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September 10, 2003

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Subject: USNRC Docket No. 71-9261, TAC L23474
HI-STAR 100 Certificate of Compliance 9261
HI-STAR License Amendment Request 9261-2, Revision 1
Overpack Closure Bolt Analysis Supplement

References: 1. Holtec Project 5014

Dear Sir:

Enclosed please find Supplement 31 to Holtec Report HI-2012786, which addresses the reduction in the minimum HI-STAR overpack closure bolt torque value requested in the subject CoC amendment request. Also enclosed are replacement pages for the main text of the calculation package for your records. Please note that while the first page of the enclosed material indicates "Holtec Proprietary," the enclosed information is not proprietary. This proprietary designation on the "Document Issuance and Revision Status" sheet applies to other information that is part of this calculation package, which is already in your possession and is not included with this submittal.

Please contact the undersigned if you require additional information.

Sincerely,

Brian Gutherman, P.E.
Manager, Licensing and Technical Services

Enclosures: As Stated

Document ID: 5014497

Distribution: Mr. Meraj Rahimi, USNRC (Cover letter with enclosure)
NRC Document Control Desk (Cover letter with enclosure)

NMSS01

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DOCUMENT ISSUANCE AND REVISION STATUS[1]

DOCUMENT NAME: STRUCTURAL CALCULATION PACKAGE FOR HI-STAR OVERPACK

DOCUMENT NO.:	HI-2012786	CATEGORY: ☐ GENERIC
PROJECT NO.:	5014	☒ PROJECT SPECIFIC

Rev. No.[2]	Date Approved	Author's Initials	VIR #	Rev. No.	Date Approved	Author's Initials	VIR #
0	5/19/03	CWB	660709				
1	7/18/03	CWB	868438				

DOCUMENT CATEGORIZATION

In accordance with the Holtec Quality Assurance Manual and associated Holtec Quality Procedures (HQPs), this document is categorized as a:

☒ Calculation Package[3] (Per HQP 3.2)

☐ Technical Report (Per HQP 3.2) (Such as a Licensing Report)

☐ Design Criterion Document (Per HQP 3.4)

☐ Design Specification (Per HQP 3.4)

☐ Other (Specify):

DOCUMENT FORMATTING

The formatting of the contents of this document is in accordance with the instructions of HQP 3.2 or 3.4 except as noted below:

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Notes

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2. A revision to this document will be ordered by the Project Manager and carried out if any of its contents is materially affected during evolution of this project. The determination as to the need for revision will be made by the Project Manager with input from others, as deemed necessary by him.
3. Revisions to this document may be made by adding supplements to the document and replacing the "Table of Contents", this page and the "Revision Log".

REVISION LOG

Revision 0 – Original Issue

The original issue of this report contains Supplements 1 through 30.

Revision 1 – Added Supplement 31.

PREFACE

This Calculation Package has been prepared pursuant to the provisions of Holtec Quality Procedures HQP 3.0 and 3.2, which require that all analyses utilized in support of the design of a safety-related or important-to-safety structure, component, or system be fully documented such that the analyses can be reproduced at *any time in the future* by a specialist trained in the discipline(s) involved. HQP 3.2 sets down a rigid format structure for the content and organization of Calculation Packages that are intended to create a document that is complete in terms of the exhaustiveness of content. The Calculation Packages, however, lack the narration smoothness of a Technical Report, and are not intended to serve as a Technical Report.

This Calculation Package acts as a compendium of all calculations supporting dry cask storage work for the HI-STAR 100 Overpack that require supporting documentation that is not part of a stand-alone report. These calculations may support statements or summaries made in the HI-STAR FSAR (HI-2012610, Chap.2 or 3), the HI-STAR SAR (HI-951251, Chap. 2), or they may be supporting calculations for an ECO or 72.48 evaluation. A discussion of the technical work included may later be incorporated in the FSAR as applicable. Each calculation is self-contained and has a cover sheet that briefly identifies the purpose of the calculation and ties it to any associated ECO, etc.. Assumptions, references to finite element work, etc. are within the individual calculation. Therefore, this report contains no "list of files" and its storage location is per the footer on this page. The HQP requirements for calculation packages are followed to the extent practical within each calculation.

It is intended that updates to the report, in the form of supplements containing one or more individual calculations, will occur at reasonable intervals to maintain the document current. No new calculation may be referenced (outside of its use in supporting an ECO where it is reviewed as part of the ECO process) until it is officially made part of a supplement in this report and the report revision updated.

When this report is updated, the changed or added pages will be:

1. Review sheet

2. Rev. log

3. Table of Contents

4. A complete new supplement containing all added calculations. A calculation cover sheet is part of the each individual calculation, and all individual cover sheets are included in the supplement with the calculation. Supplements may consist of a single calculation, or a group of calculations addressing related component modifications.

5. Appendix A – Holtec Approved Computer Program List (if necessary)

Revisions shall be made, as necessary, to maintain the report as a living document.

1.0 INTRODUCTION AND SCOPE

This Calculation Package is compiled to provide archival information to supplement the material presented in the HI-STAR FSAR (HI-2012610) [11.2.2] and the HI-STAR SAR (HI-951251) [11.2.3], and to support any engineering change orders (ECO) and 72.48 modifications. In particular, this Calculation Package contains calculations related to the HI-STAR overpack, including all of its versions. Similar Calculation Packages have been created for the MPC, HI-STORM overpack, and HI-TRAC transfer cask. The material presented in this Calculation Package is not needed to comprehend the material presented in the above-mentioned Technical Report (which are self-contained documents in full compliance with the USNRC regulations), unless the reader wishes to examine the computational details. Herein, we document only specific "singular" calculations that support a specific FSAR or SAR result. Where a large body of calculations is necessary to support an FSAR or SAR conclusion (such as high seismic supports for anchored casks, for example), this calculation package is supplemented by other specialized reports that deal exclusively with the single topic requiring a substantial calculation effort. The results from these specialized calculation packages are simply summarized in the FSAR or SAR.

Because of its function as a repository of analyses performed on the subject of its scope, this document will be revised only if an error is discovered in the computations or the equipment design is modified. Additional analyses in the future, supporting either a new amendment or a change supported by a 72.48 evaluation, will be added as numbered supplements to this Package. (Each time a supplement is added or the existing material is revised, the revision status of this Package is advanced to the next number and the Table of Contents is amended).

In order to fully understand the format and layout of this Calculation Package, it is necessary to understand its two key attributes. First, unlike most calculation packages, this package contains a multitude of discrete analyses, all of which share a common body of input data, but are otherwise entirely distinct in their methods, models, and computer simulations. This calculation package is in fact a compendium of an array of distinct calculations.

All new SAR and FSAR submittals or 72.48 evaluations requiring structural calculations are supported by the work herein and by other specialized calculation packages.

2.0 METHODOLOGY

Calculation specific supplements are attached to this report. In general, the problem descriptions are provided in the introductory section of each calculation in the HI-STAR FSAR [11.2.2] or HI-STAR SAR [11.2.3]. The problem descriptions, unique to each calculation, include the description of the component to be analyzed, the nature and source of the applied loading on the component, and the acceptance criteria. Where the calculation is performed to support a 72.48 evaluation, and does not yet appear in summary form in any of the Technical Reports, the calculation itself is complete insofar as having a full description of the problem, methodology, etc.

All structural calculations are either based on classical strength of materials solutions, or are based on finite element numerical analysis. Each calculation contains detailed explanation of the analysis methods. As noted earlier, this Calculation Package contains supporting calculations for results that may only be summarized in the HI-STAR FSAR [11.2.2] or HI-STAR SAR [11.2.3]. Where the work supports a detailed appendix that is included in the FSAR or SAR, no detailed text is included within the supporting calculation herein except to describe the nature of the supporting calculation.

3.0 ACCEPTANCE CRITERIA

This calculation package contains one or more supplements that deal with specific calculation items. If acceptance criteria are different for the individual calculations, then the appropriate acceptance criteria associated with each individual calculation are stated within the specific supplement.

The design criteria are compiled in Chapters 2.0 of the FSAR [11.2.2] and the SAR [11.2.3]. The design criteria represent the basis for the acceptance criteria for the design of the HI-STAR overpack. The stress limits for the steel structure of the overpack are listed in the HI-STAR FSAR in Table 2.2.12. (The ASME Code stress allowable associated with the stress limits are listed in the FSAR in Tables 3.1.6 through 3.1.17.) The applicable design codes for cask components are listed in the HI-STAR FSAR in Tables 2.2.6 and 2.2.7.

4.0 ASSUMPTIONS

In general, each calculation in this package contains a unique set of conservative analysis assumptions. In most cases these assumptions are listed under a separate section in each of the calculations; for some calculations that supplement work already detailed in the FSAR or in another calculation, references are made to the originating document section for the assumptions.

5.0 INPUT DATA

Input data is provided in the calculation supplements as needed for the specific analysis. Data input requirements for geometry, material properties, and applicable load combinations are provided below:

The sources for the input data that are specific to a calculation are provided within that calculation.

The sources of the input data that are repetitively used are listed as references in Section 11. The global sources of input data are compiled below for quick reference. All dimensional data for the HI-STAR overpack is obtained from the drawings [11.2.4].

HI-STAR Weight:	Table 3.2.1 of [11.2.2]
Center of Gravity:	Table 3.2.2 of [11.2.2]
Design Pressure:	Table 2.2.1 of [11.2.2]
Component Design Temperature:	Table 2.2.3 of [11.2.2]
Mechanical Properties:	Tables 3.3.1 through 3.3.5 of [11.2.2]
Material Strength:	Tables 3.1.6 through 3.1.17 of [11.2.2]

6.0 COMPUTER CODES

The main section of this report is written using Microsoft Word (Office 2000), while the calculation supplements are prepared using MathCAD (Version 2000 unless otherwise noted below), or are also written in MS Word and contain manual calculations and/or finite element results. The computer codes used are documented and referenced within each supplement.

All computer codes used for the analysis and design of HI-STAR overpack are approved under Holtec's QA program. A complete listing of all of the computer codes used in this report, including all supplements, is maintained in Appendix A.

7.0 ANALYSES

Analyses to support the FSAR and SAR amendments and 72.48 evaluations are contained in supplements. As new supporting calculations are added, the revision log and the table of contents will note the additions or modifications to this document.

8.0 COMPUTER FILES

All relevant computer files associated with this calculation package are archived on the Holtec Server. A directory listing appropriate to the supplements is included within each supplement.

9.0 RESULTS OF ANALYSES

All calculations are documented, as appropriate, in the HI-STAR FSAR [11.2.2] or the HI-STAR SAR [11.2.3] along with an evaluation of the analysis. The analysis evaluation contains details of the analysis results and the comparison of the result to applicable code allowables. The design adequacy is also conclusively demonstrated by the computation of the positive margins of safety. The specific calculations within each supplement also evaluate, if applicable, the margins of safety and the results where applicable.

10.0 SUMMARY AND CONCLUSIONS

This Calculation Package supports the structural integrity evaluation of the HI-STAR overpack designs required by the 10CFR71 and 10CFR72 Submittals and also supports interim 72.48 evaluations. All analysis calculations and documentation meet Holtec's Q.A requirements and procedures.

11.0 REFERENCES

11.1 Generic References

A comprehensive list of all references that may be applicable to some or all of the specific calculations performed within this document are given below. Not all references need to be cited within this document to be contained in this comprehensive listing.

[11.1.1] NUREG-0612, "Control of Heavy Loads at Nuclear Power Plants," United States Nuclear Regulatory Commission, July 1980.

[11.1.2] ANSI N14.6-1993, "American National Standard for Special Lifting Devices for Shipping Containers Weighing 10000 Pounds (4500 kg) or More for Nuclear Materials," American National Standards Institute, Inc.

[11.1.3] D. Burgreen, Design Methods for Power Plant Structures, Arcturus Publishers, 1975.

[11.1.4] NUREG/CR-1815, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick".

[11.1.5] ASME Boiler & Pressure Vessel Code, Section II, Part D, 1995 Edition with Addenda through 1997.

[11.1.6] American Concrete Institute, "Building Code Requirements for Reinforced Concrete (ACI 318-95) and Commentary - ACI 318R-95", or Latest Edition.

[11.1.7] American Concrete Institute, "Code Requirements for Nuclear Safety Related Structures" (ACI-349-85 to95) and Commentary (ACI-349R-85 to95).

[11.1.8] ASME Boiler & Pressure Vessel Code, Section III, Subsection NF, 1995 Edition with Addenda through 1997.

[11.1.9] ASME Boiler & Pressure Vessel Code, Section III, Appendices, 1995 Edition with Addenda through 1997.

[11.1.10] ASME Boiler & Pressure Vessel Code, Section III, Subsection NB, 1995 Edition with Addenda through 1997.

[11.1.11] Theory of Elastic Stability, S.P. Timoshenko and J. Gere, McGraw Hill, 2nd Edition.

[11.1.12] Marks Standard Handbook for Mechanical Engineering, 9th Ed.

[11.1.13] ASME Boiler and Pressure Vessel Code, Section III, Subsection NG, 1995 Edition with Addenda through 1997.

[11.1.14] Manual of Steel Construction – Load and Resistance Factor Design, 1st Edition, AISC, 1986.

[11.1.15] Manual of Steel Construction, AISC.

[11.1.16] Mechanical Engineering Design, J. Shigley, and C. Mischke, 5th Edition, McGraw-Hill, 1989.

[11.1.17] Mechanical Design of Heat Exchangers and Pressure Vessel Components, K.P. Singh, and A.I. Soler, Arcturus Publishers, 1984.

[11.1.18] Strength of Materials, S.P Timoshenko, Vols. I, and II, 3rd Edition, Van Nostrand, 1955.

[11.1.19] Mechanical Design and Systems Handbook, H. Rothbart, Editor, 2nd Edition, McGraw-Hill, 1985.

[11.1.20] Theory of Elasticity, S.P. Timoshenko, and J. Goodier, 3rd Edition, McGraw-Hill, 1951.

[11.1.21] Theory of Elastic Stability, S.P. Timoshenko, and J.M. Gere, 2nd Edition, Mcgraw-Hill, 1961.

11.2 Specific References

In addition to the comprehensive reference list provided in Section 11.1, additional project specific references are cited below. If any reference cited below conflicts with an identical reference in Section 11.1 (e.g., a different applicable year for a Code or Standard), then the specific reference takes precedence.

[11.2.1] Not used.

[11.2.2] HI-STAR FSAR, HI-2012610, Rev. 1.

[11.2.3] HI-STAR SAR, HI-951251, Rev. 9.

[11.2.4] Holtec Drawings:

1397, Sheets 1 thru 7 (HI-STAR 100)

1398, Sheets 1 thru 3 (HI-STAR 100)

1399, Sheets 1 thru 3 (HI-STAR 100)

3930, Sheet 1 thru 2 (HI-STAR 100 ASSEMBLY)

12.0 LIST OF SUPPLEMENTS

Supplement No.	Description	In Support of	Revision	Specific Locations in FSAR†
1	Tie Down Calculations Supporting 10CFR71.45(b) Evaluation	HI-STAR SAR	Proposed Rev. 10	2.5.2, Table 2.5.1, Table 2.5.2
2	Calculations Supporting Specific Computations in the SAR Text (formerly Appendix 2.R)	HI-STAR SAR	Proposed Rev. 10	2.5.2.7, 2.6.1.4.1, 2.7.1.3.1
3	Top Flange Bolt Hole Analysis	HI-STAR SAR	Rev. 9	2.6.1.3.3, 2.7.3.4, Appendix 2.A
4	Lifting Trunnion Stress Analysis	HI-STAR SAR	Rev. 9	2.5.1.1, 2.5.1.2.2, 2.5.3, Appendix 2.B
5	Overpack Protection Lip Deformation Analysis	HI-STAR SAR	Rev. 9	Appendix 2.I
6	Code Case N-284 Stability Calculations (formerly Appendix 2.J)	HI-STAR SAR	Proposed Rev. 10	2.6.1.3.1.3, Table 2.6.3, Table 2.6.10, 2.7.1.1, 2.7.1.3, 2.7.3.3.1, 2.7.5, Table 2.7.2, Table 2.7.3, Table 2.7.7, Table 2.7.8
7	Calculation of Dynamic Load Factors	HI-STAR SAR	Rev. 9	2.6.1.4.1, 2.6.5, Appendix 2.K
8	Fabrication Stresses	HI-STAR SAR	Rev. 9	2.6.1.3.2.2, 2.6.1.3.3, Table 2.6.11, Appendix 2.Q
9	Overpack Closure Plate Lifting Bolts	HI-STAR SAR	Rev. 9	2.5.1.2.1, Appendix 2.S
10	Stress Analysis of Overpack Closure Bolts	HI-STAR SAR	Rev. 9	2.6.1.3.2.3, 2.6.1.3.3, Table 2.6.11, 2.7.1.1, 2.7.2, Table 2.7.8, Appendix 2.U, Appendix 2.AD
11	Stress Analysis of Overpack Closure Bolts During Fire	HI-STAR SAR	Rev. 9	2.7.3.3.3, Table 2.7.3, Appendix 2.V

Supplement No.	Description	In Support of	Revision	Specific Locations in FSAR[†]
12	ANSYS Finite Element Results for Overpack	HI-STAR SAR	Rev. 9	2.6.1.4.2.1, 2.6.1.4.3, 2.6.2.3, Table 2.6.5, Table 2.6.9, Table 2.6.12, Table 2.6.13, 2.7.1, 2.7.3.3.2, Table 2.7.3, Table 2.7.5, Table 2.7.6, Appendix 2.P, Appendix 2.AD, Appendix 2.AE
13	Impact Limiter Attachment Bolts	HI-STAR SAR	Rev. 9	Appendix 2.H (changed to Appendix 2.A in Proposed Rev. 10), Appendix 2.AF
14	Cask Under Three Times Dead Load	HI-STAR SAR	Rev. 9	2.5.1.2.2, 2.5.1.3, Appendix 2.AG
15	Overpack Closure Bolt Capacity – Normal Condition of Transport	HI-STAR SAR	Rev. 9	2.6.2.3, Appendix 2.AL
16	Stress Analysis of HI-STAR 100 Enclosure Shell Under 30psi Internal Pressure	HI-STAR SAR	Rev. 9	2.6.1.3.2.4, Appendix 2.AM
17	Pocket Trunnion Stress Analysis	HI-STAR SAR	Rev. 9	Appendix 2.AN
18	HI-STAR Deceleration Under Postulated Drop Events and Tipover	HI-STAR FSAR	Rev. 1	3.4.4.4.1, 3.4.9, Appendix 3.A, Appendix 3.X
19	Response of Cask to Tornado Wind Load and Large Missile Impact	HI-STAR FSAR	Rev. 1	3.4.8, Appendix 3.C
20	Lifting Trunnion Stress Analysis	HI-STAR FSAR	Rev. 1	3.4.3.1, 3.4.3.2.1, Appendix 3.D
21	Stress Analysis of Overpack Closure Bolts	HI-STAR FSAR	Rev. 1	3.4.4.3.2.3, Appendix 3.F
22	Missile Penetration Analysis	HI-STAR FSAR	Rev. 1	3.4.8, Table 3.4.5, Appendix 3.G

Supplement No.	Description	In Support of	Revision	Specific Locations in FSAR†
23	Code Case N-284 Stability Calculations	HI-STAR FSAR	Rev. 1	3.4.4.3.1.7, 3.4.4.3.2.5, Table 3.4.19, Appendix 3.H
24	Fabrication Stresses	HI-STAR FSAR	Rev. 1	3.4.4.3.2.2, Appendix 3.H, Appendix 3.L
25	Calculation of Dynamic Load Factors	HI-STAR FSAR	Rev. 1	3.4.4.4.1, Appendix 3.M, Appendix 3.X
26	Cask Under Three Times Dead Load	HI-STAR FSAR	Rev. 1	3.4.3.2.2, 3.4.3.3, Appendix 3.Y
27	Top Flange Bolt Hole Analysis	HI-STAR FSAR	Rev. 1	Appendix 3.Z
28	Stress Analysis of Overpack Closure Bolts Under Cold Conditions of Storage	HI-STAR FSAR	Rev. 1	3.4.5, Appendix 3.AE
29	Stress Analysis of Overpack Closure Bolts for the Storage Fire Accident	HI-STAR FSAR	Rev. 1	Appendix 3.AF
30	Stress Analysis of HI-STAR 100 Enclosure Shell Under 30psi Internal Pressure	HI-STAR FSAR	Rev. 1	3.4.4.3.2.6, Appendix 3.AG
31	Stress Analysis of Overpack Closure Bolts and Top Flange Bolt Holes (formerly Appendices 2.A, 2.U, and 2.V)	HI-STAR SAR	Proposed Rev. 10	2.6.1.3.2.3, 2.6.1.3.3, Table 2.6.11, 2.7.1.1, 2.7.2, 2.7.3.3.3, 2.7.3.4, Table 2.7.3, Table 2.7.8

† References to appendices indicate the location of the calculation in Revision 0 of the HI-STAR FSAR or Revision 9 of the HI-STAR SAR. All of the appendices (with the exception of Appendix 3.A) were removed from the HI-STAR FSAR in Licensing Amendment Request 1014-2 (i.e., Proposed Rev. 1) and transferred to Calculation Packages. Likewise, all of the appendices (with the exception of Appendices 2.A and 2.B) were removed from the HI-STAR SAR in Licensing Amendment Request 9261-2 (i.e., Proposed Rev. 10) and transferred to Calculation Packages.

HOLTEC CALCULATION

Title: Stress Analysis of Overpack Closure Bolts and Top Flange Bolt Holes

PROJECT No. – ECO No. – REV. No.:	**5014 - -**		
Calculation Package No. for MPC ( ) HI-TRAC ( ); HI-STAR (X); HI-STORM ( ); Other ( )	**HI-2012786**	**Supplement No.:**	**31**

CALCULATION SUMMARY INFORMATION

Scope: The calculations, which appeared previously as Appendices 2.A, 2.U, and 2.V in Revision 9 of the HI-STAR SAR, have been revised to support LAR 9261-2 Rev. 1, Supplement 3 (i.e., Proposed Rev. 10C). These three appendices deal specifically with the stresses in the overpack closure bolts and the top flange bolt holes under various loading conditions. The changes include:

1. an increase in the gasket seating load from 3600lbf/in to 4400 lbf/in;
2. a decrease in the closure bolt torque from 2895 +/- 90 ft-lb to 2000 +250/-0 ft-lb;
3. an increase in the overpack accident internal pressure from 125 psi to 200 psi.

Method: The calculations employ the methodology of NUREG/CR-6007 ("Stress Analysis of Closure Bolts for Shipping Casks") and FED-STD-H28/2A ("Federal Standard Screw – Thread Standards for Federal Services").

UPDATES REQUIRED TO FSAR, TO DRAWINGS

Text Modifications (Chapter): HI-STAR SAR Subsections 2.1.2.1, 2.7.3.3.2, 2.7.3.3.3, 2.7.3.4

Table Modifications: HI-STAR SAR Tables 2.1.1, 2.7.3, 2.7.8

Drawing Modifications: None

REVISION LOG

Rev. No.	Preparer Initials /Date	Reviewer Initials /Date
0	CWB / 7-17-03	
1		
2		

The Calculation presented herein provides the analytical basis to adopt the proposed change contemplated by the ECO (see Note 1). The Design Verification Checklist (DVC) documenting the technical review of this calculation is associated with the applicable ECO in the computerized ECO network database.

This Calculation is technically reviewed and QA validated in accordance with HQP 5.1.

This Calculation is archived in the above-referenced Calculation Package as a labeled supplement. This document may be shared as an autonomous piece of work with external organizations and revised, if necessary, to secure their concurrence to the proposed change.

Note 1: All analyses performed to respond to a query or to initiate a design change are archived in a new Calculation Package or added to an existing Calculation Package as a Supplement and the revision number of the Calculation Package is advanced. A supplement to a Calculation Package may consist of one analysis or a number of discrete analyses (each containing this cover sheet) supporting a number of ECOs.

APPENDIX 2.A - TOP FLANGE BOLT HOLE ANALYSIS

2.A.1 Introduction

This appendix contains an analysis of the threaded holes for the closure bolts in the top flange of the HI-STAR 100 Overpack. The objective of the analysis is to demonstrate that the design of the threaded region is conservative and that the limiting region for structural integrity evaluation is the bolt shaft in tension rather than the threaded region in shear.

The following steps are performed in this analysis:

1. It is shown that the depth of engagement of the closure bolts in the top flange is adequate.

2. It is demonstrated that the limiting section for evaluating the design is the bolt shaft, as opposed to thread shear in either the bolt or in the flange.

3. A lower bound on the preload required to ensure that the hypothetical accident load can be supported without closure plate/top flange separation is determined.

2.A.2 Composition

This appendix was created using the Mathcad (version 6.0+) software package. Mathcad uses the symbol ':=' as an assignment operator, and the equals symbol '=' retrieves values for constants or variables.

2.A.3 References

[2.A.1] E. Oberg and F.D. Jones, *Machinery's Handbook*, Fifteenth Edition, Industrial Press, 1957.

[2.A.2] FED-STD-H28/2A, *Federal Standard Screw-Thread Standards for Federal Services*, United States Government Printing Office, April, 1984.

[2.A.3] K.P. Singh and A.I. Soler, *Mechanical Design of Heat Exchangers and Pressure Vessel Components*, First Edition, Arcturus Publishers, Inc., 1984.

[2.A.4] Letter from Mr. Joe Kedves of American Seal & Engineering Co., Inc. to Mr. Steve Agace of Holtec International, dated September 6, 1996.

[2.A.5] FEL-PRO Technical Bulletin, N-5000 Nickel Based - Nuclear Grade Anti-Seize Lubricant, 8/97.

2.A.4 Assumptions

1. Thermal effects are neglected in this analysis, but material properties are taken at design temperatures.

2. In determining the minimum preload required for the closure bolts, the overpack closure plate is assumed to be rigid.

3. In determining the most stress limiting area, the capacity of each section is based on ASME Code Section III, Subsection NB stress limits.

4. The design temperature for the closure bolts is set as 350°F.

2.A.5 Input Data

Figure 2.A.1 shows the HI-STAR 100 Overpack closure plate/top flange interface schematically. A free-body diagram of the system used to determine the minimum preload is given in Figure 2.A.2. The following is a list of the basic input parameters required to perform the calculations. All dimensions are obtained from the Design Drawings in Section 1.5.

The number of closure plate bolts (including two short bolts over the lifting trunnions),

$$NB := 54$$

The nominal radius of the closure bolt shaft, $a := 0.8125 \cdot in$

The major diameter of the bolt, $d_b := 2 \cdot a$

The cross-sectional area of the bolt unthreaded section, $A_d := \pi \cdot \frac{d_b^{\,2}}{4}$

The thread engagement length of the closure plate short bolts, $L_{eng} := 2.75 \cdot in$

The diameter of the sealing gasket compression load, $D_{seal} := 71.565 \cdot in$

The gasket seating load (from Reference 2.A.4), $f_{seal} := 4400 \cdot \frac{lbf}{in}$ (2 gaskets)

The internal pressure of the overpack, $P_{int} := 100 \cdot psi$

For conservatism the internal pressure of the overpack is set equal to the design internal pressure of the MPC under normal conditions (see Table 2.2.1). This accounts for the unlikely failure of the MPC pressure boundary.

The upper bound MPC weight (from Table 3.2.4), $W_{mpc} := 90000 \cdot lbf$

The upper bound closure plate weight (from Table 3.2.4), $W_{lid} := 8000 \cdot lbf$

The design maximum drop acceleration (from Table 3.1.2), $GLoad_{des} := 60$

The root area of the bolt is the area derived from the minor diameter of the bolt. The following values are obtained from page 100 of Reference 2.A.3 and page 987 of Reference 2.A.1.

The root area of the bolt, $A_{root} := 1.680 \cdot in^2$

The pitch diameter of the bolt, $d_{pitch} := 1.542 \cdot in$

The minor diameter of the bolt, $dm_{ext} := 1.472 \cdot in$

The minor diameter of the threaded hole, $dm_{int} := 1.490 \cdot in$

The number of threads per inch, $N := 8 \cdot in^{-1}$

From the tables in Section 3.3, the yield and ultimate strengths of the closure plate/top flange material (at the design temperature of 400 °F) and the bolt material (at the bolt design temperature of 350 °F) are:

The forging material ultimate strength, $Su_{forg} := 64600 \cdot psi$

The forging material yield strength, $Sy_{forg} := 32200 \cdot psi$

The forging material design stress intensity, $Sm_{forg} := 21500 \cdot psi$

The bolt material ultimate strength, $Su_{bolt} := 172050 \cdot psi$

The bolt material yield strength, $Sy_{bolt} := 139500 \cdot psi$

The bolt material design stress intensity, $Sm_{bolt} := 46500 \cdot psi$

2.A.6 Length of Engagement/Strength Calculations

In this section, it is shown that the length of thread engagement is adequate, and that tensile stress in the bolt governs the analysis. The method and terminology of Reference 2.A.2 are adhered to.

The thread pitch, $p := \frac{1}{N}$

On page 987 of Reference 2.A.1, the height of a sharp V-thread (H) is defined as:

$$H := 0.86603 \cdot p$$

$$H = 0.108\,in$$

The thread depth of an internal thread (i.e. the forging top flange bolt hole) is determined as:

$$D_{int} := \frac{5}{8} \cdot H \qquad D_{int} = 0.068\,in$$

and the thread depth of an external thread (i.e. the bolt) is determined as:

$$D_{ext} := \frac{17}{24} \cdot H$$

$$D_{ext} = 0.077\,in$$

The major diameter of the bolt can be determined from the minor diameter and the thread depth of an external thread as:

$$dmaj_{ext} := dm_{ext} + 2 \cdot D_{ext}$$

$$dmaj_{ext} = 1.625\,in$$

As defined on page 103 of Reference 2.A.2, the bolt thread shear area is determined as:

$$A_{bolt} := \pi \cdot N \cdot L_{eng} \cdot dm_{int} \cdot \left[\frac{1}{2 \cdot N} + .57735 \cdot \left(d_{pitch} - dm_{int} \right) \right]$$

$$A_{bolt} = 9.528\,in^2$$

and the forging thread shear area is determined as:

$$A_{frg} := \pi \cdot N \cdot L_{eng} \cdot dmaj_{ext} \cdot \left[\frac{1}{2 \cdot N} + 0.57735 \cdot \left(dmaj_{ext} - d_{pitch} \right) \right]$$

$$A_{frg} = 12.428\,in^2$$

The load capacities of the bolt, bolt thread and the top flange thread, based on the appropriate Subsection NB stress limits under normal conditions, are:

$$LC_{bolt} := 2 \cdot Sm_{bolt} \cdot A_{root}$$

$$LC_{bolt} = 156240\,lbf$$

$$LC_{thrd} := 0.6 \cdot Sm_{bolt} \cdot A_{bolt}$$

$$LC_{thrd} = 265833\,lbf$$

$$LC_{forg} := 0.6 \cdot Sm_{forg} \cdot A_{frg}$$

$$LC_{forg} = 160316\,lbf$$

If the load capacity of the forging thread is greater than the load capacity of the bolt, then the bolt tension will govern. If the margin of safety calculated below is greater than 0.0, then the bolt tension will govern in this analysis.

$$MS := \frac{LC_{forg}}{LC_{bolt}} - 1 \qquad MS = 0.03$$

These calculations confirm that all strength checks can be based on the bolt tensile capacity, and that the depth of engagement is adequate to support the loads.

2.A.7 Determination of Minimum Preload

In this section, a lower bound estimate of preload requirements for the overpack closure bolts is obtained. The load on the closure plate due to design internal pressure is determined as:

$$L_{press} := \pi \cdot \frac{D_{seal}^{2}}{4} \cdot P_{int} \qquad L_{press} = 402246\,lbf$$

The required gasket seating load (f_{seal}), in pounds per unit circumferential length, is specified by the gasket manufacturer as:

$$f_{seal} = 4400\frac{lbf}{in}$$

and the total gasket load can therefore be determined as: $L_{gask} := f_{seal} \cdot \pi \cdot D_{seal}$

$$L_{gask} = 989244\,lbf$$

The force applied to the closure plate by quasi-static impact loads is determined as:

$$G_{load} := GLoad_{des} \cdot \left(W_{mpc} + W_{lid}\right) \qquad G_{load} = 5880000\,lbf$$

The preload torque needs only to be set to seal the joint under steady state loads or to insure gasket seating, whichever governs. Under an accident, the only criteria is that the bolt meets the allowable stress under accident conditions (i.e. momentary joint decompression is permitted as long as the bolt does not yield). Appendix 2.U demonstrates that allowable stress conditions are met using the preload set herein under normal and accident loads. However, to provide additional conservatism to the joint by minimizing the potential for gross joint unloading, the preload is increased to a value that also maintains comprression under normal loading plus 80% of the peak impact load. This insures an adequate safety factor for bolt stress under normal conditions and minimizes the potential for a gross unloading of all bolts during a hypothetical accident (short-duration non-uniform loading around the bolt circle).

The total preload force required to seat the gasket or seal under steady state loads plus 80% of impact load is:

$$Preload := L_{press} + .80 \cdot G_{load} \qquad Preload = 5106246\,lbf$$

and the preload per bolt is therefore:

$$Bolt_{pl} := \frac{Preload}{NB} \qquad Bolt_{pl} = 94560\,lbf$$

The nominal nut factor is 0.15 [2.A.5] with an allowable tolerance of +/- 5%. The maximum torque corresponds to a nut factor of 0.1575, and the value is:

$$T_{pl} := 0.1575 \cdot Bolt_{pl} \cdot dm_{ext} \qquad T_{pl} = 1826.9\,lbf \cdot ft$$

Therefore, the minimum bolt torque, which equals the nominal value minus an acceptable tolerance, must exceed the value of T_{pl} which is calculated above. For the HI-STAR 100 System, where the final torque for the closure bolts is specified as 2,000 +250/-0 ft-lb in Table 7.1.3, the minimum bolt torque is 2,000 ft-lb.

The bolt preload force becomes a maximum when the maximum bolt torque is combined with the minimum nut factor. This combination leads to the maximum preload stress in the bolt. For a minimum nut factor of 0.1425, which is five percent less than the torque coefficient in Appendix 1.C, the preload force is calculated as:

$$T_{max} := 2000 \cdot ft \cdot lbf + 250 \cdot ft \cdot lbf$$

$$Bolt_{pl} := \frac{T_{max}}{0.1425 \cdot dm_{ext}} \qquad Bolt_{pl} = 128719\,lbf$$

and the corresponding preload stress is determined as:

$$\sigma := \frac{Bolt_{pl}}{A_{root}} \qquad \sigma = 76618\,psi$$

The average stress in the closure bolts, according to Subsection NB, must not exceed twice the design stress intensity. Thus, the ratio of the allowable stress to the closure bolt stress must be greater than 1.0. This ratio, under the loadings examined in this appendix, is determined as:

$$\frac{2 \cdot Sm_{bolt}}{\sigma} = 1.21$$

which is greater than 1.0.

2.A.8 Conclusion

The analyses presented in this appendix demonstrate that the length of thread engagement is sufficient and conservative, and that the load capacity of the bolts is less than the load capacity of the threaded region in the top flange. In addition, the minimum bolt preload (and corresponding bolt torque) required to maintain compression on the seals during normal operation is established. The preload torque is set to insure a large safety margin on bolt stress during normal operation.

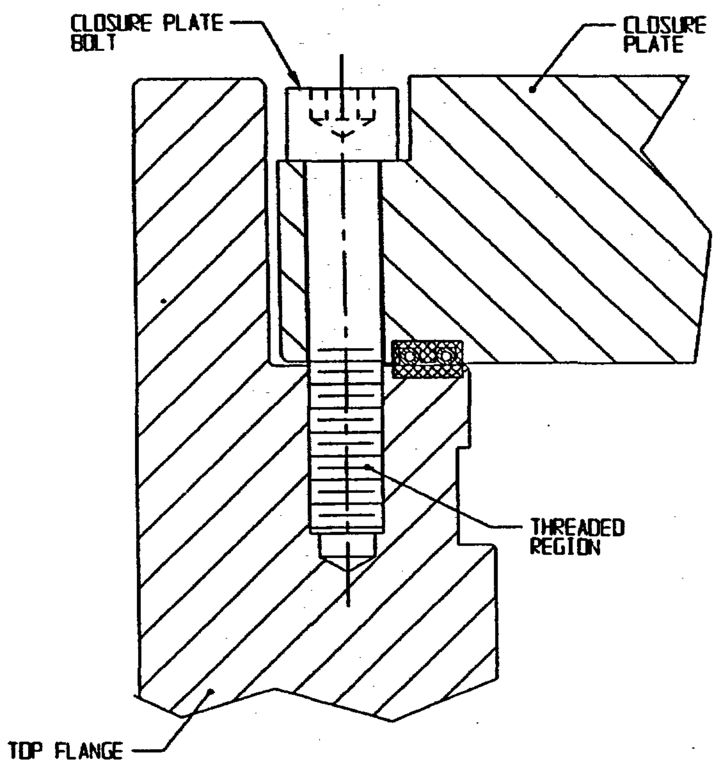

FIGURE 2.A.1; SCHEMATIC OF CLOSURE PLATE/TOP FLANGE INTERFACE

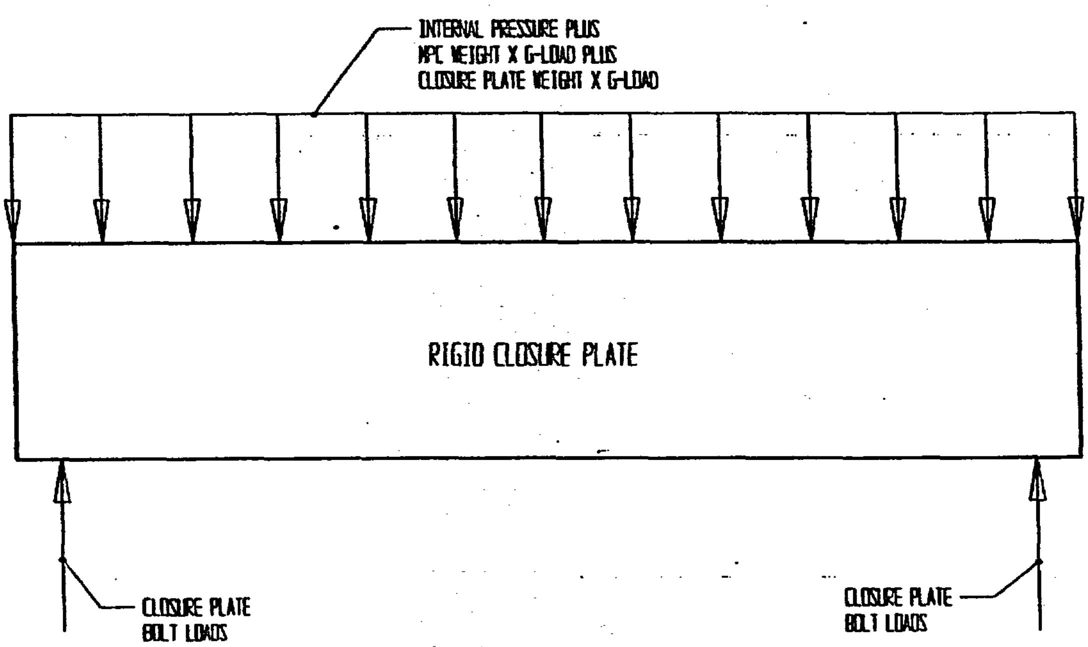

FIGURE 2.A.2; FREE BODY DIAGRAM FOR THE DETERMINATION OF MINIMUM CLOSURE PLATE BOLT PRELOAD

APPENDIX 2.U - STRESS ANALYSIS OF OVERPACK CLOSURE BOLTS

2.U.1 Introduction

This appendix contains a stress analysis of the HI-STAR 100 Overpack closure bolts. The purpose of the analysis is to demonstrate that stresses in the closure bolts do not exceed allowable maximums.

The HI-STAR 100 package can be used for both transportation and storage of spent nuclear fuel. Loadings from the normal and hypothetical accident conditions of transport as specified in Federal Regulation 10 CFR part 71 are more severe than the loadings placed on the bolts in the storage condition.

The complex interaction of forces and moments in bolted joints of shipping casks has been investigated in Reference 2.U.1, resulting in a comprehensive method of closure bolt stress analysis. That method is employed here. The analysis is presented in a step-by-step form for each loading combination considered. For each set of formulas or calculations used, reference to the appropriate table in [2.U.1] is given. Tables 4.3, 4.4, 4.5, and 4.7 are reproduced directly from [2.U.1] and placed at the end of this appendix to assist the reader. Where necessary, the formulas are modified to reflect the particulars of the HI-STAR system. For example, the loads due to impact from the MPC are applied as a pressure band near the bolt circle rather than as a uniform pressure load since the MPC contacts the overpack closure plate only around the periphery. Further, since the HI-STAR 100 closure lid has a raised face outside of the bolt circle, no prying forces can develop from loads directed outward (such as internal pressure or impact loads on the lid from the internals).

2.U.2 References

[2.U.1] Mok, Fischer, Hsu, *Stress Analysis of Closure Bolts for Shipping Casks* (NUREG/CR-6007 UCRL-ID-110637), Lawrence Livermore National Laboratory/Kaiser Engineering, 1993.

[2.U.2] Horton, H. (Ed.), *Machinery's Handbook*, 15th Ed., The Industrial Press, 1957.

[2.U.3] FEL-PRO Technical Bulletin, N-5000 Nickel Based - Nuclear Grade Anti-Seize Lubricant, 8/97.

[2.U.4] K.P. Singh and A.I. Soler, *Mechanical Design of Heat Exchangers and Pressure Vessel Components*, First Edition, Arcturus Publishers, Inc., 1984.

2.U.3 Assumptions

The assumptions used in the analysis are given as a part of Reference 2.U.1. The assumptions in that reference are considered valid for this analysis except where noted below.

1. No bolt prying can occur from outward directed loads since the closure lid has a raised face outside of the bolt circle that eliminates the potential for prying due to positive bending moments.

2. The forces and moments in the bolts due to the gasket load are included in the preload imposed.

3. Puncture forces are calculated using pressure equal to 3 times the lid yield strength. This is conservative since a dynamic analysis of the impact would demonstrate lower contact loads.

4. The forces and moments in the bolts due to vibration loads are small relative to the forces and moments generated by all other loads, and are considered negligible.

5. A recess is provided in the overpack closure plate that causes the MPC to contact the bottom face of the overpack closure plate over an annular region at the outer periphery of the closure plate. The formulas for plates under uniform pressure used in the reference are replaced here by formulas for plates loaded uniformly over an annular region at the outer periphery.

6. As the HI-STAR 100 Overpack includes a protected lid, shear bolt forces are defined to be zero.

7. The temperatures used in the analyses are taken from the thermal analysis of the HI-STAR.

8. The actual weight of the overpack closure plate is replaced by a somewhat larger weight in this analysis. This is conservative because loads on the bolts are increased with a heavier closure plate.

9. The impact load in this analysis is assumed to be 60 g. This is conservative because actual accelerations of the cask are less than 60 g. An impact angle of 80 degrees is assumed since the impact limiter will load the closure plate in the near top drop condition.

2.U.4 Terminology

Some terminology in Reference 2.U.1 differs from Holtec's terminology. In this analysis, the 'cask wall' is Holtec's 'main flange'. The 'cask' is Holtec's 'Overpack'. 'Closure lid' and 'closure plate' are used interchangeably.

Wherever possible, parameter names are consistent with Reference 2.U.1.

2.U.5 Composition

This appendix was created with the Mathcad (version 7.0) software package. Mathcad uses the symbol ':=' as an assignment operator, and the equals symbol '=' retrieves values for constants or variables. Inequalities are also employed. Mathcad returns 0 for a false inequality, and 1 for a true inequality.

Units are also carried with Mathcad variables.

2.U.6 Analysis Procedure

The analysis procedure is taken from Section 6.4 of Reference 2.U.1. The following general steps are taken:

1. Identification of individual loadings.

2. Identification of critical combined load cases. Three critical combined load cases are considered in the HI-STAR bolt analysis.

3. Identification and evaluation of load parameters.

4. Determination of the forces and moments acting on the bolts due to each of individual loading.

5. Determination of the forces and moments acting on the bolts for the combined load case under analysis.

6. Evaluation of the stresses in the bolts for the combined load case.

7. Comparison with acceptance criteria.

2.U.7 Identification of Individual Loadings

The individual loadings acting on the cask closure are the following:

a. Bolt preload. Bolt preload is present in all loadings and includes any gasket sealing loads.

b. Pressure. Design internal pressure is applied to the overpack wall and lid for all load combinations.

c. Temperature. Temperatures from an appropriate thermal analysis are used.

d. Impact. An impact angle and g-level are specified. A near top end drop resulting in an 80 degree impact angle is consistent with the assumption that the impact limiter does not load the closure plate.

e. Puncture. The cask is subjected to a puncture load from an 6 inch diameter mild steel punch. A punch angle of 90 degrees is used. This simulates the hypothetical puncture condition.

2.U.8 Identification of Critical Combined Load Cases

The critical combined load cases that apply to the HI-STAR 100 system in the transport mode are as follows:

1. Normal condition maximum stress analysis: Preload + pressure + temperature

2. Accident condition maximum stress analysis: Preload + pressure + temperature + puncture
3. Accident condition maximum stress analysis: Preload + pressure + temperature + impact

These three cases are examined below.

2.U.9 Geometry Parameters

The parameters which define the HI-STAR 100 closure geometry are given in this section.

The nominal closure bolt diameter, $Db := 1.625 \cdot in$

The total number of closure bolts, $Nb := 54$

The stress area of a closure bolt (from [2.U.4], p. 100), $A_b := 1.680 \cdot in^2$

The closure lid diameter at the bolt circle, $Dlb := 74.75 \cdot in$

Closure lid diameter at the location of the gasket load reaction, $Dlg := 71.565 \cdot in$

The HI-STAR overpack gasket system includes two concentric seals. The value for Dlg above locates the gasket load reaction between the two seal diameters.

The thickness of the cask wall, $tc := 6.25 \cdot in$

The minimum thickness of the closure lid, $tl := \left(6 - \frac{1}{16}\right) \cdot in$

This value for the closure lid thickness accounts for the thickness reduction (recess) in the bottom face of the lid.

The effective thickness of the closure lid flange, $tlf := 4.25 \cdot in$

The closure plate diameter at the inner edge, $Dli := 69.75 \cdot in$

The closure plate diameter at the inner edge is overpack inner diameter plus twice the width of the cut-out in the top flange which accommodates the inflatable annulus seal.

The closure plate diameter at the outer edge, $Dlo := 77.375 \cdot in$

The bolt length, $Lb := 4.25 \cdot in$

The bolt length is the length between the top and bottom surfaces of the closure plate, at the bolt circle location.

The number of bolt threads per inch, $n := 8 \cdot \frac{1}{in}$

The bolt thread pitch, $p := \frac{1}{n}$

The upper bound MPC weight (Table 2.2.4), $Wc := 90000 \cdot lb$

The bounding weight used for closure plate (Table 2.2.4), $Wl := 8000 \cdot lb$

The overpack closure lid recess inner diameter, $d_l := 52.75 \cdot in$

2.U.10 Material Properties

The overpack closure bolts are SB-637-N07718 steel, and the closure plate and top flange are SA-350-LF3 steel. The following material properties are used in the analysis based on a design temperature of 400 degrees F.

The Young's modulus of the cask wall material, $Ec := 26100000 \cdot psi$

The Young's modulus of the closure plate material, $El := 26100000 \cdot psi$

The Poisson's ratio of the closure plate material, $NUl := 0.3$

The closure bolt material coefficient of thermal expansion, $ab := 7.45 \cdot 10^{-6} \cdot R^{-1}$

The cask wall material coefficient of thermal expansion, $ac := 6.98 \cdot 10^{-6} \cdot R^{-1}$

The closure plate material coefficient of thermal expansion, $al := 6.98 \cdot 10^{-6} \cdot R^{-1}$

The zero points of the Fahrenheit and Rankine scales differ by a constant (1 °F = 1 R), therefore the above numbers are accurate with either unit.

Young's modulus of the closure bolt material, $Eb := 27600000 \cdot psi$

Yield strength of closure plate material, $Syl := 32200 \cdot psi$

Tensile strength of closure plate material, $Sul := 64600 \cdot psi$

Young's modulus of top flange material, $Elf := 26100000 \cdot psi$

Bolt material minimum yield stress or strength (room temperature), $Sy1 := 150000 \cdot psi$

Bolt material minimum yield stress or strength (design temperature), $Sy2 := 138300 \cdot psi$

Bolt material minimum ultimate stress or strength, $Su := 170600 \cdot psi$

2.U.11 Combined Load Case 1

Normal Condition maximum stress analysis: Preload + pressure + temperature

2.U.11.1 Identification and Evaluation of Load Parameters, Combined Load Case 1

For each individual loading in this combined load case, the load parameters must be defined. The load parameters for the first individual load case in load combination 1 are as follows:

Loading parameters for preload (Nominal value 2000 ft lbf. torque):

The nominal value of the nut factor is 0.15 from Reference 2.U.3.
The minimum nut factor, based on a tolerance of +/- 5%, is $K := 0.1425$

The maximum bolt preload torque per bolt (Table 7.1.3), $Q := 2000 \cdot ft \cdot lbf + 250 \cdot ft \cdot lbf$

Loading parameters for pressure load:

The pressure inside the cask wall, $Pci := 100 \cdot psi$

The pressure outside the cask wall, $Pco := 14.7 \cdot psi$

The pressure inside the closure lid, $Pli := 100 \cdot psi$

The pressure outside the closure lid, $Plo := 14.7 \cdot psi$

Loading parameters for the normal condition temperature load: (bolt installation at 70 deg. F)

The maximum temperature rise of the main flange, $Tc := (155 - 70) \cdot R$

The maximum temperature rise of the closure lid inner surface, $Tli := (155 - 70) \cdot R$

The maximum temperature rise of the closure lid outer surface, $Tlo := (150 - 70) \cdot R$

The maximum temperature change of the closure lid, $Tl := \frac{Tli + Tlo}{2}$ $Tl = 82.5R$

The maximum temperature change of the closure bolts, $Tb := \frac{Tl + Tc}{2}$ $Tb = 83.75R$

As these parameters are all temperature differences, the Fahrenheit-to-Rankine conversion factor of 460° can be omitted. The temperature values are obtained from the normal steady state analysis of a bounding MPC (highest heat load and temperatures).

2.U.11.2 Determination of Bolt Forces and Moments for the Individual Loadings

Array parameters are used to account for the multiple individual loadings within one combined load case. In combined load case 1, there are three individual loadings, so let i include the range from 1 to 3 as follows:

Let $i := 1..3$

The forces and moments generated by each individual load case are represented by the following symbols:

The non-prying tensile bolt force per bolt = Fa_i

The shear bolt force per bolt = Fs_i

The fixed-edge closure lid force = Ff_i

Fixed-edge closure lid moment = Mf_i

The subscript i is used only to keep track of each individual load case within a load combination.

The first individual loading in this load combination is the residual load after the preload operation. The forces and moments generated by this load are defined as [2.U.1, Table 4.1]:

The non-prying tensile bolt force per bolt, $Fa_1 := \frac{Q}{K \cdot Db}$

The maximum residual tensile bolt force (preload) per bolt, $Far_1 := Fa_1$

The maximum residual torsional bolt moment per bolt, $Mtr := 0.5 \cdot Q$

The preload stress in each bolt (based on stress area), $Preload := \frac{Fa_1}{A_b}$

Substituting the appropriate input data, the values of these parameters are determined as:

$Fa_1 = 116599\,lbf$

$Far_1 = 116599\,lbf$

$Mtr = 13500\,in \cdot lbf$

$Preload = 69404\,psi$

The second individual loading in this load combination is the pressure load. The forces and moments generated by this load are defined as follows [2.U.1, Table 4.3]:

The non-prying tensile force per bolt, $Fa_2 := \frac{\pi \cdot Dlg^2 \cdot (Pli - Plo)}{4 \cdot Nb}$

The shear bolt force per bolt, $Fs_2 := \frac{\pi \cdot El \cdot tl \cdot (Pci - Pco) \cdot Dlb^2}{2 \cdot Nb \cdot Ec \cdot tc \cdot (1 - NUl)}$

The fixed-edge closure lid force, $Ff_2 := \frac{Dlb \cdot (Pli - Plo)}{4}$

The fixed-edge closure lid moment, $Mf_2 := \frac{(Pli - Plo) \cdot Dlb^2}{32}$

Substituting the appropriate input data, the values of these parameters are determined as:

$$Fa_2 = 6354\,lbf$$

$$Fs_2 = 18816\,lbf$$

$$Ff_2 = 1594\,\frac{lbf}{in}$$

$$Mf_2 = 14894\,lbf$$

The third individual loading in this load combination is the temperature load. The forces and moments generated by this load are defined as [2.U.1, Table 4.4]:

The non-prying tensile bolt force per bolt, $Fa_3 := 0.25 \cdot \pi \cdot Db^2 \cdot Eb \cdot (al \cdot Tl - ab \cdot Tb)$

The shear bolt force per bolt, $Fs_3 := \frac{\pi \cdot El \cdot tl \cdot Dlb \cdot (al \cdot Tl - ac \cdot Tc)}{Nb \cdot (1 - NUl)}$

The fixed-edge closure lid force, $Ff_3 := 0 \cdot \frac{lbf}{in}$

The fixed-edge closure lid moment, $Mf_3 := \frac{El \cdot al \cdot tl^2 \cdot (Tlo - Tli)}{12 \cdot (1 - NUl)}$

Substituting the appropriate input data, the values of these parameters are determined as:

$$Fa_3 = -2753\,lbf$$

$$Fs_3 = -16800\,lbf$$

$$Ff_3 = 0\,\frac{lbf}{in}$$

$$Mf_3 = -3823\,lbf$$

2.U.11.3 Determination of Combined Bolt Forces and Combined Bolt Moments

The calculations in the following subsections are performed in accordance with Tables 4.9, 2.1 and 2.2 of Reference 2.U.1.

2.U.11.3.1 Tensile Bolt Force

First, combine the non-prying tensile bolt forces (Fa_i):

The total preload and temperature load, $Fa\_pt := Fa_1 + Fa_3$

$$Fa\_pt = 113847\,lbf$$

The sum of the remaining forces (pressure), $Fa\_al := Fa_2$

$$Fa\_al = 6354\,lbf$$

The combined non-prying tensile bolt force, $Fa\_c := Fa\_al\cdot(Fa\_al > Fa\_pt) + Fa\_pt\cdot(Fa\_pt > Fa\_al)$

$$Fa\_c = 113847\,lbf$$

If the combined non-prying tensile bolt force (Fa_c) is negative, set it equal to zero. Per Appendix 3 of Reference [2.U.1], inward directed loads are not reacted by the bolts, but the developed formulations are still valid if the spurious bolt forces < 0.0 are removed from the calculation.

$$Fa\_c := Fa\_c\cdot(Fa\_c > 0\cdot lbf)$$

$$Fa\_c = 113847\,lbf$$

Next, combine the prying tensile bolt forces and moments (these bolt forces develop due to Ff_i and Mf_i):

The sum of the fixed edge forces, $Ff\_c := Ff_1 + Ff_2 + Ff_3$

$$Ff\_c = 1594\frac{lbf}{in}$$

If the combined fixed-edged force (Ff_c) is negative, set it equal to zero.

$$Ff\_c := Ff\_c\cdot\left(Ff\_c > 0\cdot\frac{lbf}{in}\right) + 0\cdot\frac{lbf}{in}\cdot\left(Ff\_c < 0\cdot\frac{lbf}{in}\right)$$

$$Ff\_c = 1.594\times 10^{3}\,\frac{lbf}{in}$$

The sum of fixed-edge moments, $Mf\_c := Mf_1 + Mf_2 + Mf_3$

$$Mf\_c = 11071 \frac{lbf \cdot in}{in}$$

Define the appropriate prying force moment arm depending on the direction of Mf_c. For inward directed loading, prying moments are developed by the lid rotating about the flange inner edge; for outward directed loading, prying moments are developed by the lid rotating about its outer edge. Thus, the moment arms are different in the two cases.

$$Arm := (Dlo - Dlb) \cdot (Mf\_c > 0 \cdot lbf) + (Dlb - Dli) \cdot (Mf\_c < 0 \cdot lbf)$$

$$Arm = 2.625\, in$$

The prying tensile bolt force for the combined loading can therefore be determined as:

The constants C_1 and C_2 are: $C_1 := 1$

$$C_2 := \left[\frac{8}{3 \cdot (Arm)^2}\right] \cdot \left[\frac{El \cdot tl^3}{1 - NUl} + \frac{(Dlo - Dli) \cdot Elf \cdot tlf^3}{Dlb}\right] \cdot \left(\frac{Lb}{Nb \cdot Db^2 \cdot Eb}\right)$$

$$C_2 = 3.347$$

The bolt preload per unit length of bolt circle, $P := Fa\_pt \cdot \left(\frac{Nb}{\pi \cdot Dlb}\right)$

$$P = 26179 \frac{lbf}{in}$$

The parameter P is the pressure/temperature force which is multiplied to determine preload per unit length of bolt circle (see Tables 2.1 and 4.9 in Section II.3 of Reference 2.U.1).

The non-prying tensile bolt force, $B := Ff\_c \cdot (Ff\_c > P) + P \cdot (P > Ff\_c)$

$$B = 26179 \frac{lbf}{in}$$

The additional tensile bolt force per bolt caused by prying action of the closure lid, $Fap := \left(\frac{\pi \cdot Dlb}{Nb}\right) \cdot \left[\frac{\frac{2 \cdot Mf\_c}{Arm} - C_1 \cdot (B - Ff\_c) - C_2 \cdot (B - P)}{C_1 + C_2}\right]$

$$Fap = -16156\, lbf$$

The prying force must be tensile. If the result is negative, set it equal to zero.

$$Fab\_c := Fap \cdot (Fap > 0 \cdot lbf) + 0 \cdot lbf \cdot (Fap < 0 \cdot lbf)$$

$$Fab\_c = 0\, lbf$$

The total tensile bolt force for stress analysis, $FA := Fa\_c + Fab\_c$

$FA = 113847\,lbf$

2.U.11.3.2 Bolt Shear Force

The sum of the shear forces, $Fs\_c := Fs_1 + Fs_2 + Fs_3$

$Fs\_c = 2016\,lbf$

$Fs := 0 \cdot lbf$ (protected cask lid)

2.U.11.3.3 Bolt Bending Moment

The calculations in this section are performed in accordance with Table 2.2 of Reference 2.U.1. The following relations are defined:

$$Kb := \left(\frac{Nb}{Lb}\right)\left(\frac{Eb}{Dlb}\right)\left(\frac{Db^4}{64}\right)$$

$$Kl := \frac{El \cdot tl^3}{3 \cdot \left[\left(1 - NUl^2\right) + (1 - NUl)^2 \cdot \left(\frac{Dlb}{Dlo}\right)^2\right] \cdot Dlb}$$

$$Mbb\_c := \left(\frac{\pi \cdot Dlb}{Nb}\right)\left(\frac{Kb}{Kb + Kl}\right) Mf\_c$$

$$Mbb := Mbb\_c$$

where Mbb is the bolt bending moment. Substituting the appropriate values, these parameters are calculated as:

$Kb = 5111136\,lbf$

$Kl = 17817619\,lbf$

$Mbb\_c = 1.343 \times 10^3\,lbf \cdot in$

$Mbb = 1.343 \times 10^3\,lbf \cdot in$

2.U.11.3.4 Bolt Torsional Moment

The torsional bolt moment is generated only by the preloading operation, therefore no combination is necessary.

2.U.11.4 Evaluation of Bolt Stresses

Per Table 5.1 of Reference 2.U.1, the average and maximum bolt stresses for comparison with the acceptance criteria are obtained. Inch-series threads are used and the maximum shear and bending are in the bolt thread.

The bolt diameter for tensile stress calculation [2.U.1, Table 5.1], $Dba := Db - 0.9743 \cdot p$

$Dba = 1.503\,in$

The bolt diameter for shear stress calculation, $Dbs := Dba$

$Dbs = 1.503\,in$

The bolt diameter for bending stress calculation, $Dbb := Dba$

$Dbb = 1.503\,in$

The bolt diameter for torsional stress calculation, $Dbt := Dba$

$Dbt = 1.503\,in$

The average tensile stress caused by the tensile bolt force FA, $Sba := 1.2732 \cdot \frac{FA}{Dba^2}$

$Sba = 64147\,psi$

The average shear stress caused by the shear bolt force Fs, $Sbs := 1.2732 \cdot \frac{Fs}{Dbs^2}$

$Sbs = 0\,psi$

The maximum bending stress caused by the bending bolt moment Mb, $Sbb := 10.186 \cdot \frac{Mbb}{Dbb^3}$

$Sbb = 4026\,psi$

The maximum shear stress caused by the torsional bolt moment Mt, $Sbt := 5.093 \cdot \frac{Mtr}{Dbt^3}$

$Sbt = 20242\,psi$

The maximum stress intensity caused by the combined loading of tension, shear, bending and torsion can therefore be determined as:

$$Sbi := \left[(Sba + Sbb)^2 + 4 \cdot (Sbs + Sbt)^2\right]^{0.5}$$

$$Sbi = 79288\,psi$$

2.U.11.5 Comparison with Acceptance Criteria: Normal Conditions, Maximum Stress Analysis

These comparisons are performed in accordance with Table 6.1 of Reference 2.U.1.

The basic allowable stress limit for the bolt material, $Sm := \frac{2}{3} \cdot Sy1 \cdot (Sy1 \le Sy2) + \frac{2}{3} \cdot Sy2 \cdot (Sy2 < Sy1)$

$$Sm = 9.22 \times 10^4\,psi$$

The average tensile stress (must be < Sm), $Sba = 64147\,psi$

The average shear stress (must be < 0.6Sm), $Sbs = 0\,psi$

For combined tensile and shear stress, the sum of the squares of the stress-to-allowable ratios (R_t and R_s) must be less than 1.0.

The tensile stress-to-allowable ratio, $R_t := \frac{Sba}{Sm}$ $\qquad R_t = 0.696$

The shear stress-to-allowable ratio, $R_s := \frac{Sbs}{0.6 \cdot Sm}$

The sum of the squares of the ratios (must be < 1.0), $R_t^2 + R_s^2 = 0.484$

For combined tension, shear, bending and torsion loadings, the maximum stress intensity must be less than 1.35 times the allowable stress limit of the bolt material (Sm).

$$1.35 \cdot Sm = 124470\,psi$$

$$Sbi = 79288\,psi$$

2.U.11.6 Conclusion

For the first loading combination, allowable stress limits are not exceeded.

2.U.12 Critical Combined Load Case 2

Accident Condition maximum stress analysis: Preload + pressure + temperature + puncture

2.U.12.1 Identification and Evaluation of Load Parameters, Combined Load Case 2

The first three individual loadings in this combined load case are the same as the individual loadings in the previous load case. Therefore, only the puncture load parameters must be defined for this load combination. The load parameters for the puncture individual load case in load combination 2 are as follows:

The diameter of the puncture bar, $D_{pb} := 6 \cdot in$

The impact angle between the cask axis and the ground, $xi := 90 \cdot deg$

2.U.12.2 Determination of Bolt Forces and Moments of Individual Loadings

Four individual loadings exist, so we define a range from 1 to 4 as follows:

Let $i := 0..4$

Bolt forces and moments for the preload, pressure, and temperature loads have already been calculated in the previous section. Determination of bolt forces and moments for the puncture load (the fourth individual load in this load combination) are required here [2.U.1, Table 4.7].

First, calculate the maximum puncture load generated by the puncture bar. The puncture force is assumed to be based on a dynamic flow stress S_y at the circular contact area between the bar and the lid surface. The dynamic flow stress is taken as the average of the yield strength and the ultimate strength of the lid material. Therefore, for this puncture analysis:

The dynamic flow stress, $Sy := .5 \cdot (Syl + Sul)$

$Sy = 4.84 \times 10^{4} psi$

The puncture contact area, $Pun := 0.75 \cdot \pi \cdot D_{pb}{}^{2} \cdot Syl$

$Pun = 2.731 \times 10^{6} lbf$

The bolt forces and moments due to the puncture load can now be determined as:

The non-prying tensile bolt force per bolt, $Fa_4 := \frac{-\sin(xi) \cdot Pun}{Nb}$

$Fa_4 = -50580 lbf$

The shear bolt force per bolt, $Fs_4 := \frac{\cos(xi) \cdot Pun}{Nb}$

$Fs_4 = -1.936 \times 10^{-11} lbf$

The fixed-edge closure lid force, $Ff_4 := \frac{-\sin(xi) \cdot Pun}{\pi \cdot Dlb}$

$Ff_4 = -11631 \frac{lbf}{in}$

The fixed-edge closure lid moment, $Mf_4 := \frac{-\sin(xi) \cdot Pun}{4 \cdot \pi}$

$$Mf_4 = -217350 \frac{lbf \cdot in}{in}$$

2.U.12.3 Determination of Combined Bolt Forces and Combined Bolt Moments

2.U.12.3.1 Bolt Tensile Force

Combine the non-prying tensile bolt forces.

The total preload and temperature load, $Fa\_pt := Fa_1 + Fa_3$

$$Fa\_pt = 113847\,lbf$$

The sum of the remaining loads (pressure and puncture), $Fa\_al := Fa_2 + Fa_4$

$$Fa\_al = -44226\,lbf$$

The combined non-prying tensile bolt force, $Fa\_c := Fa\_al \cdot (Fa\_al > Fa\_pt) + Fa\_pt \cdot (Fa\_pt > Fa\_al)$

$$Fa\_c = 113847\,lbf$$

If Fa_c is negative, set it equal to zero: $Fa\_c := Fa\_c \cdot (Fa\_c > 0 \cdot lbf)$

$$Fa\_c = 113847\,lbf$$

Combine the prying tensile bolt forces.

The sum of the fixed-edge forces, $Ff\_c := Ff_1 + Ff_2 + Ff_3 + Ff_4$

$$Ff\_c = -10037 \frac{lbf}{in}$$

If Ff_c is negative, set it equal to zero: $Ff\_c := Ff\_c \cdot \left(Ff\_c > 0 \cdot \frac{lbf}{in}\right) + 0 \cdot \frac{lbf}{in} \cdot \left(Ff\_c < 0 \cdot \frac{lbf}{in}\right)$

$$Ff\_c = 0 \frac{lbf}{in}$$

The sum of the fixed-edge moments, $Mf\_c := Mf_1 + Mf_2 + Mf_3 + Mf_4$

$$Mf\_c = -206279 \frac{lbf \cdot in}{in}$$

Determine the appropriate prying force moment arm depending on the direction of Mf_c.

$$Arm := (Dlo - Dlb) \cdot (Mf\_c > 0 \cdot lbf) + (Dlb - Dli) \cdot (Mf\_c < 0 \cdot lbf)$$

$$Arm = 5\,in$$

Determine the prying tensile bolt force for the combined loading.

The non-prying tensile bolt force, $B := Ff\_c \cdot (Ff\_c > P) + P \cdot (P > Ff\_c)$

$$B = 26179 \frac{lbf}{in}$$

The additional tensile force per bolt caused by prying action of the lid can now be determined as:

The constants C_1 and C_2 are: $C_1 := 1$

$$C_2 := \left[\frac{8}{3 \cdot (Arm)^2}\right] \cdot \left[\frac{El \cdot tl^3}{1 - NUl} + \frac{(Dlo - Dli) \cdot Elf \cdot tlf^3}{Dlb}\right] \cdot \left(\frac{Lb}{Nb \cdot Db^2 \cdot Eb}\right)$$

$$C_2 = 0.923$$

The additional tensile force per bolt caused by prying action of the closure lid, $Fap := \left(\frac{\pi \cdot Dlb}{Nb}\right) \left[\frac{\frac{2 \cdot Mf\_c}{Arm} - C_1 \cdot (B - Ff\_c) - C_2 \cdot (B - P)}{C_1 + C_2}\right]$

$$Fap = -245857 lbf$$

If the prying force is negative, set it equal to zero: $Fab\_c := Fap \cdot (Fap > 0 \cdot lbf) + 0 \cdot lbf \cdot (Fap < 0 \cdot lbf)$

$$Fab\_c = 0 lbf$$

The total tensile bolt force for stress analysis, $FA := Fa\_c + Fab\_c$

$$FA = 113847 lbf$$

2.U.12.3.2 Bolt Shear Force

The sum of the shear forces, $Fs\_c := Fs_1 + Fs_2 + Fs_3 + Fs_4$

$$Fs\_c = -1.936 \times 10^{-11} lbf$$

$Fs := 0 \cdot lbf$ (protected cask lid)

2.U.12.3.3 Bolt Bending Moment

The bolt bending moment can be determined as:

$$Mbb\_c := \left(\frac{\pi \cdot Dlb}{Nb}\right)\left(\frac{Kb}{Kb + Kl}\right) Mf\_c$$

$$Mbb\_c = -25016 in \cdot lbf$$

$$Mbb := Mbb\_c$$

$$Mbb = -25016 \, in \cdot lbf$$

2.U.12.3.4 Bolt Torsional Moment

The torsional bolt moment is generated only by the preloading operation. No combination is necessary.

2.U.12.4 Evaluation of Bolt Stresses

Per Table 5.1 of Reference 2.U.1, the average and maximum bolt stresses are obtained for comparison to the acceptance criteria.

The average tensile stress caused by the bolt tensile force FA, $Sba := 1.2732 \cdot \frac{FA}{Dba^2}$

$$Sba = 64147 \, psi$$

The average shear stress caused by the bolt shear force Fs, $Sbs := 1.2732 \cdot \frac{Fs}{Dbs^2}$

$$Sbs = 0 \, psi$$

The maximum bending stress caused by the bolt bending moment Mb, $Sbb := 10.186 \cdot \frac{Mbb}{Dbb^3}$

$$Sbb = -75018 \, psi$$

The maximum shear stress caused by the bolt torsional moment Mt, $Sbt := 5.093 \cdot \frac{Mtr}{Dbt^3}$

$$Sbt = 20242 \, psi$$

2.U.12.5 Comparison with Acceptance Criteria: Accident Conditions, Maximum Stress Analysis

the comparison with acceptance criteria is performed as per Table 6.3 of Reference 2.U.1.

Compute $0.7 \cdot Su = 119420 \, psi$

$$Sy2 = 1.383 \times 10^5 \, psi$$

The average tensile stress (must be < the smaller of 0.7Su and Sy2), $Sba = 64147 \, psi$

Compute $0.42 \cdot Su = 71652 \, psi$

$$0.6 \cdot Sy2 = 82980 \, psi$$

The average shear stress (must be < the smaller of 0.42Su and 0.6Sy), $Sbs = 0 \, psi$

For combined tensile and shear stress, the sum of the squares of the stress-to-allowable ratios (R_t and R_s) must be less than 1.0.

The tensile stress-to-allowable ratio, $R_t := \dfrac{Sba}{0.7 \cdot Su \cdot (0.7 \cdot Su \le Sy2) + Sy2 \cdot (Sy2 \le 0.7 \cdot Su)}$ $R_t = 0.537$

The shear stress-to-allowable ratio, $R_s := \dfrac{Sbs}{0.42 \cdot Su \cdot (0.42 \cdot Su \le 0.6 \cdot Sy2) + 0.6 \cdot Sy2 \cdot (0.6 \cdot Sy2 \le 0.42 \cdot Su)}$

The sum of the squares of the ratios (must be < 1.0), $R_t^2 + R_s^2 = 0.289$

2.U.12.6 Conclusion

For the second loading combination, allowable stress limits are not exceeded.

2.U.13 Critical Combined Load Case 3

Accident condition maximum stress analysis: Preload + pressure + temperature + impact

The preload, pressure, and temperature individual loadings in this combined load case are the same as in the two previous load cases. Therefore, only the impact load parameters must be defined for this load combination.

2.U.13.1 Identification and Evaluation of Impact Load Parameters

Impact load parameters are defined in Table 4.5 of Reference 2.U.1. Impact decelerations have been accurately computed elsewhere using a dynamic analysis. Nevertheless, an additional dynamic load factor is applied for conservatism in the results.

The applied dynamic load factor, $DLF := 1.05$ (Bounds expected DLF in vicinity of bolts

Impact angle between the cask axis and the target surface, $xi := 80 \cdot deg$

Maximum rigid-body impact acceleration (g) of the cask, $ai := 60 \cdot g$

We conservatively assume that if an impact limiter is in place, it will provide a reacting load at a location r_p, relative to the pivot point assumed in [2.U.1]. The distance from the pivot point to the center of pressure on an impact limiter r_p must therefore be specified. The following formula is used to ensure, for any given case, that r_p is underestimated.

$$r_p := \left(\frac{Dlo}{2}\right) \cdot \sin(xi)^8$$

$$r_p = 34.228\,in$$

For conservatism, this offset is neglected since it will reduce the tensile load in the bolts.

$$r_p := 0 \cdot in$$

2.U.13.3 Determination of Bolt Forces and Moments of Individual Loadings

The fourth and final individual loading in this load combination is the impact load. The forces and moments generated by this load are determined (per Reference 2.U.1, Table 4.5) as:

The non-prying force per bolt, $$Fa_4 := \frac{1.34 \cdot \sin(xi) \cdot DLF \cdot ai \cdot (Wl + Wc)}{Nb} \cdot \frac{\frac{Dlo}{2} - r_p}{\left(\frac{Dlb}{2}\right)}$$

$$Fa_4 = 156178\,lbf$$

This formula has been modified by addition of the correct location of the load from the impact limiter (non zero r_p), although for storage, r_p is zero.

The shear bolt force per bolt, $$Fs_4 := \frac{\cos(xi) \cdot ai \cdot Wl}{Nb}$$

$$Fs_4 = 1544\,lbf$$

The fixed-edge closure lid force, $$Ff_4 := \frac{1.34 \cdot \sin(xi) \cdot DLF \cdot ai \cdot (Wl + Wc)}{\pi \cdot Dlb}$$

$$Ff_4 = 34695 \frac{lbf}{in}$$

The fixed-edge closure lid moment, $$Mf_4 := \frac{1.34 \cdot \sin(xi) \cdot DLF \cdot ai \cdot (Wl + Wc)}{8 \cdot \pi} \cdot \left[1 - \left(\frac{d_1}{Dlb}\right)^2\right]$$

$$Mf_4 = 162740 \frac{in \cdot lbf}{in}$$

The above formula has been modified to reflect the physical fact that in the HI-STAR 100 system the MPC transfers load to the overpack closure plate only around the periphery, because of the recess at the center of the closure plate. Therefore, the formula for a fixed edge plate with a pressure load applied only around the surface greater than $r = d_1/2$ has been used.

2.U.13.4 Determination of Combined Bolt Forces and Combined Bolt Moments

2.U.13.4.1 Bolt Tensile Force

First, combine the non-prying bolt tensile forces.

The total preload and temperature load, $Fa\_pt := Fa_1 + Fa_3$

$$Fa\_pt = 113847\,lbf$$

The sum of the remaining loads (pressure and impact), $Fa\_al := Fa_2 + Fa_4$

$$Fa\_al = 162531\,lbf$$

The combined non-prying tensile bolt force, $Fa\_c := Fa\_al \cdot (Fa\_al > Fa\_pt) + Fa\_pt \cdot (Fa\_pt > Fa\_al)$

$$Fa\_c = 162531\,lbf$$

If Fa_c is negative, set it equal to zero: $Fa\_c := Fa\_c \cdot (Fa\_c > 0 \cdot lbf)$

$$Fa\_c = 162531\,lbf$$

Next, combine the prying bolt tensile forces.

The sum of the fixed-edge forces, $Ff\_c := Ff_1 + Ff_2 + Ff_3 + Ff_4$

$$Ff\_c = 36289\,\frac{lbf}{in}$$

The sum of the fixed-edge moments, $Mf\_c := Mf_1 + Mf_2 + Mf_3 + Mf_4$

$$Mf\_c = 173811\,\frac{in \cdot lbf}{in}$$

Define the appropriate prying force moment arm depending on the direction of Mf_c.

$$Arm := (Dlo - Dlb) \cdot (Mf\_c > 0 \cdot lbf) + (Dlb - Dli) \cdot (Mf\_c < 0 \cdot lbf)$$

$$Arm = 2.625\,in$$

Determine the prying bolt tensile force for the combined loading.

The non-prying tensile bolt force, $B := Ff\_c \cdot (Ff\_c > P) + P \cdot (P > Ff\_c)$

$$B = 3.629 \times 10^4\,\frac{lbf}{in}$$

The additional tensile force per bolt caused by prying action of the closure lid can be determined as:

The constants C_1 and C_2 are: $C_1 := 1$

$$C_2 := \left[\frac{8}{3 \cdot (Arm)^2}\right] \cdot \left[\frac{El \cdot tl^3}{1 - NUl} + \frac{(Dlo - Dli) \cdot Elf \cdot tlf^3}{Dlb}\right] \cdot \left(\frac{Lb}{Nb \cdot Db^2 \cdot Eb}\right)$$

$$C_2 = 3.347$$

The additional tensile force per bolt caused by prying action of the closure lid,

$$Fap := \left(\frac{\pi \cdot Dlb}{Nb}\right)\left[\frac{\frac{2 \cdot Mf\_c}{Arm} - C_1 \cdot (B - Ff\_c) - C_2 \cdot (B - P)}{C_1 + C_2}\right]$$

$$Fap = 98627\,lbf$$

If the prying bolt force is negative, set it equal to zero: $Fab\_c := Fap \cdot (Fap > 0 \cdot lbf) + 0 \cdot lbf \cdot (Fap < 0 \cdot ll$

$$Fab\_c = 98627\,lbf$$

For a raised face flange outboard of the bolt circle, no prying force can be developed

$$Fab\_c := 0 \cdot lbf$$

The total tensile bolt force for stress analysis, $FA := Fa\_c + Fab\_c$

$$FA = 162531\,lbf$$

2.U.13.4.2 Bolt Shear Force

The sum of the shear forces, $Fs\_c := Fs_1 + Fs_2 + Fs_3 + Fs_4$

$$Fs\_c = 1544\,lbf$$

$Fs := 0 \cdot lbf$ (protected cask lid)

2.U.13.4.3 Bolt Bending Moment

The bolt bending moment can now be determined as:

$$Mbb\_c := \left(\frac{\pi \cdot Dlb}{Nb}\right)\left(\frac{Kb}{Kb + Kl}\right) Mf\_c$$

$$Mbb\_c = 21079\,in \cdot lbf$$

$Mbb := Mbb\_c$ $\qquad Mbb = 21079\,in \cdot lbf$

2.U.13.4.4 Bolt Torsional Moment

The torsional bolt moment is generated only by the preloading operation. No combination is necessary.

2.U.13.5 Evaluation of Bolt Stresses

Per Table 5.1 of Reference 2.U.1, obtain the average and maximum bolt stresses for comparison to the acceptance criteria.

The average tensile stress caused by the bolt tensile force FA, $Sba := 1.2732 \cdot \frac{FA}{Dba^2}$

$Sba = 91578\,psi$

The average shear stress caused by the bolt shear force Fs, $Sbs := 1.2732 \cdot \frac{Fs}{Dbs^2}$

$Sbs = 0\,psi$

The maximum bending stress caused by the bolt bending moment Mb, $Sbb := 10.186 \cdot \frac{Mbb}{Dbb^3}$

$Sbb = 63211\,psi$

The maximum shear stress caused by the bolt torsional moment Mt, $Sbt := 5.093 \cdot \frac{Mtr}{Dbt^3}$

$Sbt = 20242\,psi$

2.U.13.5 Comparison with Acceptance Criteria: Accident Conditions, Maximum Stress Analysis

The comparison with acceptance criteria is performed as per Table 6.3 of Reference 2.U.1.

$0.7 \cdot Su = 119420\,psi$

$Sy2 = 1.383 \times 10^5\,psi$

The average tensile stress (must be <0.7Su and Sy2), $Sba = 91578\,psi$

$0.42 \cdot Su = 71652\,psi$ $0.6 \cdot Sy2 = 82980\,psi$

The average shear stress (must be < 0.42Su and 0.6Sy), $Sbs = 0\,psi$

For combined tensile and shear stress, the sum of the squares of the stress-to-allowable ratios (R_t and R_s) must be less than 1.0.

The tensile stress-to-allowable ratio, $R_t := \frac{Sba}{0.7 \cdot Su \cdot (0.7 \cdot Su \le Sy2) + Sy2 \cdot (Sy2 \le 0.7 \cdot Su)}$

$R_t = 0.767$

$\frac{1}{R_t} = 1.304$

The shear stress-to-allowable ratio, $R_s := \frac{Sbs}{0.42 \cdot Su \cdot (0.42 \cdot Su \le 0.6 \cdot Sy2) + 0.6 \cdot Sy2 \cdot (0.6 \cdot Sy2 \le 0.42 \cdot Su)}$

The sum of the squares of the ratios (must be < 1.0), $R_t^2 + R_s^2 = 0.588$

2.U.13.6 Conclusion

For the third loading combination, allowable stress limits are not exceeded.

2.U.14 Bolt Analysis Conclusion

Using the standard method presented in Reference 2.U.1, the above analysis demonstrates that stresses closure bolts for the HI-STAR 100 Overpack will not exceed allowable limits.

APPENDIX 2.V - STRESS ANALYSIS OF OVERPACK CLOSURE BOLTS DURING FIRE

2.V.1 Introduction

This appendix contains a stress analysis of the HI-STAR 100 Overpack closure bolts under the temperature conditions which exist during the hypothetical 30-minute fire accident. The purpose of the analysis is to demonstrate that the closure bolts do not "unload" during this condition and the stresses in the closure bolts do not exceed allowable maximums.

The complex interaction of forces and moments in bolted joints of shipping casks has been investigated in Reference 2.V.1, resulting in a comprehensive method of closure bolt stress analysis. That method is employed here. For each set of formulas or calculations used, reference to the appropriate table in [2.V.1] is given. Where necessary, the formulas are modified to reflect the particulars of the HI-STAR system. For example, since the HI-STAR 100 closure lid has a raised face outside of the bolt circle, no prying forces can develop from loads directed outward (such as internal pressure).

2.V.2 References

[2.V.1] Mok, Fischer, Hsu, *Stress Analysis of Closure Bolts for Shipping Casks* (NUREG/CR-6007 UCRL-ID-110637), Lawrence Livermore National Laboratory/Kaiser Engineering, 1993.

[2.V.2] Horton, H. (Ed.), *Machinery's Handbook*, 15th Ed., The Industrial Press, 1957.

[2.V.3] FEL-PRO Technical Bulletin, N-5000 Nickel Based - Nuclear Grade Anti-Seize Lubricant, 8/97.

[2.V.4] K.P. Singh and A.I. Soler, *Mechanical Design of Heat Exchangers and Pressure Vessel Components*, First Edition, Arcturus Publishers, Inc., 1984.

2.V.3 Assumptions

The assumptions used in the analysis are given as a part of Reference 2.V.1. The assumptions in that reference are considered valid for this analysis except where noted below.

1. The temperature conditions of the bolt circle area at the end of the 30-minute hypothetical fire accident are utilized in this analysis. These temperatures are obtained from the thermal analysis of the HI-STAR 100.

2. Bolt forces due to prying action can only develop from inward directed loads because of the raised face on the closure lid which precludes metal-to-metal contact outside of the bolt circle.

3. The forces and moments in the bolts due to the gasket load are included in the preload imposed.

4. The forces and moments in the bolts due to vibration loads are small relative to the forces and moments generated by all other loads, and are considered negligible.

5. A recess is provided in the overpack closure plate that causes the MPC to contact the bottom face of the overpack closure plate over an annular region at the outer periphery of the closure plate. The formulas for plates under uniform pressure used in the reference are replaced here by formulas for plates loaded uniformly over an annular region at the outer periphery.

6. As the HI-STAR 100 Overpack includes a protected lid, shear bolt forces are defined to be zero.

7. The actual weight of the overpack closure plate is replaced by a somewhat larger weight in this analysis. This is conservative because loads on the bolts are increased with a heavier closure plate.

8. No prying action can occur from outward directed loads since the closure lid has a raised face outside of the bolt circle which eliminates the potential for prying action from positive bending moments.

2.V.4 Terminology

Some terminology in Reference 2.V.1 differs from Holtec's terminology. In this analysis, the 'cask wall' is Holtec's 'main flange'. The 'cask' is Holtec's 'Overpack'. 'Closure lid' and 'closure plate' are used interchangeably.

Wherever possible, parameter names are consistent with Reference 2.V.1.

2.V.5 Composition

This appendix was created with the Mathcad (version 7.0) software package. Mathcad uses the symbol ':=' as an assignment operator, and the equals symbol '=' retrieves values for constants or variables. Inequalities are also employed. Mathcad returns 0 for a false inequality, and 1 for a true inequality.

Units are also carried with Mathcad variables.

2.V.6 Analysis Procedure

The analysis procedure is taken from Section 6.4 of Reference 2.V.1. The following general steps are taken:

1. Identification of individual loadings.

2. Identification and evaluation of load parameters.

3. Determination of the forces and moments acting on the bolts due to each of individual loading.

4. Determination of the forces and moments acting on the bolts for the combined load case under analysis.

5. Evaluation of the stresses in the bolts for the combined load case.

6. Comparison with acceptance criteria.

2.V.7 Identification of Individual Loadings

The individual loadings acting on the cask closure are the following:

a. Bolt preload. Bolt preload is present in all loadings and includes any gasket sealing loads.

b. Pressure. Accident internal pressure is applied to the overpack wall and lid for all load combinations.

c. Temperature. Temperatures from the fire condition thermal analysis are used.

2.V.8 Geometry Parameters

The parameters which define the HI-STAR 100 closure geometry are given in this section.

The nominal closure bolt diameter, $Db := 1.625 \cdot in$

The total number of closure bolts, $Nb := 54$

The stress area of a closure bolt (from [2.V.4], p. 100), $A_b := 1.680 \cdot in^2$

The closure lid diameter at the bolt circle, $Dlb := 74.75 \cdot in$

Closure lid diameter at the location of the gasket load reaction, $Dlg := 71.565 \cdot in$

The HI-STAR overpack gasket system includes two concentric seals. The value for Dlg above locates the gasket load reaction between the two seal diameters.

The thickness of the cask wall, $tc := 6.25 \cdot in$

The minimum thickness of the closure lid, $tl := \left(6 - \frac{1}{16}\right) \cdot in$

This value for the closure lid thickness accounts for the thickness reduction (recess) in the bottom face of the lid.

The effective thickness of the closure lid flange, $tlf := 4.25 \cdot in$

The closure plate diameter at the inner edge, $Dli := 69.75 \cdot in$

The closure plate diameter at the inner edge is overpack inner diameter plus twice the width of the cut-out in the top flange which accommodates the inflatable annulus seal.

The closure plate diameter at the outer edge, $Dlo := 77.375 \cdot in$

The bolt length, $Lb := 4.25 \cdot in$

The bolt length is the length between the top and bottom surfaces of the closure plate, at the bolt circle location.

The number of bolt threads per inch, $n := 8 \cdot \frac{1}{in}$

The bolt thread pitch, $p := \frac{1}{n}$

The upper bound MPC weight (Table 2.2.4), $Wc := 90000 \cdot lb$

The bounding weight used for closure plate (Table 2.2.4), $Wl := 8000 \cdot lb$

The overpack closure lid recess inner diameter, $d_l := 52.75 \cdot in$

2.V.9 Material Properties

The overpack closure bolts are SB-637-N07718 steel, and the closure plate and top flange are SA-350-LF3 steel. The following material properties are used in the analysis based on a fire temperature of 500-600 degrees F. Extrapolation of table data is carried out where necessary.

The Young's modulus of the cask wall material, $Ec := 25400000 \cdot psi$

The Young's modulus of the closure plate material, $El := 25400000 \cdot psi$

The Poisson's ratio of the closure plate material, $NUl := 0.3$

The closure bolt material coefficient of thermal expansion, $ab := 7.60 \cdot 10^{-6} \cdot R^{-1}$

The cask wall material coefficient of thermal expansion, $ac := 7.34 \cdot 10^{-6} \cdot R^{-1}$

The closure plate material coefficient of thermal expansion, $al := 7.34 \cdot 10^{-6} \cdot R^{-1}$

The zero points of the Fahrenheit and Rankine scales differ by a constant (1 °F = 1 R), therefore the above numbers are accurate with either unit.

Young's modulus of the closure bolt material, $Eb := 26800000 \cdot psi$

Young's modulus of top flange material, $Ef := 25400000 \cdot psi$

Bolt material minimum yield stress or strength (550 deg. F), $Sy := 136050 \cdot psi$

Bolt material minimum ultimate stress or strength (550 deg. F), $Su := 167800 \cdot psi$

2.V.10 Bolt Stress Calculations

2.V.10.1 Identification and Evaluation of Load Parameters, Combined Load Case 1

The load parameters for each individual loading are defined as follows.

Loading parameters for preload (Nominal pretorque = 2000 ft.lbf.):

The nominal value of the nut factor is 0.15 from Reference 2.V.3.
The minimum nut factor, based on a tolerance of +/- 5%, is $K := 0.1425$

The maximum bolt preload torque per bolt (Table 7.1.3), $Q := 2000 \cdot ft \cdot lbf + 250 \cdot ft \cdot lbf$

Loading parameters for pressure load:

The pressure inside the cask wall, $Pci := 200 \cdot psi$

The pressure outside the cask wall, $Pco := 14.7 \cdot psi$

The pressure inside the closure lid, $Pli := 200 \cdot psi$

The pressure outside the closure lid, $Plo := 14.7 \cdot psi$

Loading parameters for the fire condition temperature load: (bolt installation at 70 deg. F)

The maximum temperature rise of the main flange, $Tc := (514 - 70) \cdot R$

The maximum temperature rise of the closure lid inner surface, $Tli := (490 - 70) \cdot R$

The maximum temperature rise of the closure lid outer surface, $Tlo := (514 - 70) \cdot R$

The maximum temperature change of the closure lid, $Tl := \frac{Tli + Tlo}{2}$ $Tl = 432R$

The maximum temperature change of the closure bolts, $Tb := (514 - 70) \cdot R$ $Tb = 444R$

As these parameters are all temperature differences, the Fahrenheit-to-Rankine conversion factor of 460° can be omitted. The temperature values are obtained from the transient fire accident analysis of a bounding MPC (highest heat load and temperatures). The maximum temperature of the closure bolts is taken from Table 3.5.4.

2.V.10.2 Determination of Bolt Forces and Moments for the Individual Loadings

Array parameters are used to account for the multiple individual loadings within the combined load case. There are three individual loadings, so let i include the range from 1 to 3 as follows:

Let $i := 1..3$

The forces and moments generated by each individual load case are represented by the following symbols:

The non-prying tensile bolt force per bolt = Fa_i

The shear bolt force per bolt = Fs_i

The fixed-edge closure lid force = Ff_i

Fixed-edge closure lid moment = Mf_i

The subscript i is used only to keep track of each individual load case within a load combination.

The first individual loading in this load combination is the residual load after the preload operation. The forces and moments generated by this load are defined as [2.V.1, Table 4.1]:

The non-prying tensile bolt force per bolt, $Fa_1 := \frac{Q}{K \cdot Db}$

The maximum residual tensile bolt force (preload) per bolt, $Far_1 := Fa_1$

The maximum residual torsional bolt moment per bolt, $Mtr := 0.5 \cdot Q$

The preload stress in each bolt (based on stress area), $Preload := \frac{Fa_1}{A_b}$

Substituting the appropriate input data, the values of these parameters are determined as:

$$Fa_1 = 116599\,lbf$$

$$Far_1 = 116599\,lbf$$

$$Mtr = 13500\,in \cdot lbf$$

$$Preload = 69404\,psi$$

The second individual loading in this load combination is the pressure load. The forces and moments generated by this load are defined as follows [2.V.1, Table 4.3]:

The non-prying tensile force per bolt, $Fa_2 := \frac{\pi \cdot Dlg^2 \cdot (Pli - Plo)}{4 \cdot Nb}$

The shear bolt force per bolt, $Fs_2 := \frac{\pi \cdot El \cdot tl \cdot (Pci - Pco) \cdot Dlb^2}{2 \cdot Nb \cdot Ec \cdot tc \cdot (1 - NUl)}$

The fixed-edge closure lid force, $Ff_2 := \frac{Dlb \cdot (Pli - Plo)}{4}$

The fixed-edge closure lid moment, $Mf_2 := \frac{(Pli - Plo) \cdot Dlb^2}{32}$

Substituting the appropriate input data, the values of these parameters are determined as:

$$Fa_2 = 13803\,lbf$$

$$Fs_2 = 40874\,lbf$$

$$Ff_2 = 3463 \frac{lbf}{in}$$

$$Mf_2 = 32355\,lbf$$

The third individual loading in this load combination is the temperature load. The forces and moments generated by this load are defined as [2.V.1, Table 4.4]:

The non-prying tensile bolt force per bolt, $Fa_3 := 0.25 \cdot \pi \cdot Db^2 \cdot Eb \cdot (al \cdot Tl - ab \cdot Tb)$

The shear bolt force per bolt, $Fs_3 := \frac{\pi \cdot El \cdot tl \cdot Dlb \cdot (al \cdot Tl - ac \cdot Tc)}{Nb \cdot (1 - NUl)}$

The fixed-edge closure lid force, $Ff_3 := 0 \cdot \frac{lbf}{in}$

The fixed-edge closure lid moment, $Mf_3 := \frac{El \cdot al \cdot tl^2 \cdot (Tlo - Tli)}{12 \cdot (1 - NUl)}$

Substituting the appropriate input data, the values of these parameters are determined as:

$$Fa_3 = -11312\,lbf$$

$$Fs_3 = -82525\,lbf$$

$$Ff_3 = 0\frac{lbf}{in}$$

$$Mf_3 = 18779\,lbf$$

2.V.10.3 Determination of Combined Bolt Forces and Combined Bolt Moments

The calculations in the following subsections are performed in accordance with Tables 4.9, 2.1 and 2.2 of Reference 2.V.1.

2.V.10.3.1 Tensile Bolt Force

First, combine the non-prying tensile bolt forces (Fa_i):

The total preload and temperature load, $Fa\_pt := Fa_1 + Fa_3$

$Fa\_pt = 105287\,lbf$

The sum of the remaining forces (pressure), $Fa\_al := Fa_2$

$Fa\_al = 13803\,lbf$

The combined non-prying tensile bolt force, $Fa\_c := Fa\_al \cdot (Fa\_al > Fa\_pt) + Fa\_pt \cdot (Fa\_pt > Fa\_al)$

$Fa\_c = 105287\,lbf$

If the combined non-prying tensile bolt force (Fa_c) is negative, set it equal to zero. Per Appendix 3 of Reference [2.V.1], inward directed loads are not reacted by the bolts, but the developed formulations are still valid if the spurious bolt forces < 0.0 are removed from the calculation.

$$Fa\_c := Fa\_c \cdot (Fa\_c > 0 \cdot lbf)$$

$$Fa\_c = 105287\,lbf$$

Next, combine the prying tensile bolt forces and moments (these bolt forces develop due to Ff_i and Mf_i):

The sum of the fixed edge forces, $Ff\_c := Ff_1 + Ff_2 + Ff_3$

$$Ff\_c = 3463 \frac{lbf}{in}$$

If the combined fixed-edged force (Ff_c) is negative, set it equal to zero.

$$Ff\_c := Ff\_c \cdot \left(Ff\_c > 0 \cdot \frac{lbf}{in} \right) + 0 \cdot \frac{lbf}{in} \cdot \left(Ff\_c < 0 \cdot \frac{lbf}{in} \right)$$

$$Ff\_c = 3.463 \times 10^3 \frac{lbf}{in}$$

The sum of fixed-edge moments, $Mf\_c := Mf_1 + Mf_2 + Mf_3$

$$Mf\_c = 51134 \frac{lbf \cdot in}{in}$$

Define the appropriate prying force moment arm depending on the direction of Mf_c. For inward directed loading, prying moments are developed by the lid rotating about the flange inner edge; for outward directed loading, prying moments are developed by the lid rotating about its outer edge. Thus, the moment arms are different in the two cases.

$$Arm := (Dlo - Dlb) \cdot (Mf\_c > 0 \cdot lbf) + (Dlb - Dli) \cdot (Mf\_c < 0 \cdot lbf)$$

$$Arm = 2.625 \, in$$

The prying tensile bolt force for the combined loading can therefore be determined as:

The constants C_1 and C_2 are: $C_1 := 1$

$$C_2 := \left[\frac{8}{3 \cdot (Arm)^2} \right] \cdot \left[\frac{El \cdot tl^3}{1 - NUl} + \frac{(Dlo - Dli) \cdot Elf \cdot tlf^3}{Dlb} \right] \cdot \left(\frac{Lb}{Nb \cdot Db^2 \cdot Eb} \right)$$

$$C_2 = 3.355$$

The bolt preload per unit length of bolt circle, $P := Fa\_pt \cdot \left(\frac{Nb}{\pi \cdot Dlb} \right)$

$$P = 24211 \frac{lbf}{in}$$

The parameter P is the pressure/temperature force which is multiplied to determine preload per unit length of bolt circle (see Tables 2.1 and 4.9 in Section II.3 of Reference 2.V.1).

The non-prying tensile bolt force, $B := Ff\_c \cdot (Ff\_c > P) + P \cdot (P > Ff\_c)$

$$B = 24211 \frac{lbf}{in}$$

The additional tensile bolt force per bolt caused by prying action of the closure lid, $Fap := \left(\frac{\pi \cdot Dlb}{Nb}\right) \left[\frac{\frac{2 \cdot Mf\_c}{Arm} - C_1 \cdot (B - Ff\_c) - C_2 \cdot (B - P)}{C_1 + C_2}\right]$

$$Fap = 18187\,lbf$$

The prying force must be tensile. If the result is negative, set it equal to zero.

$$Fab\_c := Fap \cdot (Fap > 0 \cdot lbf) + 0 \cdot lbf \cdot (Fap < 0 \cdot lbf)$$

$$Fab\_c = 18187\,lbf$$

The total tensile bolt force for stress analysis, $FA := Fa\_c + Fab\_c$

$$FA = 123475\,lbf$$

2.V.10.3.2 Bolt Shear Force

The sum of the shear forces, $Fs\_c := Fs_1 + Fs_2 + Fs_3$

$$Fs\_c = -41650\,lbf$$

$Fs := 0 \cdot lbf$ (protected cask lid)

2.V.10.3.3 Bolt Bending Moment

The calculations in this section are performed in accordance with Table 2.2 of Reference 2.V.1. The following relations are defined:

$$Kb := \left(\frac{Nb}{Lb}\right)\left(\frac{Eb}{Dlb}\right)\left(\frac{Db^4}{64}\right)$$

$$Kl := \frac{El \cdot tl^3}{3 \cdot \left[\left(1 - NUl^2\right) + (1 - NUl)^2 \cdot \left(\frac{Dlb}{Dlo}\right)^2\right] \cdot Dlb}$$

$$Mbb\_c := \left(\frac{\pi \cdot Dlb}{Nb}\right)\left(\frac{Kb}{Kb + Kl}\right) Mf\_c$$

$$Mbb := Mbb\_c$$

where Mbb is the bolt bending moment. Substituting the appropriate values, these parameters are calculated as:

$$Kb = 496320\,lbf$$

$$Kl = 17339752\,lbf$$

$$Mbb\_c = 6.188 \times 10^3\,lbf \cdot in$$

$$Mbb = 6.188 \times 10^3\,lbf \cdot in$$

2.V.10.3.4 Bolt Torsional Moment

The torsional bolt moment is generated only by the preloading operation, therefore no combination is necessary.

2.V.10.4 Evaluation of Bolt Stresses

Per Table 5.1 of Reference 2.V.1, the average and maximum bolt stresses for comparison with the acceptance criteria are obtained. Inch-series threads are used and the maximum shear and bending are in the bolt thread.

The bolt diameter for tensile stress calculation [2.V.1, Table 5.1], $Dba := Db - 0.9743 \cdot p$

$$Dba = 1.503\,in$$

The bolt diameter for shear stress calculation, $Dbs := Dba$

$$Dbs = 1.503\,in$$

The bolt diameter for bending stress calculation, $Dbb := Dba$

$$Dbb = 1.503\,in$$

The bolt diameter for torsional stress calculation, $Dbt := Dba$

$$Dbt = 1.503\,in$$

The average tensile stress caused by the tensile bolt force FA, $Sba := 1.2732 \cdot \frac{FA}{Dba^2}$

$$Sba = 69572\,psi$$

The average shear stress caused by the shear bolt force Fs, $Sbs := 1.2732 \cdot \frac{Fs}{Dbs^2}$

$$Sbs = 0\,psi$$

The maximum bending stress caused by the bending bolt moment Mb, $Sbb := 10.186 \cdot \frac{Mbb}{Dbb^3}$

$Sbb = 18556 psi$

The maximum shear stress caused by the torsional bolt moment Mt, $Sbt := 5.093 \cdot \frac{Mtr}{Dbt^3}$

$Sbt = 20242 psi$

The maximum stress intensity caused by the combined loading of tension, shear, bending and torsion can therefore be determined as:

$$Sbi := \left[(Sba + Sbb)^2 + 4 \cdot (Sbs + Sbt)^2\right]^{0.5}$$

$$Sbi = 96982 psi$$

2.V.10.5 Comparison with Acceptance Criteria: Accident Conditions, Maximum Stress Analysis

The comparison with acceptance criteria is performed as per Table 6.3 of Reference 2.V.1.

$$0.7 \cdot Su = 117460 psi$$

$$Sy = 1.361 \times 10^5 psi$$

The average tensile stress (must be <0.7Su and Sy), $Sba = 69572 psi$

$0.42 \cdot Su = 70476 psi$ $0.6 \cdot Sy = 81630 psi$

The average shear stress (must be < 0.42Su and 0.6Sy), $Sbs = 0 psi$

For combined tensile and shear stress, the sum of the squares of the stress-to-allowable ratios (R_t and R_s) must be less than 1.0.

The tensile stress-to-allowable ratio, $R_t := \frac{Sba}{0.7 \cdot Su \cdot (0.7 \cdot Su \le Sy) + Sy \cdot (Sy \le 0.7 \cdot Su)}$

$R_t = 0.592$ $\frac{1}{R_t} = 1.688$

The shear stress-to-allowable ratio, $R_s := \frac{Sbs}{0.42 \cdot Su \cdot (0.42 \cdot Su \le 0.6 \cdot Sy) + 0.6 \cdot Sy \cdot (0.6 \cdot Sy \le 0.42 \cdot Su)}$

The sum of the squares of the ratios (must be < 1.0), $R_t^2 + R_s^2 = 0.351$

The average tensile stress in the closure bolts under the combined loading of preload, internal pressure and normal operating temperatures was calculated in Appendix 2.U as 64,147 psi. In order to ensure that the closure bolts do not unload during the hypothetical fire accident, the average tensile stress under the fire condition (with preload and accident internal pressure) should be close to this value.

The average tensile stress, $Sba = 69572\text{psi}$

The average shear stress, $Sbs = 0\text{psi}$

$$\frac{Sba}{64147 \cdot \text{psi}} = 1.085$$

The average tensile stress under the imposed fire condition is close to the corresponding stress under normal operating temperature conditions.

2.V.11 Conclusion

Using the standard method presented in Reference 2.V.1, the above analysis demonstrates that the stresses in the closure bolts do not exceed allowable limits under the imposed preload, pressure and temperature conditions. Furthermore, since the increase in tensile stress in the closure bolts due to the hypothetical fire accident is small (i.e., less than 10%), the seal will not unload.

APPENDIX A

HOLTEC APPROVED COMPUTER PROGRAM LIST

HOLTEC APPROVED COMPUTER PROGRAM LIST				**REV. 53** **April 11, 2003**	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
ANSYS (A)	5.3, 5.4, 5.6,5.6.2,5.7,7.0	JZ, EBR, PKC, CWB, SPA, AIS, IR, SP, JRT, AK	Windows		5.3
AC-XPERT	1.12		Windows		
AIRCOOL	5.2I, 6.1		Windows		
BACKFILL	2.0		DOS/ Windows		
BONAMI (Scale)	4.3, 4.4		Windows		
BULKTEM	3.0		DOS/ Windows		
CASMO-4 (A)	1.13.04 (UNIX), 2.05.03 (WINDOWS)	ELR, SPA, DMM, KC, ST, VJB	UNIX/ Windows	Version 1.13.04 should not be used for new projects and should only be used when necessary for additional calculations on previous projects. The user should refer to the error notice documented in c4ser.04-results.pdf located in \generic\library\ nuclear\error notices\ concerning the use of version 1.13.04.	
CASMO-3 (A)	4.4, 4.7	ELR, SPA, DMM, KC, ST	UNIX		
CELLDAN	4.4.1		Windows		
CHANBP6 (A)	1.0	SJ, PKC, CWB, AIS, SP, JRT	DOS/Windows		
CHAP08 (CHAPLS10)	1.0		Windows		
CONPRO	1.0		DOS/Windows		
CORRE	1.3		DOS/Windows		
DECAY	1.4, 1.5		DOS/Windows		
DÉCOR	1.0		DOS/Windows		
DR.BEAMPRO	1.0.5		Windows		
DR.FRAME	2.0		Windows		
DYNAMO (A)	2.51	AIS, SP, CWB, PKC, SJ, JRT	DOS/Windows	Personnel qualified to use MR216 are automatically qualified to use DYNAMO.	
DYNAPOST	2.0		DOS/Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 53 April 11, 2003	
PROGRAM (Category)	VERSION	CERTIFIED USERS	OPERATING SYSTEM	REMARKS	CODE USED
FIMPACT	1.0		DOS/Windows		
FLUENT (A)	4.32, 4.48, 4.56, 5.1 (see error notice), 4.2.8 (UNS), 5.5	EBR, IR, DMM, SPA	Windows	Do not use porous medium with zero velocity.	
FTLOAD	1.4		DOS		
GENEQ	1.3		DOS		
INSYST	2.01		Windows		
KENO-5A (A)	4.3, 4.4	ELR, SPA, DMM, KC, ST, VJB	Windows		
LONGOR	1.0		DOS/Windows		
LNSMTH2	1.0		DOS/Windows		
LS-DYNA3D (A)	936, 940, 950, 960	JZ, AIS, SPA, SP	Windows		
MAXDIS16	1.0		DOS/Windows		
MCNP (A)	4A, 4B	ELR, SPA, KC, ST, DMM, VJB	Windows/ UNIX		
MASSINV	1.4, 1.5, 2.1		DOS/Windows		
MR216 (A)	1.0, 2.0, 2.2, 2.4	AIS, SP, CWB, PKC, SJ, JRT	DOS/Windows	Versions 2.2 and 2.4 for use in dry storage analyses only. Use DYNAMO for liquefaction problems.	
MSREFINE	1.3, 2.1		DOS/Windows		
MULPOOLD	2.1		DOS/Windows		
MULTI1	1.3, 1.4, 1.5, 1.54, 1.55		Windows		
NITAWL (Scale)	4.3, 4.4		Windows		
NASTRAN DESKTOP (WORKING MODEL)	6.2, 2001, 6.4, 2002		Windows		
ONEPOOL	1.4.1, 1.5, 1.6		DOS/Windows		
ORIGEN	2.1		DOS/Windows		
ORIGENS (Scale)	4.3, 4.4		Windows		
PD16	1.1, 1.0, 2.0		Windows		
PREDYNA1	1.5, 1.4		DOS/Windows		
PSD1	1.0		DOS/Windows		
QAD	CGGP		Windows		
SAS2H (Scale)	4.3, 4.4		Windows		
SFMR2A	1.0		DOS/Windows		
SHAPEBUILDER	3.0		DOS/Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 53 April 11, 2003	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
SIFATIG	1.0		DOS/Windows		
SOLIDWORKS	2001		DOS/Windows	This program may be used to calculate Weight, Volume, Centroid and Moment of Inertia. As a precaution, user should avoid keeping more than one drawing files open at any given time during a Solidworks session. If there is a need for multiples drawing files to be open at once, user should ensure that the part names for all open files are uniquely named (i.e. no two parts have the same name.)	
SPG16	1.0, 2.0, 3.0		DOS/Windows		
SHAKE2000	1.1.0		DOS/Windows		
STARDYNE (A)	4.4, 4.5	SP	Windows		
STER	5.04		Windows		
TBOIL	1.7, 1.9		DOS/Windows	See HI-92832 for restriction on v1.7.	
THERPOOL	1.2, 1.2A		DOS/Windows		
TRIEL	2.0		DOS/Windows		
VERSUP	1.0		DOS		
VIB1DOF	1.0		DOS/Windows		
VMCHANGE	1.4, 1.3		Windows		
WEIGHT	1.0		Windows		

NOTES:

1. XXXX = ALPHANUMERIC COMBINATION
2. GENERAL PURPOSES UTILITY CODES (MATHCAD, EXCEL, ETC.) MAYBE USED ANYTIME.