Report on the FY17 Development of Computer Program for ASME Section III, Division 5, Subsection HB, Subpart B Rules

Nuclear Engineering Division

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Argonne National Laboratory

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ABSTRACT

One of the objectives of the high temperature design methodology activities is to develop and validate both improvements and the basic features of ASME Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Facility Components, Division 5, High Temperature Reactors, Subsection HB, Subpart B (HBB). The overall scope of this task is to develop a computer program to aid assessment procedures of components under specified loading conditions in accordance with the elevated temperature design requirements for Division 5 Class A components.

There are many features and alternative paths of varying complexity in HBB. The initial focus of this computer program is a basic path through the various options for a single reference material, 316H stainless steel. However, the computer program is being structured for eventual incorporation all of the features and permitted materials of HBB. This report will first provide a description of the overall computer program, particular challenges in developing numerical procedures for the assessment, and an overall approach to computer program development. This is followed by a more comprehensive appendix, which is the draft computer program manual for the program development. The strain limits rules have been implemented in the computer program. The evaluation of creep-fatigue damage will be implemented in future work scope.

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1 Introduction

One of the objectives of this work is to develop and validate both improvements and the basic features of Section III, Div 5, Subsection HB, Subpart B (HBB) [1]. To accomplish this, it is usually necessary to provide a comparison between the proposed improvement and the reference rules in HBB. HBB is also used to assess components in comparative design studies. However, there are many features and alternative paths of varying complexity in HBB and even the most direct can be costly to evaluate. Also, because of the complexities of HBB, there can be difficulty in the correct application of the requirements. For these evaluations in accordance with HBB, it would be advantageous to have the rules incorporated in a computer program to achieve economical and correct solutions. Because of the many features and alternative paths of varying complexity in HBB, the initial focus of this task is a basic path through the various options for a single reference material, 316H stainless steel. The program will be structured for eventual incorporation of all the features and permitted materials of HBB.

The computer program must also be structured to allow for input from commercial structural analysis computer program, i.e. finite element analysis, which was less common when the original rules of the high temperature code were developed. Stress Classification, a necessary and foundational step in the elastic and simplified inelastic approaches is difficult to implement unless it has been taken into account during the analysis.

2 Overview of HBB Methodology

HBB provides rules for both design Loadings and Level A, B, C and D Service Level Loadings. The rules cover both base material and bolting. Factors are provided to account for deterioration of materials in service and strength of weldments. The requirements for design by analysis are provided in HBB-3200. Additional, component specific rules are provided in HBB-3300, -3400, -3500 and -3600 for vessels, pumps, valves and piping, respectively.

In most ASME code design, the focus is on keeping the calculated stress within certain limits or allowable values. These limits are the maximum sustained stresses the structure can tolerate reduced by whatever factor of safety is deemed necessary to account for variation in properties or unknown damage mechanisms, etc. The sustained stresses are not necessarily the stresses calculated in an elastic analysis, because it can be assumed that small amounts of inelastic material behavior will lead to a redistribution of loads. The sustained stresses are essentially the primary stresses necessary to maintain equilibrium with the applied pressures, forces, and moments and other “secondary stresses with a large amount of elastic follow-up” (HBB-3213 (a)). This design approach anticipates the limit load approach, but HBB does not currently have this option for primary loads unlike Section III, Division 1 Subsection NB [2].

The most important distinction between the limits in HBB and other sections of the code is the consideration of time. For design loads HBB uses a stress limit, S_0 , which is generally equivalent to the values in Section II, Part D. Though S_0 incorporates time-dependent mechanisms it is, itself, not dependent on the design life of the component. However, for evaluation of service loading, the time independent allowable, S_m , a time dependent allowable, S_t , and the lower of the two, S_{mt} , are used. Roughly speaking for times in excess of 100,000 hours, the time dependent allowable stresses, S_t and S_{mt} are below the limit used for design, S_0 . In addition, for service loads, it is also necessary to calculate the time use-fractions for any load case. In order to do this, the minimum stress to cause rupture in a given time, S_r , is also required.

HBB also requires evaluation of strain and deformation, ratcheting, creep-fatigue, buckling and instability. These are called strain and deformation controlled quantities (HBB-3213 (b)). No specific method is required, but Nonmandatory Appendix HBB-T provides a set of rules and limits to perform the evaluation.

There are two sets of design rules in Appendix HBB-T. In one case, these rules are based on the use of inelastic analysis, which requires constitutive equations describing the materials response. In the second case, the rules are based on the use of elastic analysis with various adjustments and procedures to account for the actual inelastic response.

Methods and limits associated with strain and deformations including a ratcheting evaluation are described in HBB-T-1300, creep-fatigue in HBB-T-1400, and buckling and instability in HBB-T-1500. These requirements are generally speaking, more difficult to assess by elastic analysis than the load-controlled limits and though less comprehensive than a full constitutive model, more material data is necessary. Some additional material specific data introduced in the appendix are isochronous stress strain curves (ISSCs), the creep-fatigue interaction diagram also called the “D-diagram,” and the design fatigue strain ranges. Of these, the ISSCs are given only in figures and not tabulated.

3 Initial Program Scope

For this initial phase, Design Loadings and Level A, B, and C Service Level Loadings are included but not Level D because these conditions are usually extreme, short term conditions that do not involve time dependent creep properties. Both base materials and weldments are considered but not bolting which is not usually part of the elevated temperature boundary. To keep the scope bounded, the component specific rules are not included at this time. However, provisions for deterioration of materials in service are included.

Material properties required for implementing the design rules, i.e. allowable stress values, are provided in HBB-I-14. Again, for this initial phase, only the properties for 316H stainless steel are included in the computer program.

The procedures based on inelastic analysis are not be included in this phase nor are the buckling limits. Thus the Appendix HBB-T strain limits based on elastic analysis (HBB-T-1320) and simplified inelastic analysis (HBB-T-1330) are included except for HBB-T-1333, which is seldom, if ever used. The evaluation of creep-fatigue limits in HBB-T-1400 will be based on elastic analysis (HBB-T-1430) and will not include the equivalent stress quantities in HBB-T-1411 for inelastic analysis. The requirements for welds in HBB-T-1710 are included.

4 Challenges in Numerical Implementation

Several significant challenges are presented in developing this computer program. One significant challenge is simply the volume of input that is required for the assessments. Though HBB is quite specific in how stress intensity is calculated, the basis for that calculation, classification of stresses, can be somewhat ambiguous from the standpoint of the finite element analysis method. This presents a structural challenge to the code, how is a stress at a given location to be interpreted. The language of HBB is better suited for a mechanics of material approach than structural analysis by the finite element analysis.

The best illustration of this is the term “gross structural discontinuity” defined in HBB-3213.2. This stress is associated with geometric or material discontinuity and produce bending and membrane forces. In a mechanics of materials approach this is relatively clear as sketched in Fig. 1.

The challenges of interpreting results from finite element analysis have been addressed for other sections of the code, including part NB of Section III and Section VIII Division 2 [4] WRC Bulletin 429 [5], and Companion Guide to the ASME Boiler & Pressure Vessel Code [6]. Provisions have been made for options to the burden of classification to the user or to the computer program for specific applications.

Another difficulty is simply how to structure the input to the computer program in such a way that it can deal with a large volume of information. Because the classification of stress depends on what the origin of stress is and the stress intensity values are not additive, separate analyses may be necessary for the thermal loads versus the mechanical loads and even different types of mechanical loading. Furthermore, the methods of HBB are used to evaluate rather arbitrary cycles; many calculations may be needed for different points along a transient to capture the full range. Nor can it be said, except in the simplest cases, that the time and location of the highest stress intensities is known a priori. The computer program therefore, is written in a way to perform an evaluation at a single location in the structure simply to make the process tractable.

ISSCs in HBB are based on data analysis that dates back to the middle 1980's and earlier. The equations behind the curves are not generally available and so an effort has been undertaken to trace back the origins so as to reproduce the curves in the figures.

5 Computer Program Structure and Development

The computer program framework relies heavily on an object oriented approach. Some familiarity with programming terminology is assumed here, but in order to differentiate terms used in the ASME BPV code from similar terms used in the computer program, names given to programming structures are set in *italics*.

To understand how the HBB computer program is intended to work it is necessary to understand the fundamental object classes of the program. The material class includes all the programming structure used to store the material data. The analysis result is the lowest level structure in the program and represents a set of stresses pertaining to a particular structural analysis and at a given location in the component. It also contains information about the type of load and origin of stress. For example, “pressure,” “external loads and moments,” and “thermal gradients” are all examples of load types. Linearization and stress classification can either be performed at the level of the analysis result, or the results of linearization or stress.

Because a spherical shell has a different stiffness than a cylindrical shell, the two components deform differently. Membrane forces and bending moments develop at the junction in order to maintain continuity of position and slope. The forces and moments could be calculated from various common solutions such as those given in Section III, Nonmandatory Appendix A “Stress Analysis Methods [3];” however, in finite element analysis, it is not a simple matter to separate stress components in such a way. Around a nozzle, for example, it can be very difficult to determine what portion of the “bending stress” is related to the gross discontinuity, and hence is secondary, as opposed to what should be classified as primary.

Classification as determined by the user may be read directly into the computer program. Multiple analysis result objects may be compiled into a single load point object which fully describes the stress state of a location in the structure at a specific condition (i.e. a specific time in a cycle). For design limits, the load point level is sufficient to evaluate the results.

For service levels A, B, and C, time enters into the evaluation. Each load point has a specific time associated with it. For example, there may be a load point for long duration steady-state operation, or a transient state may be broken up into multiple load points that represent individual sub steps. Multiple load points are assembled into a load cycle, and multiple load cycles into an analysis case. The analysis case objects correspond to Design Limits, Service Level A and B loading, and Service Level C loading. These analysis case objects are then assembled into an analysis object which contains, in addition to the analysis case objects, the material object and the location object of the evaluation. Some examples of location objects are, “shell remote from discontinuities” or “nozzle within the limits of reinforcement.” Thus, the structure of the analysis computer program can be thought of as a series of containers as shown in Fig. 2.

Fig. 2. Container structure of the HBB computer program

The naming and description of the object classes suggests how these object classes relate. The flow diagrams, therefore, closely follow the analysis flow diagrams in Figure HBB-3221-1. Load-controlled limits are evaluated at the level of the load point for Design Limits or for the load cycle when considering the calculation of the Use Fractions (HBB-3224(b)).

The methods of Appendix HBB-T sometimes require additional information from the analysis results objects. The inelastic multiaxial adjustment used in calculating the total strain range (HBB-T-1432) requires the principal stresses. These results are calculated up front and stored for each load point whether or not they are needed subsequently.

Visual Basic for Applications (VBA) in Microsoft Excel serves as the platform for the computer program. Data input is structured sequentially in worksheet cells similar to an input deck. For example, information for a simple analysis is shown in Fig. 3. The values in the cells represent names to describe certain objects, quantities, such as number of load points in a cycle, number of cycles in analysis, the components of the membrane stress and so on, or types of objects: pressure or thermal gradient for load types, design loads or service loads for analysis case types. The computer program provides tools to help guide the user through the input deck and ensure proper formatting. An example is shown in Fig. 4.

AN	10	11	0	2	FALSE	0
shell under pressure loads						
3	AC1	AC2	AC3			
AC	AC1	1	100000			
Load Controlled Stress Limits						
1	LC1					
AC	AC2	1	100000			
Load Controlled Stress Limits						
1	LC2					
LC	LC1	0	1	FALSE		
Design Loads Cycle						
1	LP1					
LP	LP1	100000	1200	1200		
design conditions						
1	AR1					
AR	AR1	10	11	FALSE		
Pressure Loading						
M	4725	2368	-158	0		
B1	0	0	-158	0		
B2	0	0	158	0		
K1	0	0	0	0		
K2	0	0	0	0		
LC	LC2	1	1	FALSE		

Fig. 3. Example input for an analysis case

HBB Tools

Analysis | Analysis Case | Load Cycle | Load Point | **Analysis Result** | End

Analysis Result Input

Analysis Result Name / Description

Analysis Result ID

Load Type

Load Sub Type

☐ Check here for Direct Stress Category Input

	S11	S22	S33	S12	S13	S23
☒ M	4725	2368	-158	0	0	0
☐ B						
☒ B1	0	0	-158	0	0	0
☒ B2	0	0	158	0	0	0
☒ K1	0	0	0	0	0	0
☒ K2	0	0	0	0	0	0
☐ N/A						
☐ N/A						

<< < > >> Insert Before Overwrite Append After Del

Fig. 4. HBB tools for user input

Output is in log file format with the results of the calculations appearing on a separate “output” spreadsheet. Example output is shown in Fig. 5. Most information focuses on whether or not the design passes or fails a particular test and what tests were conducted.

XX												
Load Controlled Stress Limits												
Analysis Case ID		AC1										
Analysis Case Name		Load Controlled Stress Limits										
Number of Load Cycles		1										
Load Cycle		LC1	Design Loads Cycle									
LP		SURFACE	PM	S0	PASS/FAIL	PL+PB	1.5 S0	PASS/FAIL				
LP1		1	4883	7400	PASS	4883	11100	PASS				
LP1		2	4883	7400	PASS	4883	11100	PASS				
XX												
Load Controlled Stress Limits												
Analysis Case ID		AC2										
Analysis Case Name		Load Controlled Stress Limits										
Number of Load Cycles		1										
Load Cycle		LC2	Operational Loads									
Number of Load Points		2										
Maximum Temperature (Tmax)		1100										
Check Load Controlled Stress Limits for Service Level A/B												
Table 1: Results of Primary Membrane Calculations for Load Cycle LC2												
LP		AVG Wall	Duration (	SURF	PM	Smt(TAVG	PASS/FAIL	Tim(PM)	UF			
LP2		70	0	1	0	20000	PASS	500000	0.00E+0			
LP2		70	0	2	0	20000	PASS	500000				
LP3		1100	10000	1	4750	13900	PASS	648275.5	1.54E-0			
LP3		1100	10000	2	4750	13900	PASS	648275.5	1.54E-0			
Table 2: Results of Primary Membrane + Bending Calculations for Load Cycle LC2												
LP		MAX AVG	SURF	PL+Pb	K Sm(TMAX)	PASS/FAIL						
LP2		1100	1	0	22200	PASS						
LP2		1100	2	0	22200	PASS						
LP3		1100	1	4750	22200	PASS						
LP3		1100	2	4750	22200	PASS						

Fig. 5. Example output from HBB computer program

Currently the computer program has incorporated the load controlled stress limits and the simple elastic analysis tests for strain limits as well as the tables in HBB for 316H. Equations for the isochronous curves have also been included based on the original Blackburn equations that produced the figures in HBB-T-1800. Other tables and figures, in Appendix HBB-T have also been written as equations such as HBB-T-1332-2 in preparation for including ratcheting and creep-fatigue assessments.

6 Summary

The elastic and simplified inelastic methodology of Section III Division 5 Subsection HB, Subpart B is complex and contains many options which require a strong familiarity with the code. In order to help make these methods more accessible, computer program is being developed in Microsoft Excel to streamline the process while including flexibility for user input.

7 Acknowledgments

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8 Appendix. Draft Computer Program Manual

8.1 Background

The workbook functions for a single *analysis location* on a *vessel component*. This *analysis location* essentially corresponds to a single location on a vessel but represents the entire thickness of the vessel. This is best considered as a “Stress Classification Line” or “SCL” for short. For a vessel component with complex geometry, such as near a nozzle, a branch, or tee, the choice of a stress classification line can be somewhat ambiguous.

In keeping with the methods and intent of HBB, stresses are classified by the location and the source of loading. This requires that stresses arising from thermal loading and mechanical loading are determined separately.

8.2 Overview Description of Elements of the Computer Program

The program is organized hierarchically with five essential object classes as shown in Table 1.

Table 1. Major Object classes of the computer program

Object Class	Description
Analysis	The main object in the program. It holds all the information about the vessel component, the location of the analysis, as well as the material id and one or more Analysis Cases.
Analysis Case	An analysis case belongs to the analysis object. Each analysis case is defined by its scope: “Load Controlled Stress Limits,” “Strain Limits,” or “Creep-Fatigue”
Load Cycle	A load cycle is essentially a collection of multiple load points used to define a cycle or simply a series of load points for the calculation of use fractions in a load controlled stress limits analysis case.
Load Point	A load point defines the conditions at the location at a particular point in time or in a cycle. It contains a collection of one or more analysis results as well as the temperature at the start and end of the SCL. A load point also has an associated time.
Analysis Result	An analysis result describes the six stress components associated with a particular load point due to a particular source (pressure, weight, external loads and moments, thermal gradient, and so forth). Each source of loading requires its own analysis result. These stresses are defined at the inside and outside surfaces of the component.

8.2.1 The Analysis Object

There is one unique analysis object for the entire program. This object stores all the other objects as well as information about the vessel component and the location. The properties of the analysis object are shown below in Table 2.

Table 2. Properties of the Analysis Object

Property	Type	Description
Name	String	Any description of the analysis
VCT	Integer	Vessel Component Type, see Table 3
VCST	Integer	Vessel Component Sub-Type, see Table 4
MAT	Integer	A unique material ID, see Table 5
WELD	Boolean	A flag to determine whether to consider the weldment reduction in allowable stresses for Service Loads
TABLE	Integer	Table to use for the R-ratio. The value depends on the weld filler. For example, 316 welded with SFA-5.22 EXXXT-G (16-8-2) uses Table 2.
LOC	Integer	Location Identifier, see Table 6
NAC	Integer	Number of Analysis Cases in the analysis
AC(...)	String	The IDs for the Analysis Cases

For weldments, a reduction factor may need to be taken into account. This is through the ratio of the weld metal creep rupture strength to the base metal creep rupture strength, R . Refer to HBB-3221(a)(2) and associated tables.

The vessel components and vessel component subtypes are provided below. This information is used in the automated stress classification algorithms for the analysis result. For user stress classification, these values can be left as “Not Specified.” Currently analysis of claddings and piping components are not permitted in the computer program.

Materials are limited to those permitted for use in Class A components. A code case for use of Alloy 617 for elevated temperature Class A construction is currently being balloted in the ASME B&PV committees. Only 316 SS is currently implemented.

The location of the analysis is critical in stress classification. These locations are shown in Table 6. Depending on the vessel component, not all locations will be available.

Table 3. Vessel component Type Identification

ID	Description
0	Not Specified
10	Shell
20	Head
30	Nozzle

Table 4. Vessel component Subtype Identification

ID	Description
0	Not Specified
10	Shell Not Specified
11	Cylindrical Shell
12	Spherical Shell
20	Head Not Specified
21	Dished Head
22	Conical Head
23	Flat Head
30	Nozzle

Table 5. Material Identification

ID	Description
1	304 SS
2	316 SS
3	800H
4	Grade 22
5	Grade 91
6	Alloy 617

Table 6. Location Identification

ID	Description
0	Not Specified
1	Remote from discontinuities
2	Junction with head or flange
3	Any Section Across Entire Vessel
4	Near Nozzle or Other Opening
5	Crown
6	Knuckle
7	Junction to Shell
8	Center Region
11	Within limits of reinforcement
12	Outside limits of reinforcement
13	Nozzle Wall

8.2.2 Analysis Case Object

The analysis case object contains the information for a specific analysis case such as a creep-fatigue assessment of combined Levels A, B, and C service limits. Properties of an analysis case object are shown in Table 7. Suggested ids for analysis case have the form “AC1.” The id is case-sensitive. Names should be descriptive. Examples of descriptive names are “Load Controlled Stress Limits for Load Cycle LC1 and LC2” or “Tests B for Load Cycles LC3, LC4, and LC5.”

Table 7. Properties of the Analysis Case Object

Property	Type	Description
ID	String	A unique identification for this analysis case
Name	String	Any description of the analysis case
Type	Integer	See Table 8 Error! Reference source not found.
LIFE	Double	The entire design life of the component
NLC	Integer	Total number of Load Cycles in this case
LC(...)	String	The ids of the load cycles for this case
Use fraction (4)	Real	Use fractions for the following Primary Membrane at location 1 (1) Primary Membrane at location 2 (2) Primary Membrane + Bending at location 1 (3) Primary Membrane + Bending at location 2 (4)

The Analysis Case Type (Table 8) roughly corresponds to Fig. 6, which is after Figure HBB-3221-1, with the strain and deformation limits separated by specific test. The rows of Fig. 6 are defined by the load cycle.

Table 8. Analysis Case Types for the Analysis Case

ID	Description
1	Load Controlled Stress Limits
2	Strain Limits Test A
3	Strain Limits Test B
4	Creep-Fatigue

8.2.3 Load Cycle Object

Load Cycles are containers for individual load points. The properties of a load cycle object are listed in Table 9. IDs for Load Cycles should be in the form “LC1” and are case sensitive. Names should be descriptive, for example, “Normal Operation, Start-Up/Shutdown Cycle.”

There are two types of load cycle objects, “Design” and “Service” as shown in Table 10. Design type load cycles are only permitted to contain one “Design” Load point. Service type load cycles can contain any number of load points and also may be repeated a number of times over the service life for the calculation of use fractions. An optional analysis procedure is to allow for the rotation of the principal stress or strain axes during the load cycle.

Table 9. Properties of the Load Cycle Object

Property	Type	Description
ID	String	A unique string id used to identify this load cycle
NAME	String	Any description of the load cycle object
TYPE	Integer	See Table 10
RPD	Boolean	An option allowing a more detailed calculation of stress and strain ranges. Set to “true” when the principal directions rotate during the cycle. (Used only for service type load cycles)
NLP	Integer	Number of Load Points in this Cycle
REPS	Integer	The number of times this load cycle is repeated over the service life of the vessel (only used for Service type load cycles)
LP(...)	String	The IDs of the load points that go into defining this cycle

Table 10. Types of Load

ID	Description
0	Design
1	Service Level A
2	Service Level B
3	Service Level C
4	Reserved for Service Level D

8.2.4 Load Point Object

Load points are used to define the current stress state at a particular location and time in a cycle. Properties of a Load Point are listed in Table 11. In the case of a design type load point,

Table 11. Properties of the Load Point

Property	Type	Description
ID	String	A unique string id used to identify this load point
Name	String	Any description of the load point object
Temp 1	Real	Temperature of the first location along the SCL
Temp 2	Real	Temperature of the second location along the SCL
t	Real	Time associated with this load point (Not used for design limits)
NR	Integer	Number of analysis results to include in this load point
AR(...)	String	The IDs of the Analysis Results that make up this load point

8.2.5 Analysis Result

An analysis result is basically a set of stresses at a specific location due to a specific type of loading. For example, an analysis result is the set of stresses that result from internal pressure. Though these results may come from a finite element model or some other numerical approach, care should be taken to properly distinguish the “origin of stress.” This is especially true when considering locations near nozzles and other features. Properties of the Analysis Result Object are shown in Table 12.

Stress classification takes place on the level of the analysis result. The vessel component type and location are passed down from the Analysis Object and combined with the Load Sub Type to classify the membrane, bending, and peak stresses from the stress linearization in terms of the stress category (see Table HBB-3217-1). The classification also sometimes depends on the details of the analysis case. For example, Tests B-1 and B-2 in a Strain Limits analysis requires certain thermally induced secondary stresses to be treated as primary stresses.

Table 12. Properties of an Analysis Result Object

Property	Type	Description
ID	String	A unique string id used to identify this load case
Name	String	Any description of the analysis result
Direct Input	Boolean	An option allowing the stresses to be input directly as opposed to being classified by the program
Load Type	Integer	See Table 13
Load Sub Type	Integer	See Table 14
M(2)	Real	Membrane stresses at each location, input
B(2)	Real	Bending stresses at each location, input
K(2)	Real	Additional stress at each location, input
Pm(2)	Real	Primary Membrane, after classification
PL(2)	Real	Primary Local Membrane, after classification
Pb(2)	Real	Primary Bending, after classification
Q(2)	Real	Secondary, after classification
F(2)	Real	Peak Stress, after classification

Table 13. Load Type Identification

ID	Description
0	Not Specified
10	Mechanical
20	Thermal
30	Structural Discontinuity
40	Displacement Controlled Loads

Table 14. Load Subtype Identification

ID	Description
0	Not Specified
10	Mechanical Not Specified
11	Pressure
14	External Load or Moment
20	Thermal Not Specified
21	Thermal Gradient
22	Axial Thermal Gradient
23	Through Thickness Thermal Gradient
30	Gross Structural Discontinuity
40	Displacement Controlled Loads

8.3 Data Input

8.3.1 General Descriptions of Input

The computer program follows a line-by-line interpreter; however, order of object creation is not critical. Lower order objects may be defined before higher order objects can use them. The exception to this rule is the Analysis Object which is defined first in the program. After the analysis is defined, the user may proceed to define a set of analysis results, followed by load points, load cycles, and analysis cases. Or the user may choose to define the analysis results first and then work upward to define the load points, load cycles, etc. Created objects may be reused, for example, a particular analysis result may be used in multiple load points, or a specific load point in multiple load cycles.

8.3.2 Analysis Input

Analysis input begins with the code “AN.” This line can only occur once in the input deck. The analysis input data line describes the vessel component and the location:

```
'AN', VCT, VCST, LOC, MAT, WELD, TABLE
```

```
NAME
```

```
NAC, AC(1), AC(2), ... AC(NAC)
```

8.3.3 Analysis Case Input

The analysis case input begins with the code “AC” and consists of the following:

```
'AC', ID, TYPE, LIFE
```

```
NAME
```

```
NLC, LC(1), LC(2), ...LC(NC)
```


8.3.4 Load Cycle Input

The load cycle input begins with the code “LC” and is as follows.

‘LC’, ID, TYPE, REPS, RPD

NAME

NLP, LP(1), LP(2), ... LP(NLP)

8.3.5 Load Point Input

The load point input begins with the code “LP” and is comprised of the following

‘LP’, ID, TIME, TEMP1, TEMP2

NAME

NAR, AR(1), AR(2), ... AR(NAR)

For design limits analysis cases, the associated time must be entered but is not used in the analysis. Proceed to input for each analysis result.

8.3.6 Analysis Result Input

Analysis result input begins with the code “AR.” The first line of the analysis result input is

‘AR’, ID, TYPE, SUBTYPE, DIFLAG

Name

Set DIFLAG to true in order to specify the stresses by category (Table 16). Set DIFLAG to false to allow the program to perform stress categorization automatically (Table 15).

Subsequently any number of lines may be entered to provide the stress components:

Category Label, S11, S22, S33, S12, S13, S23

The category label provides the interpretation of the stress components. Category labels are case sensitive.

Table 15. Category Labels for Analysis Results (Auto-Categorization)

Category Label	Definition
M	The membrane (average) of the stresses across the SCL
B1	The bending component on surface 1
B2	The bending component on surface 2
K1	Additional stress (difference from linearization) at surface 1
K2	Additional stress (difference from linearization) at surface 2
B	The bending stress at surface 1, the bending stress at surface 2 is opposite in sign

For bending stresses, either category label “B” should be entered or both “B1” and “B2.” Both options are provided for compatibility with output from finite element analysis. If no stress categories are provided, all stress components are assumed to be zero. This is useful when defining the stress free end of a cycle.

Table 16. Category Labels for Analysis Results (Direct Input)

Category Label	Definition
PM1	Primary membrane stress components on surface 1
PM2	Primary membrane stress components on surface 2
PL1	Local Primary membrane stress components on surface 1
PL2	Local Primary membrane stress components on surface 2
PB1	Primary bending stress components on surface 1
PB2	Primary bending stress components on surface 2
Q1	Secondary stress components on surface 1
Q2	Secondary stress components on surface 2
F1	The peak stress at surface 1
F2	The peak stress at surface 2

8.4 Load Cycles and Load Points

Below are some examples of Service related load cycles. Load Points are defined at important sets of conditions during the cycle.

8.4.1 Start-Up/Shut-Down Cycle

A start-up/shut-down cycle may consist of only two load points, an initial “stress-free” load point and the normal operating conditions. The time associated with the initial load point can be zero. The time associated with the operating conditions can be the entire service life, or can be broken down into shorter repeated cycles between planned outages. Additional load points can be used for more detailed analysis of the stresses arising during start-up and shut-down transients. An example is given in Fig. 7.

8.4.2 Warm-Hold Cycle

A warm-hold cycle is considered Service Level A conditions. An example is given in Fig. 8. It also may consist of only two load points: the normal operating conditions and the hold period. Since the cycle begins and ends at the operating conditions, the time associated with load point 1 may be considered negligible for this cycle, or could include the time between events. The time associated with Load Point 2 is simply the warm hold time. Again, additional load points can be used for more detailed analysis of the stresses arising during the transients.

8.4.3 Minor Upset Cycle

Minor upsets in conditions that do not require an outage or force an outage but do not require corrective action are considered Service Level B events. An example is given in Fig. 9. These events have moderate frequency. In this example, a sudden pressure drop causes a temporary increase in temperature. This condition is corrected and the plant returns to normal operation. Three load points are used to describe this cycle. If Load Point 2 is considered the damaging condition, the time associated with it should be conservatively estimated.

Service Level B: Minor Upset

Fig. 9. Example of a service level B minor upset cycle

8.4.4 Major Upset Cycle

Major upsets in conditions require an outage and corrective action or repair. They are anticipated to be infrequent (less than 25 in the lifetime) and are designated as Level C events. An example is given in Fig. 10. In this example, a sudden pressure rise leads to a short-term spike in temperature. The plant is shut-down and repaired before it is returned to service after a normal start-up. Three load points are used to describe this cycle. More may be required in modeling such an event. The time associated with Load Point 3 can be taken as zero.

Service Level C: Major Upset

Fig. 10. Example of a service level C major upset cycle

8.5 Analysis Procedures

Most evaluations begin on the Analysis Case structure.

8.5.1 Load-Controlled Stress Limits

8.5.1.1 Design Limits Evaluation

The following steps are taken for both surface 1 and surface 2 at every load point in the load cycle associated with the design loads. Usually the load cycle for a design limits evaluation will contain a single load point, however,

- 1) Set the Stress Components in each category for this load point to zero
- 2) For each result in the Load Point
 - a) Classify the stress components as P_m , P_L , or P_b
 - b) Add the categorized stress components for this result to the value for this load point
- 3) Calculate the stress intensity for the P_m Category
- 4) Calculate the stress intensity for the combined $P_L + P_b$ category
- 5) Retrieve the value of S_0 at the temperature of the surface as defined for the load point
- 6) Compare the value of the stress intensity P_m to S_0

$$P_m \leq S_0$$

- 7) Compare the value of the stress intensity $P_L + P_b$ to $1.5 S_0$

$$P_L + P_b \leq 1.5 S_0$$

8.5.1.2 Service Levels A&B Evaluation and Service Level C

An analysis case may contain multiple service load cycles. Service Load cycles are classified as either A, B, or C. They also may be repeated multiple times (REPS). The load cycle consists of a number of load point and each load point has an associated time. But an analysis case consists of a single service life.

Here we consider all load points for all load cycles in the analysis case. HBB uses the term “loading event” in a way roughly equivalent to a load point. Each loading event is individually designated by the subscript i . This corresponding load point is a member of a specific cycle, designated by the subscript j , and its order is designated by the subscript k . The reason for distinguishing loading events and load points separately is that a load point may be reused within a load cycle or between load cycles.

The number of repetitions of an individual cycle is designated by n_j , the duration of a load point within a load cycle is t_k . Thus the total duration of any individual loading event is the product of the number of repetitions of the load cycle and the duration of the load point. The sum of all the durations of load events must be greater than or equal to the designated design life for the Analysis Case.

Table 17. Example use of time durations in an Analysis Case

Analysis Case	Load Cycle	Load Point	Loading Event, i	Associated Time, t _i
AC1	LC1 (REPS = n ₁)	LP1 (t=t ₁)	1	n ₁ ·t ₁
		LP2 (t=t ₂)	2	n ₁ ·t ₂
		LP3 (t=t ₃)	3	n ₁ ·t ₃
		TOTAL		n ₁ ·(t ₁ +t ₂ +t ₃)
	LC2 (REPS = n ₂)	LP4 (t=t ₄)	4	n ₂ ·t ₄
		LP5 (t=t ₅)	5	n ₂ ·t ₅
		LP6 (t=t ₆)	6	n ₂ ·t ₆
		TOTAL		n ₂ ·(t ₄ +t ₅ +t ₆)
	LC3 (REPS = n ₃)	LP7 (t=t ₇)	7	n ₃ ·t ₇
		LP8 (t=t ₈)	8	n ₃ ·t ₈
		LP9 (t=t ₉)	9	n ₃ ·t ₉
		TOTAL		n ₃ ·(t ₇ +t ₈ +t ₉)
	TOTAL			≥ LIFE

A description of temperature within the analysis case is also needed, because different stress limits are based on different temperatures within the cycle. Each Load Point, k , has an associated averaged wall temperature, T_k . The maximum of T_k for all load points used in the analysis case is designated by $T_{\max}$.

Three equations, HBB-3223 (3), (4), and (5) must be satisfied for each load point (c.f. “loading event”) for service levels A and B, Table 18. Equations HBB-3224 (7), (9), and (10) must be satisfied for service levels C, Table 19.

Table 18. Criteria for each load point for service levels A and B

Equation	Criterion	Time, t _i	Temperature, T _i
(3) $P_m \leq S_{mt}$	S_{mt}	$n_j t_k$	T_k
(4) $P_L + P_b \leq K S_m$	S_m	N/A	T_k
(5) $P_L + P_b / K_t \leq S_t$	S_t	$n_j t_k$	T_k

Table 19. Criteria for each load point for service level C

Equation	Criterion	Time, t _i	Temperature, T _i
(7) $P_m \leq \begin{cases} 1.2 S_m \\ 1.0 S_t \end{cases}$	S_m	N/A	T_k
	S_t	$n_j t_k$	T_k
(9) $P_L + P_b \leq 1.2 K S_m$	S_m	N/A	T_k
(10) $P_L + P_b / K_t \leq S_t$	S_t	$n_j t_k$	T_k

The associated time for any load point (loading event) will typically be less than the total specified service life of the component and thus the rules of HBB-3223(b) come into effect for all service levels. Use fractions are of two types: those associated with the primary membrane stresses (see HBB-3224, equation

(8)) and those associated with the primary membrane + bending (see HBB-3224, equation 11). The use fractions are derived from all the load points in the analysis case, Table 20.

Table 20. Use fractions for each load point

Equation	Service Levels	S_i	Time, t_i	Temperature, T_i
(8) $\sum_i \left(\frac{t_i}{t_{im}} \right) \leq B$	A & B	P_{mk}	$n_j t_k$	T_k
	C	P_{mk}	$n_j t_k$	T_k
(11) $\sum_i \left(\frac{t_i}{t_{ib}} \right) \leq 1.00$	A & B	$(P_L + P_b / K_t)_k$	$n_j t_k$	T_k
	C	$(P_L + P_b / K_t)_k$	$n_j t_k$	T_k

The following steps are taken for both surface 1 and surface 2

- 1) Determine the maximum averaged wall temperature, T_{max} , for all load points in the analysis case
- 2) Zero the Use Fractions Arrays
- 3) Calculate the factors, K and K_t , using the appropriate value for K (1.5 for across-the-wall bending of shell structures or rectangular sections). See HBB-3223 (c) (6).

$$K_t = (K + 1) / 2$$

- 4) For each load cycle in the analysis case
 - a) Set up the incremental use fraction array for as many load points as needed for this load cycle
 - b) For each load point in this load cycle
 - i) Calculate the associated time for this load point as $t_i = REPS_{LC} \times t_{i,LP}$
 - ii) Clear the stress components for each stress category
 - iii) For each result in the Design Limits Load Point
 - (1) Classify the stress components as P_m , P_L , P_b
 - (2) Add the categorized stress components for this result to the value for this load point
 - iv) Calculate the stress intensity associated with
 - (1) P_m
 - (2) $P_L + P_b$
 - (3) $P_L + P_b / K_t$
 - v) Retrieve the appropriate stress limits: S_{mt} , S_m , and S_t at the average wall temperature for this load point. Note, for weldments, the allowable values S_t and S_{mt} could be replaced by:

$$0.8 S_r \times R$$

See HBB-3221(a)(2) for more information.

- vi) For Service Levels A & B, compare the following:

$$P_m \leq S_{mt}$$

$$P_L + P_b \leq K S_m$$

$$P_L + P_b / K_t \leq S_t$$

vii) or, for Service Level C, compare the following

$$P_m \leq \begin{cases} 1.2 \times S_m \\ 1.0 \times S_t \end{cases}$$

$$P_L + P_b \leq 1.2 K \times S_m$$

$$P_L + P_b / K_t \leq S_t$$

- viii) Determine the maximum allowed time under the load stress intensity for both membrane and the local primary membrane + bending adjusted for K_t .
- ix) Calculate the use factors for each load point in the cycle based on the duration of the loading event.
- c) Sum the use factors for each load point in the cycle and compare
- 5) Sum the use factors for the analysis case for each load cycle.

8.5.2 Strain and Deformation Limits

Strain and deformation limits only apply to analysis cases comprised of service load cycles. Design loads are ignored.

8.5.2.1 Strain Limits, Test Nos. A-1 and A-2

These rules are described in HBB-T-1321, 1322, and 1323. An analysis case must contain all relevant load cycles (see HBB-T-1321 (a), (b), and (c)). For this evaluation the separate load cycles in the analysis case are combined.

- 1) Create a new load cycle combining all the load points of the individual load cycles
- 2) Determine the maximum and minimum averaged wall temperature among all the load points
- 3) On each surface, determine the maximum bending adjusted primary stress intensity over all the load points
- 4) On each surface, determine the maximum secondary stress range as follows
 - a. For each load point determine the secondary stress components
 - b. Calculate the difference between the components of load point i and load point j
 - c. Calculate the secondary stress intensity of the difference between components, $(Q_{diff})_{i,j}$
 - d. Record the load points, LP1 and LP2, that results in the maximum stress intensity of and the value of the difference $(Q_R)_{max}$
- 5) Calculate the following:
 - a. Mean of the maximum and minimum averaged wall temperatures over the cycle, $T_{wall,avg}$
 - b. Yield strength of the material at $T_{wall,avg}$
 - c. Yield strength at the maximum averaged wall temperature, $(S_y)_{max}$

- d. Yield Strength at the minimum averaged wall temperature $(S_y)_{\min}$
- e. The time dependent allowable stress, S_t , for 10,000 hrs at the maximum averaged wall temperature.
- f. The stress criteria for Test No. A-1, S_a which is the lesser of $1.25 \times S_t$ and the average of $(S_y)_{\min}$ and $(S_y)_{\max}$.
- g. The primary stress intensity factor, X :

$$X \equiv \frac{\left(P_L + \frac{P_b}{K_t} \right)_{\max}}{S_y}$$

- h. The secondary stress intensity factor Y :

$$Y \equiv \frac{(Q_R)_{\max}}{S_y}$$

- 6) For Test A-1, compare

$$X + Y \leq \frac{S_a}{S_y}$$

- 7) For Test A-2

- a. Check to make sure that the averaged wall temperature at either LP1 or LP2 is below the applicable temperature limit (see Table HBB-T-1323)
- b. Compare

$$X + Y \leq 1$$

The load cycle passes if it satisfies either of Test A-1 or Test A-2.

8.5.2.2 Strain Limits, Test Nos. B-1 and B-2

These rules are described in HBB-T-1331 and 1332. These tests are similar to Tests A-1 and A-2 as far as determining the stress intensity ranges.

There are also some subtleties with how secondary stresses are classified in these tests. See HBB-T-1331 (d).

Of more immediate significance is the use of “time blocks” in the analysis (see HBB-1332(b)). Note that a time block is different from the “Load Event” of Tests A-1 and A-2 in that it represents a portion of the entire service history. Time blocks are also defined by the load point object, but some important calculations in the analysis span multiple load points based as described below. So the order of load cycles in the analysis case as well as the order of load points within the load cycle can play a significant role in the analysis.

Each load cycle is analyzed separately resulting in a single value of the effective creep stress, or core stress, σ_c . For Test B-1, the core stress is calculated in several steps: in the first step, the maximum primary stress intensity $P_L + P_b / K_t$ is determined for the time block. Second, the maximum secondary stress range, Q_R is determined. It is important to note “that the average wall temperature at one of the stress extremes defining each secondary stress intensity range” must be below the value in Table HBB-T-1323. The primary and secondary stress intensity values are used to calculate the primary and secondary stress parameters, X and Y respectively (see HBB-T-1331 (f)), which, in turn, are used to calculate the parameter Z from figure HBB-T-1332-1. Z is the ratio of the core stress to the yield strength at the “cold end” of the cycle, S_{YL} .

The core stress is used to calculate the creep ratcheting strain from the appropriate isochronous curve. HBB-T-1332(b) provides a description of the procedure, including placing restrictions on the time used in a block followed by a block with a reduced core stress.

As an example, consider the load history as shown in Fig. 11. Here, three load cycles are pictured, each composed of a different set of load points which represent individual temperature-time blocks. The temperatures for some load points fall above the temperature limit, T_{lim} , defined in Table HBB-T-1323, and for others below T_{lim} . Between the last block of load cycle 1 and the first block of load cycle 2 there is an increase in the core stress, which requires no special action. Between load cycle 2 and load cycle 3, on the other hand, there is a decrease in the core stress. This may require that the final temperature-time block in the second load cycle is extended to allow for the core stress to “relax” to the 3rd load cycle condition. This is explained further below.

The simplified inelastic analysis makes use of the isochronous stress-strain curve (ISSC) in calculating the inelastic creep ratcheting strain. For a given load point (block), an increment in inelastic strain is calculated by subtracting the elastic strain from the total.

Of course, for Test B-1, the core stress cannot exceed the yield at the “hot end” of the secondary stress range, which, in effect, eliminates time-independent inelastic strain from the calculation and the inelastic strain is identical to the creep strain.

The method of calculating the creep strain increment for the first cycle is shown in Fig. 12. Here the core stress is designated by σ_{c1} . In this example, a 10,000-hour time block (t_1), produces an inelastic strain of $\Delta\epsilon_{c1}$. The inelastic strains are accumulated over the service history. Fig. 13 shows the calculation of the strain accumulated in the i^{th} increment. Here the isochronous curve is entered at the past strain, ϵ_{0i} which is the sum of the elastic strain at the current temperature and the sum of all increments of strains from prior blocks. An effective past time, t_{0i} , is determined as the time to reach the prior strain at the core stress and temperature for the current block. In this case, $t_{0i} = 100$ hrs. The increment of creep strain for this block is calculated as the difference between the initial strain and the strain calculated from at the effective past time and the duration of the current block (in this example, the sum is 100,000 hours).

Fig. 12. Calculation of creep strain increment in the first cycle

Fig. 13. Calculation of creep strain increment in a subsequent cycle where the core stress has not decreased between cycles

When the core stress decreases between temperature-time blocks, HBB-T requires adjustment to the time. As described in HBB-T-1322(b): “When σ_c is reduced at the end of a block of loading, the time of the block of loading must be longer or equal to the time needed for σ_c to relax at constant total strain to the σ_c value for the subsequent block.” The calculation method is illustrated by example in Fig. 14. Path *a* shows the creep strain increment from an effective past time of 30 hours to a total time of 10,000 hours at a core stress of σ_{cj} . Because the core stress is reduced in the next block, additional time must be added. Path *b* shows a relaxation path from the core stress σ_{cj} to the core stress σ_{cj+1} . This provides a time to reach σ_{cj+1}

at the current block time t_j of 100,000 hrs. Using t_j in place of the $t_{0j} + t_j$, the strain increment $\Delta\epsilon_{cj}$ is calculated.

Fig. 14. Calculation of creep strain increment when the core stress decreases between cycles

Test B-2 proceeds similarly but there is no restriction on the core stress. The core stress is calculated from the Z parameter from figure HBB-T-1332-2.

- 1) On each surface, determine the maximum bending adjusted primary stress intensity over all the service related load cycles in this analysis case
- 2) On each surface, determine the maximum secondary stress range as follows
 - a. for each load point in each service related load cycle determine the secondary stress components
 - b. calculate the difference between the components of load point i and load point j
 - c. calculate the secondary stress intensity of the difference between components, $(Q_{diff})_{i,j}$
 - d. record the load points, LP_1 and LP_2 , that results in the maximum stress intensity of and the value of the difference $(Q_R)_{\max}$
- 3) Calculate the following:
 - a. Yield strength at the lower of the wall-averaged temperatures defining, the maximum secondary stress range, S_{yL}
 - b. Yield strength at the higher of the wall-averaged temperatures defining, the maximum secondary stress range, S_{yH}
 - c. The primary stress intensity factor, X with $S_y = S_{yL}$:

$$X \equiv \frac{\left(P_L + \frac{P_b}{K_t} \right)_{\max}}{S_y}$$

- d. The secondary stress intensity factor Y with $S_y = S_{yL}$:

$$Y \equiv \frac{(Q_R)_{\max}}{S_y}$$

- e. Z_{B1} for Test B-1 from HBB-T-1322-1.
- f. Z_{B2} for Test B-2 from HBB-T-1322-2.
- g. $(\sigma_c)_{B1} = Z_{B1} S_{yL}$
- h. $(\sigma_c)_{B2} = Z_{B2} S_{yL}$
- 4) Store the following for the temperature time-block
 - a. The values of the core stress for each Test B-1 and B-2. These values are constant over the Load Cycle
 - b. The time of the block from the time associated with the load point
 - c. The temperature of the block as the averaged wall temperature associated with the load point
 - d. For every repetition of the load cycle add one instance of the block
- 5) For the each temperature-time blocks up to $n_{block} - 1$

- a. If this is the first block
 - i. Calculate the hot tensile strain
 - ii. Calculate the total creep strain for the core stress, temperature, and actual time
- b. otherwise
 - i. Calculate the total strain at the beginning of the block from the accumulated inelastic strain and the elastic strain at the temperature and core stress for the current block.
 - ii. Determine the effective past time from the ISSC with strain equal to the total strain at the beginning of the block, the core stress and temperature for the current block
 - iii. Calculate the candidate total strain at the end of this block using the time equal to the effective accumulated time plus the time associated with this block and the current core stress.
 - iv. If the subsequent block has a smaller value of core stress
 - 1. Calculate the time at relaxation to the subsequent core stress from the ISSC with strain equal to the candidate total strain from (5)(b)(ii), temperature equal to the current block temperature, and stress equal to the subsequent core stress.
 - 2. Calculate the total strain at the end of this block from the time from above, the current core stress, and the current temperature
 - 3. The increment of inelastic strain for this step is the difference between the total strain at the end of the block and the total strain at the beginning of the block
 - v. If the subsequent block has the same or larger core stress
 - 1. The total strain at the end of the block is equal to the candidate strain.
 - 2. The increment of inelastic strain for this step is the difference between the total strain at the end of the block and the total strain at the beginning of the block
- 6) Compare the total inelastic strain at the end of the block to the strain limits as described in HBB-T-1322(b).

8.6 Interpretations of the ASME HBB in the Computer Program

In several places the language in the code language is ambiguous. Interpretation of some of the more important areas is described below.

8.6.1 HBB-3223

8.6.1.1 Temperature for evaluation of S_m in equation (4)

Paragraph HBB-3223 (a)-(e) describe the stress limit for the primary membrane, and combinations of primary membrane and bending stresses. The temperatures to use for S_{mt} and S_t are provided, but not for S_m . Based on the language of (b) it is interpreted as the maximum averaged wall temperature corresponding to that particular loading event.

8.6.1.2 Temperature for evaluation of S_t in equation (5)

Paragraph HBB-3223 (a)-(e) describe the stress limit for the primary membrane, and combinations of primary membrane and bending stresses. The temperatures to use for S_m and S_t are provided. Paragraph (a) states that the temperature used in calculating S_m corresponds to the “the maximum wall averaged temperature that occurs during the particular loading event.” Paragraph (e) describes T as “the maximum wall averaged temperature,” but follows this with the phrase “during the entire service life of the component.” This could be taken as meaning the temperature used in evaluating S_m in equation (5) is the maximum wall averaged temperature for all loading events during the entire service life. However, that interpretation would go against paragraphs (b) and (f) that describe the advantage of “subdividing loading history into several load levels and into several temperatures at any given load level” in the use fractions analysis. Therefore, we interpret the temperature for calculation of S_m in equation (5) to be the same as the temperature for calculation of S_t in equation (3).

8.6.2 HBB-T-1331

Paragraph (f) refers to definitions of X_L , Y_L , X_H , and Y_H , to distinguish between the cold and hot ends. However, none of these parameters are referred to in any equation for Test B-2.

Intentionally Blank

9 References

- [1] ASME Boiler and Pressure Vessel Code, Section III, Div 5, Subsection HB, Subpart B (HBB), 2015 Edition.
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