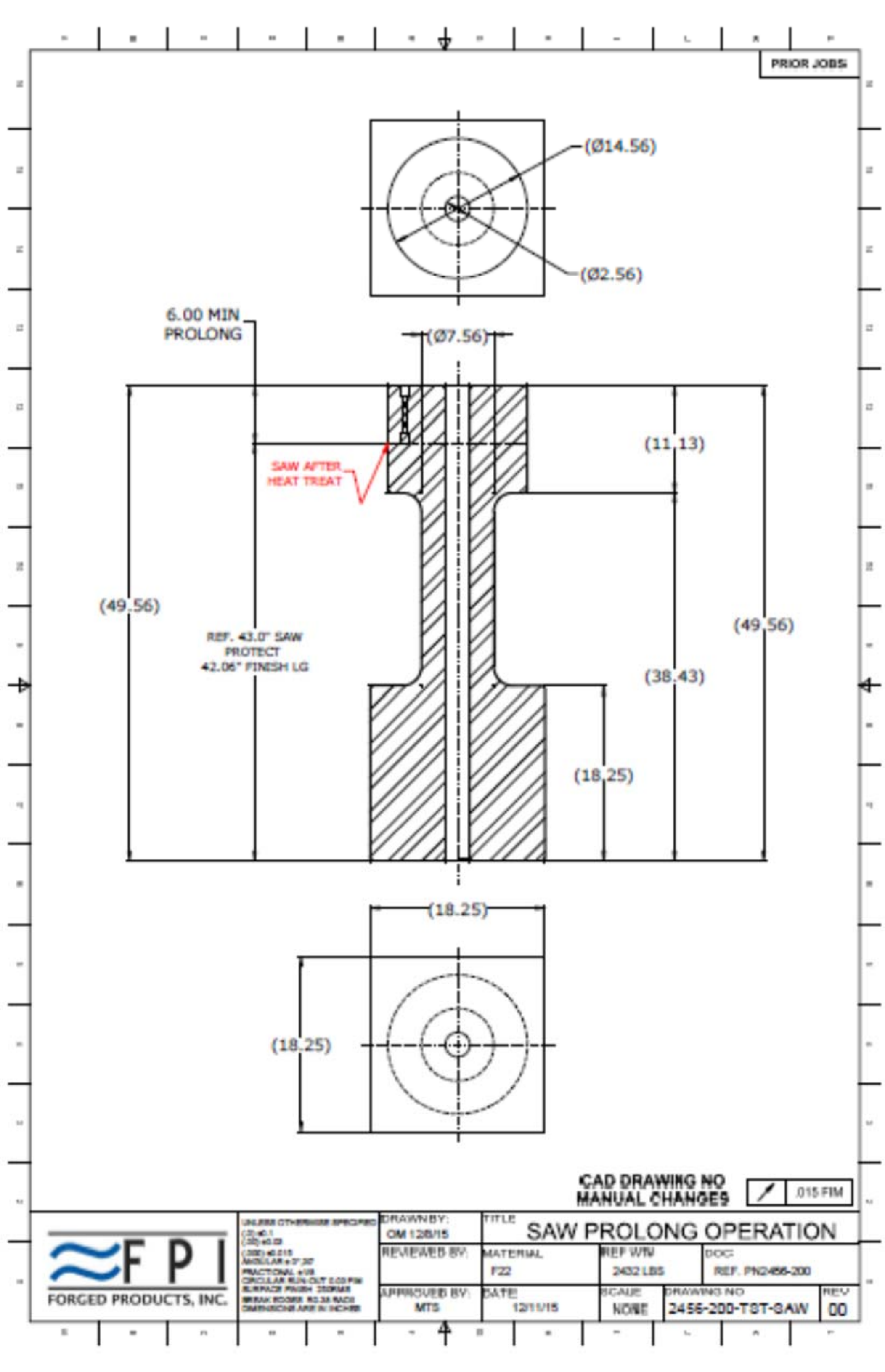
ANL should consider specifying conclusions/recommendations with consideration to the many facets to HPHT equipment design and the industry codes/standards addressing these challenging HPHT issues, such as, 17TR8 2nd Edition Annex D, API 20B/20C, API 19TR1, etc.

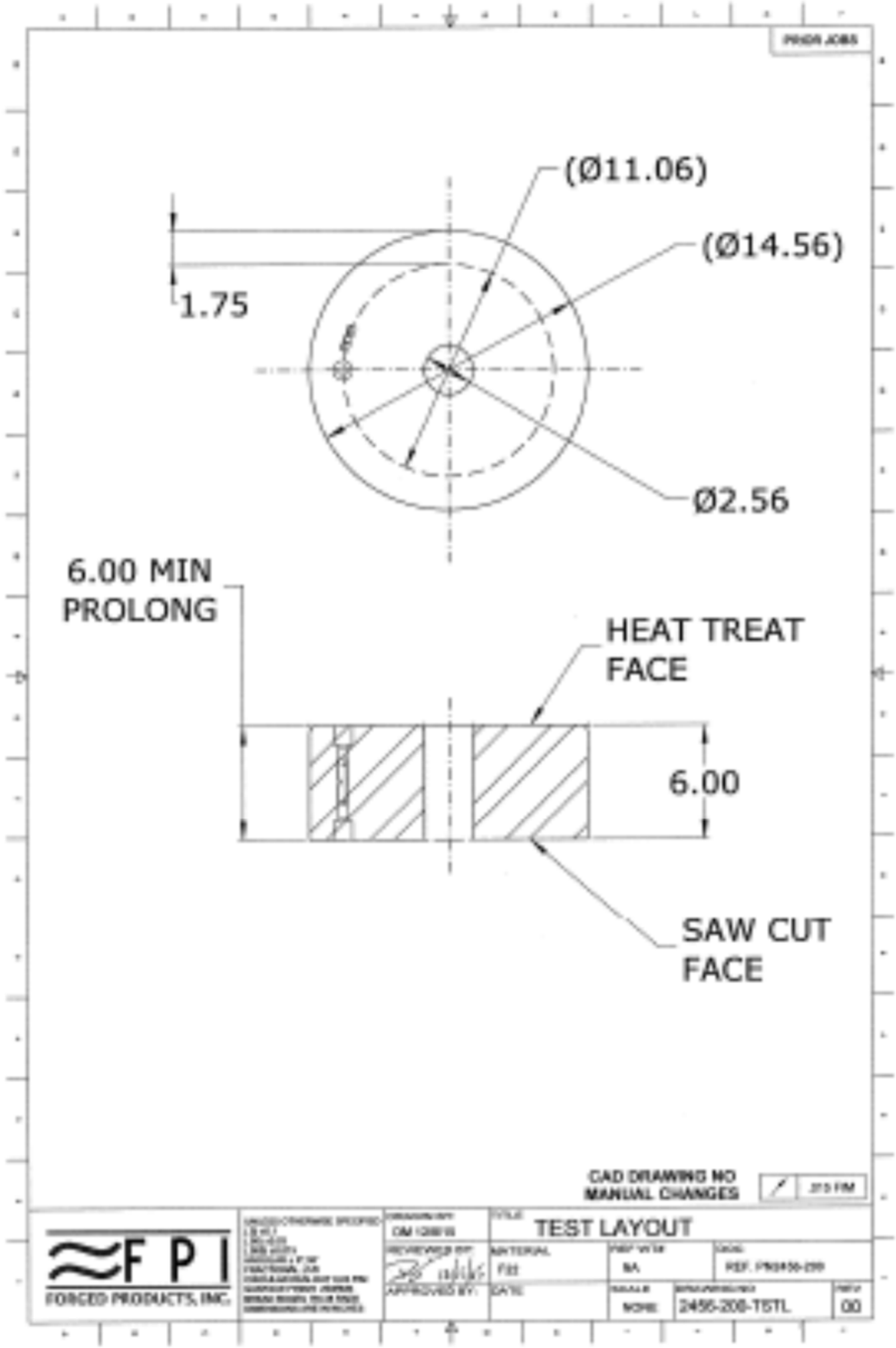
Additionally, industry can assist with defining an HPHT R&D project for further evaluation of HPHT equipment and design requirements.

API 6A is working on its 21st Edition and it will use von Mises as the stress criterion for linear-elastic analysis.

It should be noted API 6A 20th Edition recognized the use of ASME VIII-3 (refer to Section 4.3.3 – Other End Connectors, Bodies and Bonnets, of API 6A

APPENDIX D: ANL ATTACHMENT 1 – DESCRIPTIONS OF PROLONGATION


PRIOR JOBS
(Ø14.56)
(Ø2.56)
6.00 MIN
PROLONG
(Ø7.56)
(11.13)
SAW AFTER
HEAT TREAT
(49.56)
REF. 43.0" SAW
PROTECT
42.06" FINISH LG
(49.56)
(38.43)
(18.25)
(18.25)
(18.25)
CAD DRAWING NO
MANUAL CHANGES
.015 FIM
FPI
FORGED PRODUCTS, INC.
DRAWN BY:
REVIEWED BY:
APPROVED BY:
MTS
TITLE
SAW PROLONG OPERATION
MATERIAL
F22
REF WT
2432 LBS
DOC
DATE
12/11/15
SCALE
NONE
DRAWING NO
2456-200-TST-SAW
REV
00

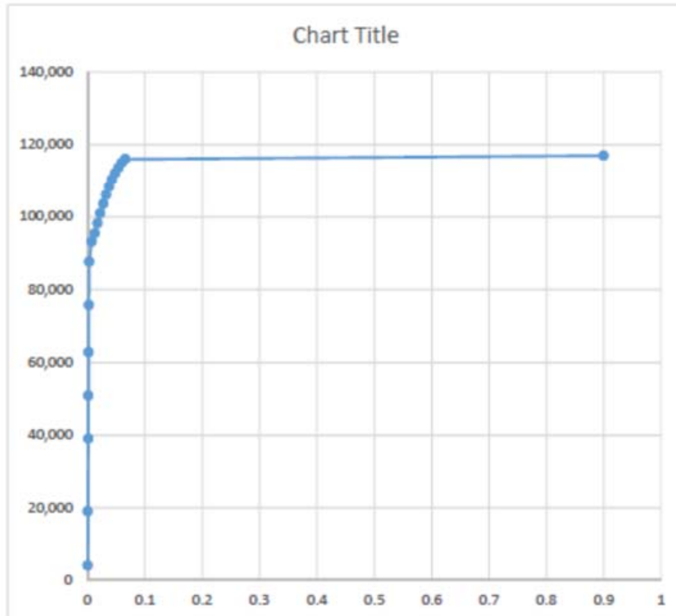

PRIOR JOBS
(Ø11.06)
(Ø14.56)
1.75
Ø2.56
6.00 MIN
PROLONG
HEAT TREAT
FACE
6.00
SAW CUT
FACE
CAD DRAWING NO
MANUAL CHANGES
FPI
FORCED PRODUCTS, INC.
TEST LAYOUT
2456-208-TSTL
00


SAW

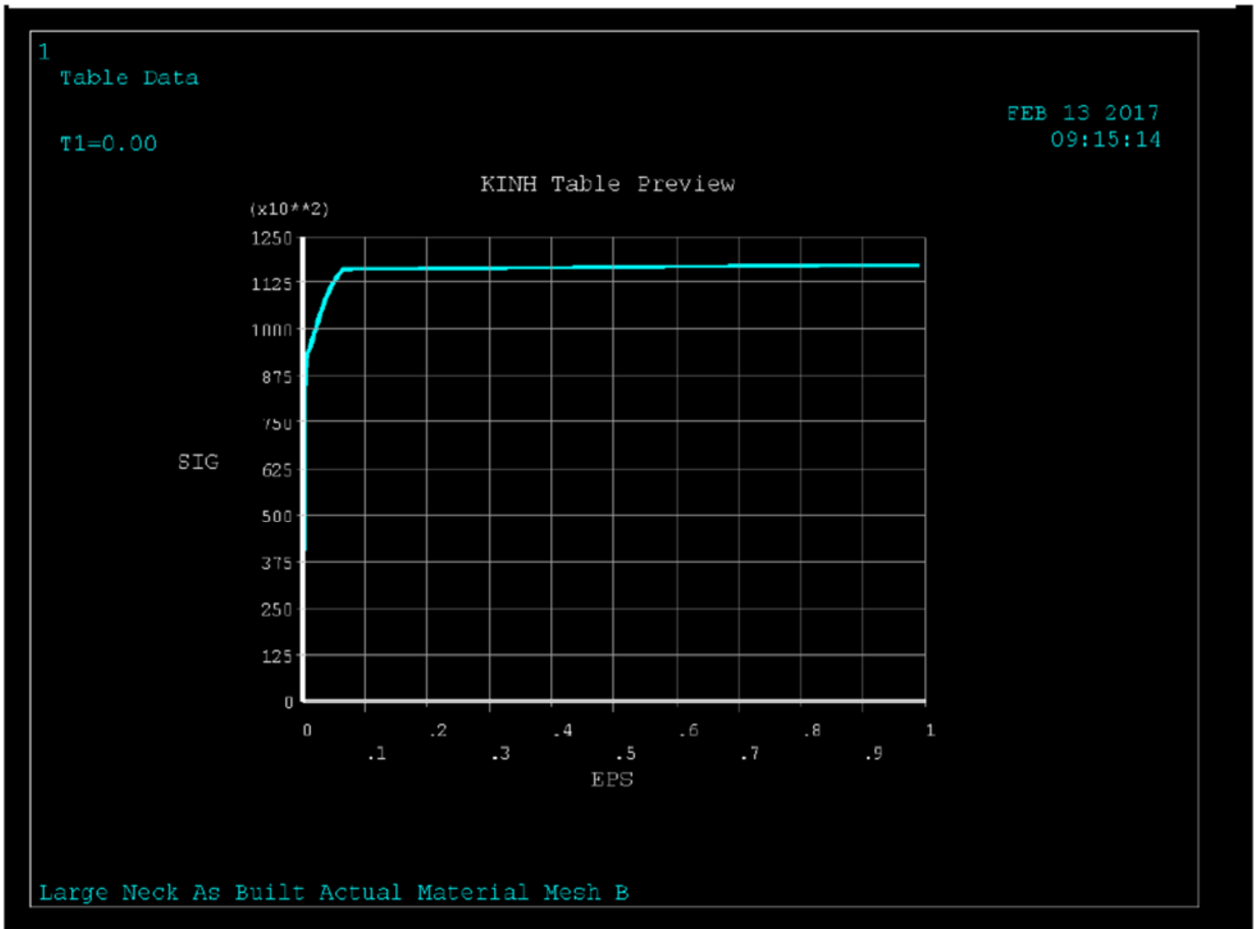
APPENDIX E: ANL ATTACHMENT 2 – TRUE STRESS-STRAIN DATA FOR ACTUAL MATERIAL

Actual Test Body Material

Stress (psi)	Strain in/in	
4,032	0.000128	4,032
18,900	0.0006	18,900
39,089	0.001248	39,089
50,990	0.001627	50,990
62,860	0.002015	62,860
75,679	0.002476	75,679
87,640	0.003198	87,640
93,093	0.007168	93,093
95,400	0.012518	95,400
98,173	0.017689	98,173
100,980	0.022638	100,980
103,620	0.02751	103,620
106,080	0.032525	106,080
108,350	0.037724	108,350
110,320	0.042948	110,320
112,040	0.048334	112,040
113,560	0.053984	113,560
114,870	0.059696	114,870
115,940	0.065734	115,940
116,910	0.9	116,910



Actual True-Stress Data from Franklyn Research Associates



True Stress-Strain Data from ANSYS DB File

APPENDIX F: ANL ATTACHMENT 3 – SUPPLEMENTAL DATA FROM FORGED PRODUCTS

Forged Products, Inc.
6505 N. HOUSTON-ROSSLYN ROAD
HOUSTON, TEXAS 77091
Phone 713-462-3416
Fax 713-460-9404

FORGED PRODUCTS, INC.

Dear Maurice,

It was nice speaking with you Thursday afternoon in regards of raised question of whether the thin section has higher or lower tensile properties than prolongation.
To answer this question it is necessary to look at the as forged configuration as well as heat treatment criteria.

It is our understanding that the failure occurred during the Burst Test at the thin wall section (so called piping or pipe section) of the valve test body (SWRI Project 18.21910 test report/analysis).

To forge the test valve bodies, the raw materials (Heat no. AH450) was forged to a bloom then reduced to <u>a shaft with 16" diameter X 51.60" long in the center</u> and <u>two square blocks identical at both ends (19.20" square - 27.20" long)</u>.Both piping area and the prolongation are from middle section forging (shaft) and had experienced tremendous cross section reduction (calculated to be around 12:1). These sections had formed fine grain structures before rough machine and heat treating. The mechanical testing results endorsed the solidity and strength of the materials in this area.

The pipe section is around 20" long and the failure during the Burst test was somewhere 5" to 25" away from the prolongation section. Since we quenched the parts with prolongation section facing the water jet first, this area (flange/Prolongation) had received the outmost agitation and definitely is the most hardened although the agitation in the quench tank at our vendors heat treat facility is quite uniform also this heat in general (Cr-Mo Steel specially F22) has an inclination to form a Bainitic microstructure which would produce a uniform microstructure through the entire cross section with appropriate heat treatment. (At least within range of 8-10" cross section).

That being said, it is expected to see the same or just slightly lower mechanical properties in thicker section and the same or slightly over in the thinner section (1/4T of thicker section and 1/2T of thin wall); we ran the simulation at FPI and reviewed the jominy end quench test to realize the hardness and UTS projection and the numbers are pretty consistent through the entire cross section. Not only this, our considerable experience with similar F22 heats indicates the tensile properties in the thin section where failure occurred would be the same or just slightly different from the prolongation section. To clear the case based on the facts we propose to perform:

1. A Tensile test from mid wall of thin section (piping) to endorse above theory and past experiences;
2. A Tensile test on thicker section (opposite thick section at relative testing location -2" below surface) to indicate the tensile properties are relatively consistent through the entire test body.

If the test results are significantly different from prolongation test results then further discussion and testing is required.

Should you or others have any comments or questions please don't hesitate to call me

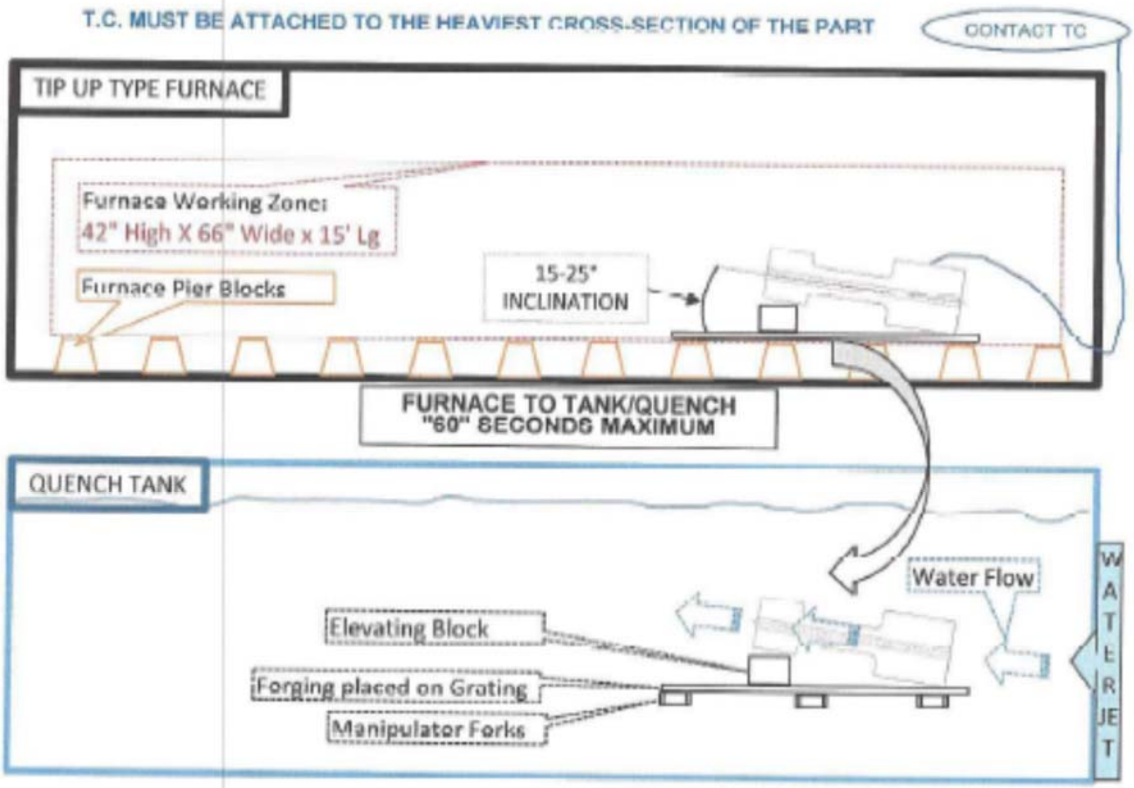
Best regards

Mehdi Rahimi
Cell Number: 210-422-2217

FPI FORGED PRODUCTS, INC.	**FORGED PRODUCTS INC** **FURNACE LOADING MAP**	**FLM-87473** REV. 01
CORRESPONDING MPP No. 2456-200 Rev 02		
DEVELOPED BY:	R. CENDEJAS	DATE 12/1/2015
USE IN CONJUNCTION WITH FPI PROCEDURE NO# 7.5.1.8 & SHTDS No 87473		
	(THERMAL TREATMENT) NORMALIZE, QUENCH AND TEMPER OPERATION	
APPROVED VENDOR	LONE STAR HEAT TREAT (LSHT)	
FURNACE(S)	GAS-FIRED BATCH TIP UP TYPE , CERTIFICATION PER AMS2750F TEMPER (+/- 15F) TOL.	
QUENCH MEDIA	WATER , MAX STARTING TEMP 100 DEG.F , MAX ENDING TEMP 120 DEG.F	
TANK ID/NO# 253	CAPACITY : 70,000 (GALS) , MEDIA COOLING EQUIPMENT : CHILLER	
AGITATION TYPE	FORCED FLOW "VERTICAL AND HORIZONTAL" (ADJUSTABLE FLOW)	
EQUIPMENT CAP.	HANDLING MANIPULATOR : REF. 20,000 LBS MAX.	
BATCH / LOAD QTY	6,100 LBS MAX	
LOAD PLAN BASED ON WORKING ZONE		

BELOW LOADING APPLIES TO NORMALIZE, QUENCH AND TEMPER CYCLES

T.C. MUST BE ATTACHED TO THE HEAVIEST CROSS-SECTION OF THE PART



MEDIA FLOW THRU BORE

NOTICE... THE LOADING OF THE FORGINGS IN THE FURNACE SHALL BE SUCH THAT THE PRESENCE OF ONE PART DOES NOT ADVERSELY AFFECT THE HEAT TREATMENT RESPONSE OF ANY OTHER FORGING WITHIN THE SAME HEAT TREATMENT LOAD.

SKETCH IS NOT PROPORTIONAL!!!

Lone Star Heat Treating Corp.
Customer Receipt

QAF-015

Date: 01/05/2016
Cust #: 002202
Cust PO#: 87473
Sticker #: 669

Customer: FORGED PRODUCTS
Due Date:
Location: db

Material: F22

Qty: 2

Wo #: 543959
Phone #: (713) 462-3416
Contact: HEATHER RAMIREZ
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

A

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.

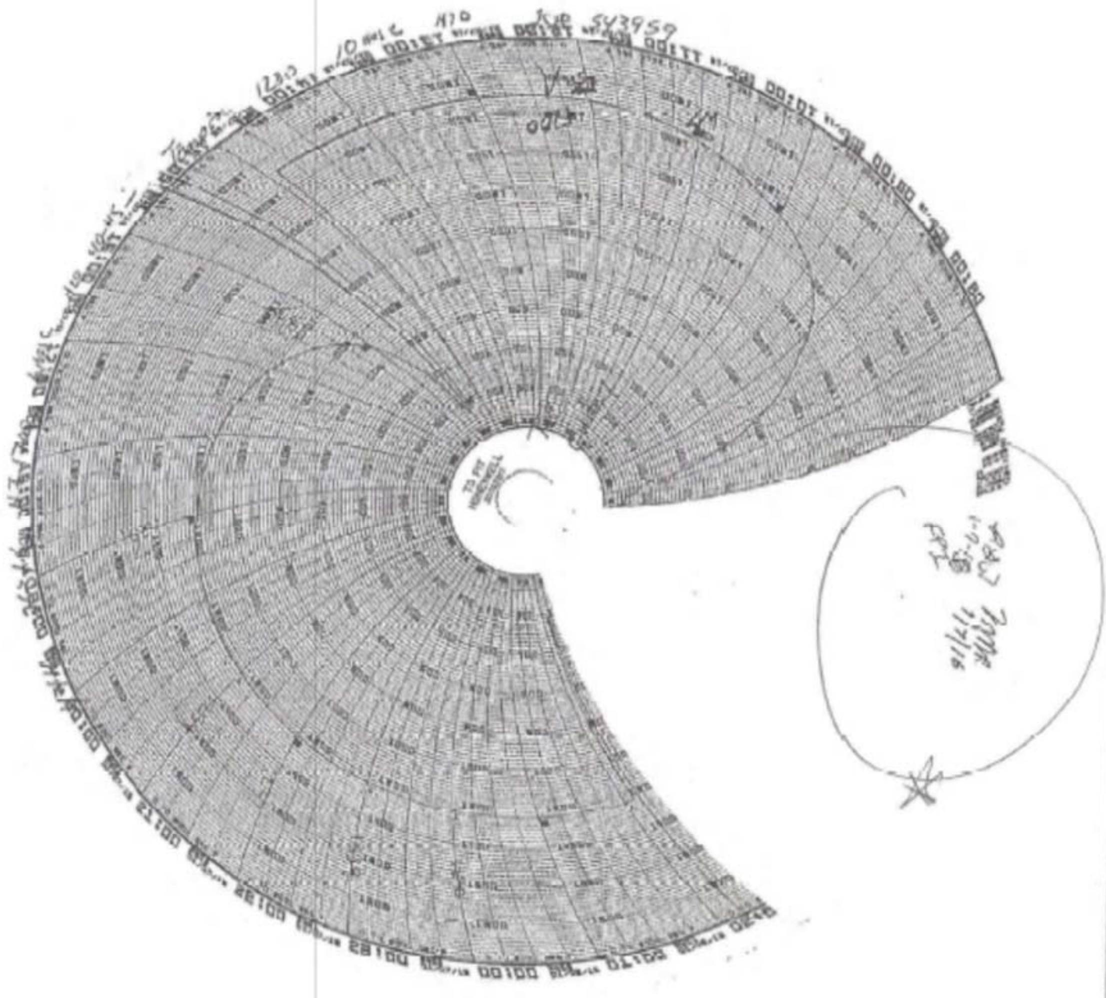
PO #2456-11-10-2015 LN 1, PN 2456-200 Rev 0, Heat #AH450, Lot #543659, SN AH450-2E1 & AH450-2E2

LONE STAR HEAT TREATING CORP.

Certificate of Heat Treatment
Work Order No: 543959

3939 Blaffer
Houston, Tx 77020
Ph. 713-672-6616
Fax (713) 672-9509

Cust No: 002202
Cust Name: FORGED PRODUCTS
Cust PO#: 87473
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



PO #2456-11-10-2015 LN 1, PN 2456-200 Rev 0, Heat #AH450, Lot #543659, SN AH450-2E1 & AH450-2E2

NOMENCLATURES

CP	collapse pressure
ID	inside diameter
ksi	1000 pounds per square inch
OD	outside diameter
psi	pound per square inch
R	outside radius
t	wall thickness

REFERENCES

- API Specification 6A, *Specification for Wellhead and Christmas Tree Equipment*
- API Specification 11D1, *Packers and Bridge Plugs*
- API Specification 14A, *Specification for Subsurface Safety Valve Equipment*
- API Specification 16A, *Specification for Drill-through Equipment*
- API Specification 17D, Design *and Operation of Subsea Production Systems—Subsea Wellhead and Tree Equipment*
- API Specification 20B, *Open Die Shaped Forgings for Use in the Petroleum and Natural Gas Industry*
- API Standard 6X, *Design Calculations for Pressure-containing Equipment*
- API Recommended Practice 17G, *Recommended Practice for Completion/Workover Risers*
- API Technical Report 1PER15K-1, *Protocol for Verification and Validation of High-pressure High-temperature Equipment*
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