STP-PT-024

DEVELOPMENT OF BASIC TIME-DEPENDENT ALLOWABLE STRESSES FOR CREEP REGIME IN SECTION VIII DIVISION I

ASME STANDARDS TECHNOLOGY, LLC

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FOREWORD

This document was developed under a research and development project which resulted from ASME Pressure Technology Codes & Standards (PTCS) committee requests to identify, prioritize and address technology gaps in current or new PTCS Codes, Standards and Guidelines. This project is one of several included for ASME fiscal year 2008 sponsorship which are intended to establish and maintain the technical relevance of ASME codes & standards products. The specific project related to this document is project 07-08 (BPVC#7), entitled, "Development of Basic Time-Dependent Allowable Stresses for Creep Regime in Section VIII Division I."

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ABSTRACT

This report provides recommendations for design rules for very short term loads for which creep should not be a design consideration, termed Occasional Loads herein, and rules for loads for which creep is a design consideration, termed Time Dependent Design Considering Creep.

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1 INTRODUCTION

The rules of Section VIII, Division 1 provide an allowable stress for design of pressure vessels that is independent of load duration. In the time dependent regime where failure by creep rupture is a consideration, the actual life of the vessel depends on a number of things, including the margins provided in the allowable stresses, the margin between design pressure and operating pressure and the margin between design temperature and operating temperature. While material properties for a time duration of 100,000 hours are included as part of the basis in establishing the allowable stress, this is not an anticipated nor a design life for the pressure vessel.

There are short term conditions for which design based on an allowable stress set based on long term creep properties is unrealistically conservative. An obvious example is earthquake loading, which is of very short duration, for which creep rupture is not a relevant failure mode. Another example, albeit more subjective, is loading due to extreme wind, the wind velocities typically used in design. With respect to overload failure, the relevant material properties are yield and tensile properties, not creep properties. Considering, for example, the ratio of yield strength to the allowable stress for Type 304H stainless steel at 1200˚F and 1400˚F are 2.3 and 5.0 (yield strength values per Section III, Subsection NH [5]), respectively, provides an indication of the conservatism of using creep properties for earthquake design.

In addition, there are processes that operate at various conditions. An example would be longer term operation at a lower temperatures combined with short term regeneration conditions at higher temperatures. If rules could explicitly consider load duration, the short term condition could be designed for a higher allowable stress than is provided in the Code allowable stresses, which are based on long term operation.

Finally, it may be desired by a user to explicitly design for a specific life, rather than accept the indeterminate life that results from the combinations of margins mentioned above. Rules that provide for consideration of time dependent allowable stresses can be used to explicitly design for a specific life, e.g., 300,000 hours.

This report provides recommendations for design rules for very short term loads for which creep should not be a design consideration, termed Occasional Loads herein, and rules for loads for which creep is a design consideration, termed Time Dependent Design Considering Creep.

2 METHODS

2.1 Method for Occasional Loads

Section VIII, Division 1 permits the allowable stress for conditions that include wind and earthquake to be 1.2 times the basic allowable stress. At temperatures in the creep regime, the allowable stress is governed by creep material properties that are based on 100,000 hour durations. However, creep rupture is not a failure mode relevant to earthquakes and may not be relevant for extreme winds (e.g., hurricane events), since the duration of these loads is short.

The allowable stress for these very short term events should be based on tensile properties of the material. These could consider both yield strength and tensile strength, or yield strength only. We recommend that the allowable stress be based on yield strength, since low cycle fatigue and ratchet are the general failure mechanisms of concern, rather than rupture for ductile materials. Note that these materials, operating in the creep range, are ductile.

The basic recommended allowable stress for the combination of sustained and occasional loads is 1.2 * 2/3* S_y = 0.8 S_y, or S_y for austenitic stainless steel and materials with similar stress strain characteristics. The first limit for other than austenitic stainless steel provides the same margin relative to yield strength as the existing rules. The second limit for austenitic stainless steel is slightly more conservative with respect to yield as the existing rules would permit 1.2 * 0.9 S_y = 1.08 S_y.

An additional consideration is that the yield strength for some materials drops somewhat over time. Yield strength reduction factors as a function of time are provided in the ASME Boiler and Pressure Vessel Code, Section III, Subsection NH for some limited materials. The reduction factors for Types 304 and 316 stainless steel and 9Cr-1Mo-V are set at 1.0; the reduction factor for 800H is set at 0.9; and the reduction factor for 2-1/4 Cr – 1 Mo, for a 100,000 hour duration at the highest temperature 1100˚F, is 0.79.

As an initial recommendation, we recommend that a material strength reduction factor of 0.8 be applied to all materials other than austenitic stainless steel. Further study could provide more specific yield strength reduction factors that provide more precise distinction between materials. However, the benefit of being able to design based on yield strength should in most all circumstances outweigh the debit of including the material strength reduction factor.

A means to define what loading conditions may be included for this allowable stress basis is required. We set an objective of a total duration of ten hours. Thus, in design, the total loading duration of all occasional loads for which these time independent allowables would be used would be ten hours. We then evaluated a variety of materials, as described in Section 3.1, for these proposed short term allowables.

The allowable duration of the occasional load was calculated for a variety of materials, as described in Section 3.1. The allowable life, using a basis consistent with the code rules (e.g., 80% min. stress rupture for the stress and duration), was determined. Based on this study, it was determined that an additional factor was required to achieve the desired ten hour allowable load duration. The additional limit is that in no case may the stress exceed four times the allowable stress in Section II, Part D [4].

Considering the yield strength reduction factor, and the desired permissible load duration of ten hours, the recommended limits for evaluation of stresses that include earthquake or extreme wind are as follows.

1. All materials other than those cited below: 0.64 S_y
2. Austenitic stainless steel: 1.0 S_y

3. Other materials with stress strain characteristics similar to austenitic stainless steel: 0.8 S_y
4. But not greater than 4S (per Section II, Part D, Table 1A).

2.2 Method for Time Dependent Design Considering Creep

To perform time dependent design, creep properties must be considered. However, these properties as a function of time and temperature are only provided with Section III, Subsection NH, within the ASME Boiler and Pressure Vessel Code, and there only for a very limited number of alloys. Time dependent properties for more alloys are provided in ASME FFS-1 [2] but design using these properties could arguably be considered to require a greater degree of sophistication than is desirable for Section VIII, Div 1 applications.

This report proposes a relatively simple approach to explicitly consider time, without requiring material data beyond what is provided in the existing allowable stress tables. The basis for the allowable stresses for Section VIII, Div 1 construction is the following (per ASME Section II, Part D, Appendix 1). At temperatures above the temperature for which time dependent properties govern the allowable stress (termed the transition temperature, the highest temperature for which allowable stresses are provided that is not governed by creep properties), the creep properties govern.

$S_T/3.5$ or $1.1\ S_T R_T/3.5$

$2/3\ S_y$ or $2/3\ S_Y R_Y$ or $0.9\ S_Y R_Y$

$F_{avg}\ S_{R\ avg}$, $0.8\ S_{R\ min}$

S_c

From ASME Section II, Part D, these values are defined (quoted) as:

F_{avg} multiplier to average stress for rupture in 100,000 hr. At 1500˚F and below, F_{avg} is 0.67. Above 1500˚F, it is determined from the slope of the log time-to-rupture versus log stress plot at 100,000 hr. such that $F_{avg} = 1/n$, but it may not exceed 0.67.

R_T ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength.

R_Y ratio of the average temperature dependent trend curve value of yield strength to the room temperature yield strength.

S_c average stress to produce a creep rate of 0.01%/1,000 hr.

S_{Ravg} average stress to cause rupture at the end 100,000 hr.

S_{Rmin} minimum stress to cause rupture at the end of 100,000 hr.

S_T specified minimum tensile strength at room temperature, ksi.

S_Y specified minimum yield strength at room temperature, ksi.

n a negative number equal to Δlog time-to rupture divided by Δlog stress at 100,000 hr.

The relationship for creep properties between time and temperature for a given stress is commonly expressed in terms of the Larson-Miller parameter. The equation is of the form:

$$LMP = \left[\left(T + 460\right)/1000\right]\left(A + B\log t\right) \tag{1}$$

A and B material dependent constants

T temperature (˚F)

T time (hours)

The Larson-Miller parameter is a constant for a given stress. Given the temperature and duration for a value of stress, the Larson-Miller parameter may be calculated.

The proposed approach is to use the Larson-Miller parameter to calculate allowable stresses (on the same creep bases as are used to set the basic Code allowable stresses) for shorter and longer durations, for a given temperature and stress. While strictly applicable to extrapolating rupture properties, this can be done with the existing allowable stress tables, as follows.

1. Calculate the stress for an operating condition.
2. Determine the temperature from the allowable stress table for which that calculated stress would be the allowable stress.
3. Calculate the Larson-Miller parameter based on the temperature determined from step 2 and a duration of 100,000 hours.
4. Given the Larson-Miller parameter that has been determined to be applicable for the value of stress, from step 3, calculate an allowable duration for the actual temperature of the operating condition.

This can be done for a number of operating conditions, and then combined in a typical time fraction summation approach, with the sum of the time fractions limited to 1.0.

The approach requires consideration of operating conditions. That is, the expected combinations of actual operating pressures and associated metal temperatures. There would still be a design pressure and temperature used in the design process to set the minimum required wall thickness. But short term high temperature events may not govern in establishing the design condition.

After establishing the basic required metal thicknesses, time dependent life calculations can be performed, including a specified life, and additional short term operating conditions. By using operating pressures and temperatures for this life assessment, design lives that are significantly greater than 100,000 hours can be calculated, even when the calculated stress for the design condition is equal to the allowable stress. This provides a uniform prediction of life, which is independent of margins placed on temperature and pressure when setting the design conditions.

There are three additional considerations

1. When the temperature for an operating condition is below the transition temperature.
2. When the calculated stress for an operating condition has an associated allowable stress that is higher than the allowable stress at the transition temperature.
3. When the calculated stress for an operating condition is less than the stress at the highest temperature for which allowable stresses are provided in the allowable stress table.

For the first condition, the temperature is below a temperature for which significant creep effects are anticipated with an additional margin (as the allowable stress at that condition is based on strength properties). For operating conditions at temperatures equal to or below the transition temperature, the condition is not considered in the life fraction calculation.

For the second and third condition to be considered, first consider a typical curve for a material showing the allowable stresses based on tensile strength versus creep properties as a function of temperature. See Figure 1. In the temperature range where creep governs the allowable stress, the slope of the allowable stress versus temperature curve is continually decreasing. This effects how conditions below the transition temperature and above the maximum temperature can be readily considered.

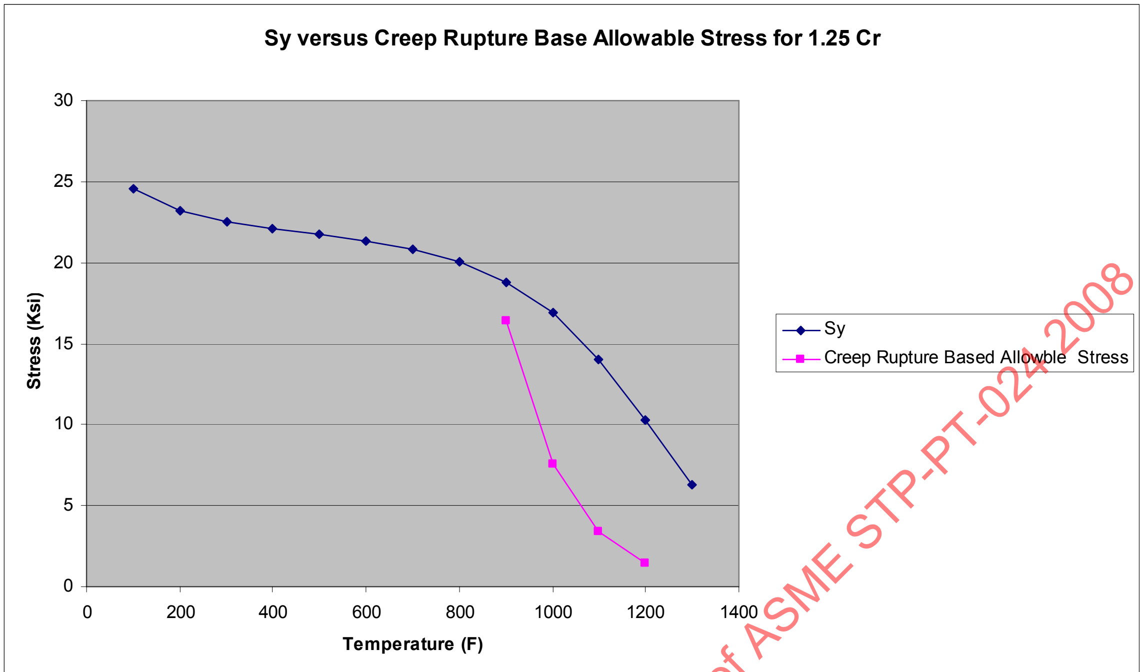


Figure 1 - Example Yield Stress and Allowable Stress Versus Temperature

For temperatures below the transition temperature, the values of allowable stress could be used, which would be conservative. This is because a lower temperature would be selected for calculating the Larson-Miller parameter, which will result in a lower value of the parameter and associated shorter lives when used to calculate life at the operating temperature. Noting that the slope is continually decreasing, a less conservative, but conservative nonetheless, approach can be used. The first two values of allowable stress above the transition temperature can be used to extrapolate the time dependent component of allowable stress to lower temperatures. This will always result in a lower value than the actual material properties would yield, with a resulting, conservatively low value of the Larson-Miller parameter.

At temperatures above the maximum temperature for which allowable stresses are provided, the curve cannot be conservatively extrapolated. Therefore, when the stress is below the minimum allowable stress value that is provided, the associated maximum temperature should be used to calculate the Larson-Miller parameter. Again, this will provide a lower temperature than the actual material properties would yield, which will provide a conservatively low value of the Larson Miller parameter and further life prediction.

The follow steps summarize the proposed method.

1. Given σ_i, t_i and T_i for number (i) of short-term and long-term elevated temperature cases.
2. Compute the Von-Mises (effective) stress for each case. Alternatively, max. principal stress for consistency with VIII-1.
3. Use effective or max. principal stress for each case to find the corresponding temperature "T_{Di}" temperatures from II-D; this presumes that such temperature is associated with the allowable stress controlled by stress rupture (i.e., this is an elevated temperature condition).
4. Compute the $LMP(t_{1000000}, T_{Di})_i$ for each case with API-579 LMP material constants and 100,000 hr. (the "basis" for VIII-1 creep rupture life).

5. Compute the allowable time $(t_i)_i$ for each case using the LPM for each case with $t_i=(10)\exp(a_i)$ where $a_i=LMP(t,T)_i/(T_i=480)-C$.
6. Compute the *life consumption*, λ for each case; $\lambda_i=t_i/(t_i)_i$.
7. $\Lambda=\Sigma\lambda_i$ Design acceptable if $\Lambda<1.0$.

3 RESULTS

3.1 Results for Occasional Loads

Table 1 summarizes material properties, allowable stress for occasional loads of short duration and allowable duration. The Yield Strength values at elevated temperatures were taken from ASME FFS-1 [2]. There are differences between the II-Part D Yield Stresses and the ASME FFS-1 yield stresses. These differences are considered to be insignificant for the purposes of evaluating these proposed short-term allowable stresses.

The column 4S provides four times the allowable stress from Section II as described in 2.2.2; the column S_y*F provides the yield based allowable, with F equal to 1.0, 0.8, or 0.64, depending upon material, as described in Section 2.1. S_{occ} is the minimum of these two, the governing condition, and the proposed allowable stress for design for loads with short duration.

Temp is the temperature in the allowable stress table associated with a stress equal to S_{occ}. C is the material constant in the Larson-Miller equation, taken from ASME FFS-1. LMP is the derived Larson-Miller Parameter and t is the allowable duration, calculated as described in Section 2.2.

When the value of S_{occ} was outside of the limits of the allowable stress table, the allowable duration was calculated based on creep rupture properties found in ASME FFS-1. A value of $1.25S_{occ}$ was used, together with the minimum rupture curve, to determine the Larson-Miller Parameter. This is the same as the 80% min. stress rupture basis.

The calculated allowable durations, in hours, are provided in the "t" column.

The ratio of the proposed allowable to the present Code allowable (using 1.2 times the allowable stress values found in Section II, Part D) are provided in the final column. This is $S_{occ}/1.2S$.

Table 1 - Proposed Allowable Stress Parameters

Nominal Composition	Spec No.	T/Grade	UNS No.	St_{min} (ksi)	$Sy_{min(}$ (ksi)	4S (ksi)	Sy*F (ksi)	S_{occ} (ksi)	Temp (F)	C	LMP	t (hr)	New/Old (%)
Carbon Steel	SA-516	70	K02700	70	38	10	15.00	10.00	837.04	20	32.4	1.6E+02	333%
1CR-1/2Mo	SA-387	12	K11757	65	40	4.4	13.85	4.40	1052.94	20	37.8	6.1E+02	333%
-	-	-	-	-	-	11.2	17.61	11.20	951.22	20	35.3	4.1E+02	333%
1-1/4Cr-1/2Mo-Si	SA-387	11	K11789	75	45	4.8	15.58	4.80	1035.71	20	37.4	3.4E+02	333%
-	-	-	-	-	-	11.2	19.81	11.20	928.41	20	34.7	1.8E+02	333%
-	-	-	-	-	-	25.2	22.82	22.82	X	20	32.7	2.6E+02	302%
-	-	-	-	-	-	54.8	24.62						
-	-	-	-	-	-	85.6	25.52						
2-1/4Cr-1Mo	SA-387	22	K21590	75	45	4.8	15.58	4.80	1042.11	20	37.6	4.2E+02	333%
-	-	-	-	-	-	12.8	19.81	12.80	934.09	20	34.9	2.2E+02	333%
-	-	-	-	-	-	31.2	22.82	22.82	X	20	31.8	6.3E+01	244%
3Cr-1Mo	SA-387	21	K31545	75	45	5.2	15.58	5.20	1042.11	20	37.6	4.2E+02	333%
-	-	-	-	-	-	12.8	19.81	12.80	904.17	20	34.1	7.3E+01	333%
-	-	-	-	-	-	27.2	22.82	22.82	X	20	32.4	1.6E+02	280%
5Cr-1/2Mo	SA-182	F5a	K42544	90	65	4	22.50	4.00	1057.69	20	37.9	7.2E+02	333%
-	-	-	-	-	-	11.6	28.62	11.60	889.71	20	33.7	4.3E+01	333%
-	-	-	-	-	-	23.2	32.96	23.20	X	20	31.0	1.7E+01	333%
9Cr-1Mo	SA-217	C12	J82090	90	60	6	20.77	6.00	1029.17	20	37.2	2.7E+02	333%
-	-	-	-	-	-	13.2	26.42	13.20	929.63	20	34.7	1.9E+02	333%

Nominal Composition	Spec No.	T/Grade	UNS No.	St_{min} (ksi)	$Sy_{min(}$ (ksi)	4S (ksi)	Sy*F (ksi)	S_{occ} (ksi)	Temp (F)	C	LMP	t (hr)	New/Old (%)
-	-	-	-	-	-	29.6	30.42	29.60	X	20	32.1	1.0E+02	333%
9Cr-1Mo-V	SA-387	91	K90901	85	60	17.2	15.72	15.72	X	30	51.7	1.3E+01	305%
13Cr	SA-240	410	S41000	65	30	4	19.20	4.00	1063.33	30	53.3	1.3E+02	333%
16Cr-12Ni-2Mo	SA-240	316H	S31609	75	30	5.2	9.42	5.20	1260.71	15	34.4	3.6E+02	333%
-	-	-	-	-	-	9.2	11.46	9.20	1162.50	15	32.5	2.8E+02	333%
-	-	-	-	-	-	16.4	13.13	13.13	X	15	30.3	1.7E+02	267%
18Cr-8Ni	SA-240	304L	S30403	70	25	12.8	12.02	12.02	X	15	30.4	2.1E+03	313%
18Cr-8Ni	SA-240	304H	S30409	75	30	5.6	9.42	5.60	1217.86	15	33.6	1.3E+02	333%
-	-	-	-	-	-	9.2	11.46	9.20	1114.29	15	31.5	8.5E+01	333%
-	-	-	-	-	-	14.8	13.13	13.13	X	15	30.0	1.1E+02	296%
-	-	-	-	-	-	24.4	14.42						
-	-	-	-	-	-	39.2	15.37						
-	-	-	-	-	-	56	16.08						
18Cr-10Ni-Cb	SA-240	347H	S34709	75	30	5.2	12.54	5.20	1273.33	15	34.7	4.9E+02	333%
-	-	-	-	-	-	10	14.86	10.00	1159.62	15	32.4	2.6E+02	333%
-	-	-	-	-	-	17.6	16.53	16.53	X	15	30.7	2.7E+02	313%
-	-	-	-	-	-	31.6	17.62	17.62	X	15	30.5	2.3E+03	186%
18Cr-10Ni-Ti	SA-240	321H	S32109	75	30	4.4	12.54	4.40	1238.46	15	34.0	2.1E+02	333%
-	-	-	-	-	-	7.6	14.86	7.60	1134.09	15	31.9	1.4E+02	333%
-	-	-	-	-	-	12.8	16.53	12.80	X	15	29.9	9.2E+01	333%
-	-	-	-	-	-	21.6	17.62	17.62	X	15	28.6	1.8E+02	272%
47Ni-22Cr-9Mo-18Fe	SB-622	…	N06002	100	40	4.8	9.37	4.80	1400.00	15	37.2	4.3E+02	333%
-	-	-	-	-	-	12	17.37	12.00	1187.50	15	33.0	6.5E+01	333%
-	-	-	-	-	-	19.2	19.71	19.20	1079.76	15	30.8	3.6E+01	333%
46Ni-27Cr-23Fe-2.75Si	SB-167	…	N06045	90	35	3.4							
57Ni-22Cr-14W-2Mo-La	SB-435	…	N06230	110	45	1.8	6.94	1.80	1625.00	15	41.7	2.8E+03	333%
-	-	-	-	-	-	4.4	11.87	4.40	1487.50	15	39.0	1.1E+03	333%
-	-	-	-	-	-	16.4	19.62	16.40	1188.24	15	33.0	6.6E+01	333%
-	-	-	-	-	-	26.8	22.40	22.40	1109.54	15	31.4	7.5E+01	279%
72Ni-15Cr-8Fe	SB-168	…	N06600	80	35	8	20.80	8.00	986.11	15	28.9	2.6E+02	333%
-	-	-	-	-	-	12	23.19	12.00	937.04	15	27.9	8.1E+02	333%
-	-	-	-	-	-	28	24.62	24.62	X	15			
33Ni-42Fe-21Cr	SB-409	…	N08800	75	30	3.2	11.06	3.20	1272.73	15	34.7	4.8E+02	333%
-	-	-	-	-	-	4.4	13.56	4.40	1245.83	15	34.1	2.2E+03	333%
-	-	-	-	-	-	8	15.33	8.00	1178.13	15	32.8	4.1E+03	333%
-	-	-	-	-	-	26.4	16.47	16.47	1056.65	15	30.3	1.9E+03	208%
33Ni-42Fe-21Cr	SB-409	…	N08810	65	25	7.6	7.71	7.60	1194.74	15	33.1	7.7E+01	333%
-	-	-	-	-	-	12	9.25	9.25	1151.26	15	32.2	2.1E+02	257%
-	-	-	-	-	-	18.8	10.43	10.43	1125.42	15	31.7	1.0E+03	185%
33Ni-42Fe-21Cr	SB-409	…	N08811	65	25	6.4	7.71	6.40	1261.54	15	34.4	3.7E+02	333%
-	-	-	-	-	-	13.6	9.25	9.25	1177.33	15	32.7	4.0E+02	227%

Figure 2 shows a comparison of current allowable stresses and the proposed allowable stresses for two selected materials. For these two materials, at least, the proposed allowable stresses are significantly, and reasonably higher than the current allowable stresses for loads of short duration, such as earthquakes.

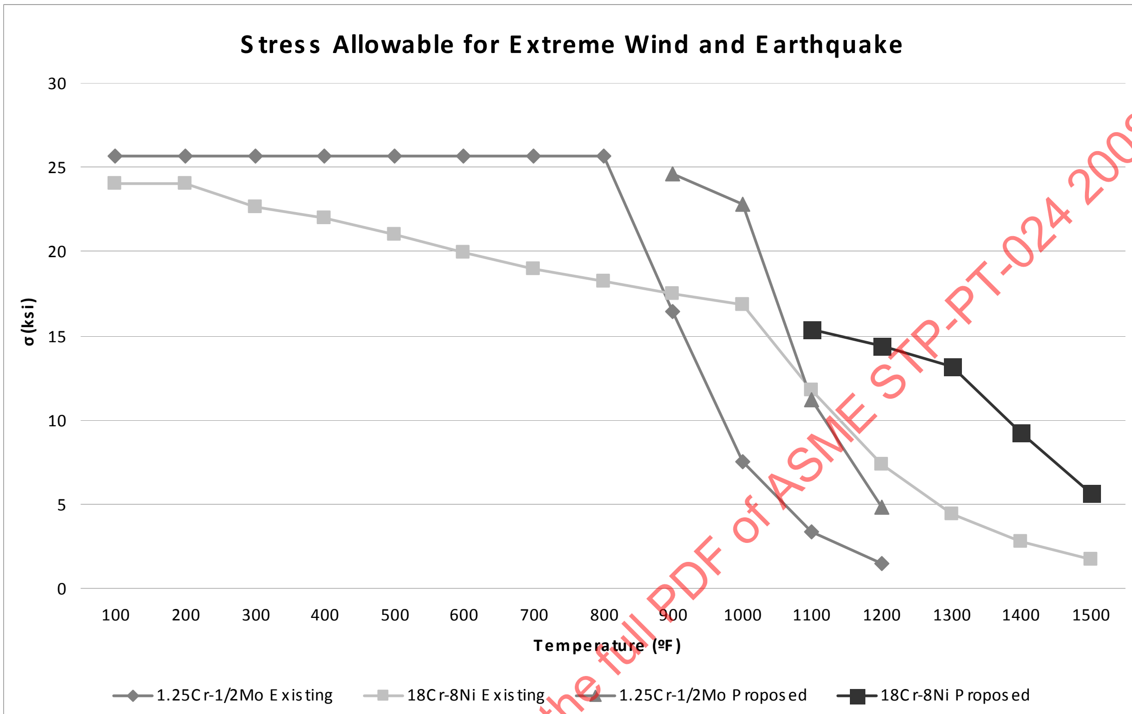


Figure 2 - Comparison of Existing Allowable Stresses with Proposed Allowable Stresses

Considering that the occasional load event is not the only consideration in the life of the vessel, the calculated allowable time must be greater than ten hours. An objective of 50 hours was set, based on which 20% of the design life would be consumed by a ten hour duration of the occasional load events. Note that this calculation includes the design margins already in the allowable stress basis.

Table 1 shows that the shortest allowable time (the "t" column) is six hours, and a total of four cases are below 50 hours. Figure 3 shows the times in Table 1. Times greater than 500 hr. are not shown to provide focus at times less than 500 hr.

1. Most cases are greater than 100 hours.
2. Eight cases are between 100 and 50 hours.
3. Three Cases are between 50 and 13 hours.
4. No cases are below 13 hr.

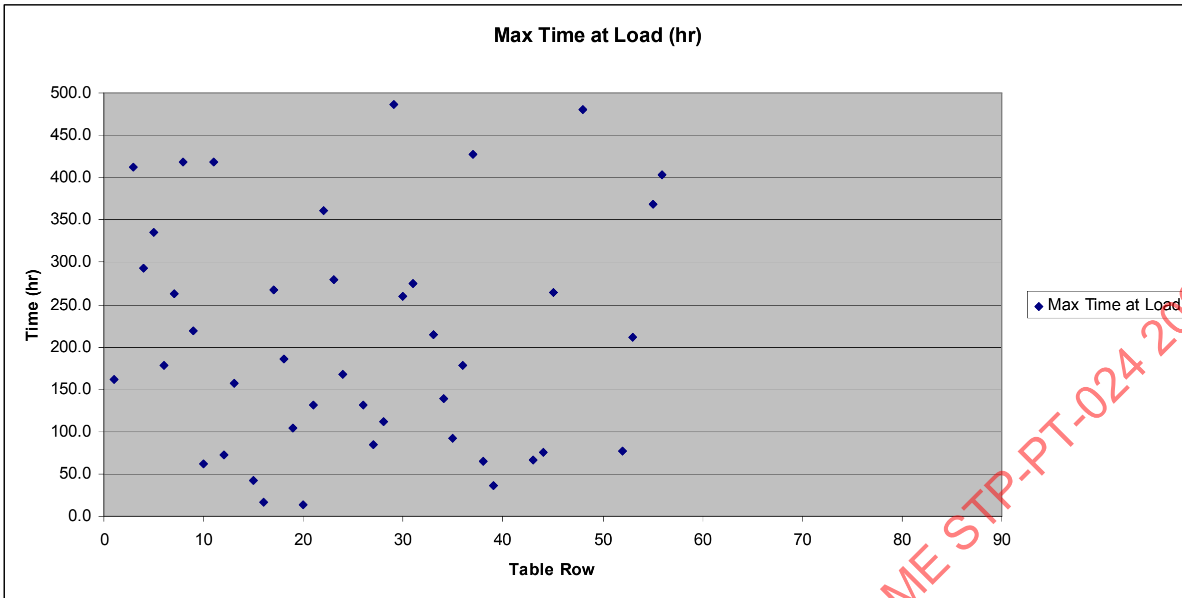


Figure 3 - Maximum Time at Load

A similar approach to this recommended treatment of occasional loads has already been incorporated into the ASME B31.3, Process Piping Code [3]. One of the differences is that a factor of 1.33 was considered rather than 1.2. The limit provided in ASME B31.3 [3] is 0.9 S_y for all materials and a material strength reduction factor of 0.8 is applied to all materials other than austenitic stainless steel, for which a factor of 1.0 is specified.

Based on the above evaluation, the proposed basis is reasonable for most all alloys. There may be exceptions, such as the case found with a six hour allowable duration. We recommend that Subcommittee II review this for all alloys, and cite specific exceptions if warranted.

3.2 Results for Time Dependent Design Considering Creep

Examples of typical process plant operating and design conditions, for elevated temperature equipment that operates at more than one condition are provided to illustrate the proposed method. These example evaluations are provided in Appendix A and Appendix B. Appendix A provides the calculations, and Appendix B shows the material data used in the calculations. The first example in Section A.1, is from the example shown in ASME B31.3, Appendix V followed by several variations using different materials. The examples in Section A.3 are representative of some current refinery applications. For these cases, the wall thickness is calculated based on a typical design condition to provide a point for comparison. Then, a new design condition was selected based on excluding short term conditions. The wall thickness was calculated for the new design condition, and the time fraction calculation was made considering all operating conditions. If the life fraction was greater than one, the wall thickness was increased until the life fraction was equal to one.

A creep damage calculation was made using the methodology provided in ASME FFS-1 for a case with 21/4Cr-1Mo material, to confirm the conservatism of the method. The ASME FFS-1 damage assessment is provided in Section A.2 of Appendix A. The proposed method is more conservative than that provided in ASME FFS-1. The margin in the proposed method is consistent with the existing Section VIII Code Criteria.

Use of operating conditions is consistent with other code calculations where life is a consideration, such as in design for fatigue, and in limiting primary plus secondary stress ranges.

If the short term condition is at a higher pressure than the design condition, there would be an issue with the set pressure for the relief valve. In this case, it may be necessary to use overpressure protection by system design, per Code Case 2211, to benefit from the proposed rules.

With respect to the calculated life for the expected long term operating conditions, there may be a concern that an operator may run the vessel at the nameplate pressure and temperature. However, since the basic allowable stresses are used in designing the equipment for the design pressure and temperature, this is essentially the same as currently permitted in the 2007 edition of Section VIII, Div. 1.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Occasional Loads

Rules for Section VIII, Division 1 should be developed based on the results provided in Section 3.1.

A user design specification or similar should be required in which the user states the conditions under which the vessel will be operated. While a post construction issue, consideration should be given on how these will be controlled and monitored.

Materials that exhibit low allowable times at temperature, such as the Grade 91 material which had six hours, as shown in Table 1, should receive additional attention for partial or complete exclusion from permitting short-term allowable stress methods. Additional margin could be applied to these materials for use in short-term evaluations.

4.2 Time Dependent Design Considering Creep

Rules for Section VIII, Division 1 should be developed based on the results provided in Section 3.2.

The method proposed for time dependent design considering creep is based on showing that a damage fraction of various partitions of life sum to less than 1.0, similar to damage fraction calculations in other sections of the Code. It is also possible to devise rules based on setting allowable stresses for life partitions (time at temperature at stress). This is acceptable as long as the damage fraction requirement is met.

REFERENCES

[1] The ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, "Rules for Construction of Pressure Vessels," 2007 Edition.

[2] API 579-1/ASME FFS-1 2007 Fitness-For-Service.

[3] The American Society of Mechanical Engineers, B31.3, "Process Piping Code," 2004 Edition.

[4] The ASME Boiler and Pressure Vessel Code, Section II, Part D "Properties–MATERIAL," 2007 Edition.

[5] The ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NH, "Class 1 Components in Elevated Temperature Service–Rules For Construction of Nuclear Facility Components," 2007 Edition.

APPENDIX A - EXAMPLE CALCULATIONS FOR TIME DEPENDENT DESIGN CONSIDERING CREEP

NOTE: Appendix B of this report contains the material properties as a function of temperature, and the interpolation for the "T_D" temperatures for the examples here, in Appendix A. The material data is from Section II, Part II of the ASME B&PV Code

A.1 Examples Part 1 -- Examples 1-6

A.1.1 Example 1 -- B31.3 Example but with II-D Properties (SA-335 P22)

Material **A335, *Grade 22*** Pipe

$C_{A335} := 20$ LMP constant for A335 material (from B31.3 Example)

$P_D := 250 \cdot psi$ design pressure (not used -- for information only)

$T_D := 1050 \cdot F$ design temperature (not used -- for information only)

$t_{life} := 200000 \cdot hr$ total service life (not used -- for information only)

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 := 178000 \cdot hr$ $t_2 := 20000 \cdot hr$ $t_3 := 2000 \cdot hr$

$T_1 := 1025F$ $T_2 := 1050F$ $T_3 := 1050F$

$\sigma_{eff.1} := 5100 \cdot psi$ $\sigma_{eff.2} := 5100 \cdot psi$ $\sigma_{eff.3} := 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex1.1} := 1066 \cdot F$ see Appendix B

$T_{D.ex1.2} := 1066 \cdot F$ see Appendix B

$T_{D.ex1.3} := 1028 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$$LMP_{ex1.1} := \left(T_{D.ex1.1} + 460 \cdot F\right)\left(C_{A335} + \log(100000)\right) \qquad LMP_{ex1.1} = 38.150 \times 10^3 F$$

$$LMP_{ex1.2} := \left(T_{D.ex1.2} + 460 \cdot F\right)\left(C_{A335} + \log(100000)\right) \qquad LMP_{ex1.2} = 38.150 \times 10^3 F$$

$$LMP_{ex1.3} := \left(T_{D.ex1.3} + 460 \cdot F\right)\left(C_{A335} + \log(100000)\right) \qquad LMP_{ex1.3} = 37.200 \times 10^3 F$$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex1.1} := \frac{LMP_{ex1.1}}{\left(T_1 + 460 \cdot F\right)} - C_{A335} \qquad a_{ex1.1} = 5.69$$

$$t_{r.ex1.1} := 1 \cdot hr\,(10)^{a_{ex1.1}} \qquad \boxed{t_{r.ex1.1} = 490045 \cdot hr}$$

$$a_{ex1.2} := \frac{LMP_{ex1.2}}{\left(T_2 + 460 \cdot F\right)} - C_{A335} \qquad a_{ex1.2} = 5.265$$

$$t_{r.ex1.2} := 1 \cdot hr\,(10)^{a_{ex1.2}} \qquad \boxed{t_{r.ex1.2} = 184035 \cdot hr}$$

$$a_{ex1.3} := \frac{LMP_{ex1.3}}{\left(T_3 + 460 \cdot F\right)} - C_{A335} \qquad a_{ex1.3} = 4.636$$

$$t_{r.ex1.3} := 1 \cdot hr\,(10)^{a_{ex1.3}} \qquad \boxed{t_{r.ex1.3} = 43228 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex1.1} := \frac{t_1}{t_{r.ex1.1}} \qquad \boxed{\lambda_{ex1.1} = 0.363}$$

$$\lambda_{ex1.2} := \frac{t_2}{t_{r.ex1.2}} \qquad \boxed{\lambda_{ex1.2} = 0.109}$$

$$\lambda_{ex1.3} := \frac{t_3}{t_{r.ex1.3}} \qquad \boxed{\lambda_{ex1.3} = 0.046}$$

STEP 7: Compute total life consumption, Λ:

$$\Lambda_{ex1} := \lambda_{ex1.1} + \lambda_{ex1.2} + \lambda_{ex1.3} \qquad \boxed{\Lambda_{ex1} = 0.518}$$

acceptable when less than 1.000

A.1.2 Example 2 -- B31.3 Example with II-D Properties (SS 316)

Material SA-240; **S31600**, Table 1A, pg 74, line 5

$C_{S316} := 15$ LMP constant (from FFS-1 579; Table F.31)

$P_D = 250 \cdot psi$ design pressure

$T_D = 1050 F$ design temperature

$t_{life} = 200000 \cdot hr$ total service life

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 = 178000 \cdot hr$	$t_2 = 20000 \cdot hr$	$t_3 = 2000 \cdot hr$
$T_1 = 1025 F$	$T_2 = 1050 F$	$T_3 = 1050 F$
$\sigma_{eff.1} = 5100 \cdot psi$	$\sigma_{eff.2} = 5100 \cdot psi$	$\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex2.1} := 1264.3 \cdot F$ see Appendix B

$T_{D.ex2.2} := 1264.3 \cdot F$ see Appendix B

$T_{D.ex2.3} := 1217.6 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$LMP_{ex2.1} := (T_{D.ex2.1} + 460 \cdot F)(C_{S316} + \log(100000))$ $LMP_{ex2.1} = 34.486 \times 10^3 F$

$LMP_{ex2.2} := (T_{D.ex2.2} + 460 \cdot F)(C_{S316} + \log(100000))$ $LMP_{ex2.2} = 34.486 \times 10^3 F$

$LMP_{ex2.3} := (T_{D.ex2.3} + 460 \cdot F)(C_{S316} + \log(100000))$ $LMP_{ex2.3} = 33.552 \times 10^3 F$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex2.1} := \frac{LMP_{ex2.1}}{(T_1 + 460 \cdot F)} - C_{S316} \qquad a_{ex2.1} = 8.223$$

$$t_{r.ex2.1} := 1 \cdot hr (10)^{a_{ex2.1}} \qquad \boxed{t_{r.ex2.1} = 167 \times 10^6 \cdot hr}$$

$$a_{ex2.2} := \frac{LMP_{ex2.2}}{(T_2 + 460 \cdot F)} - C_{S316} \qquad a_{ex2.2} = 7.838$$

$$t_{r.ex2.2} := 1 \cdot hr (10)^{a_{ex2.2}} \qquad \boxed{t_{r.ex2.2} = 69 \times 10^6 \cdot hr}$$

$$a_{ex2.3} := \frac{LMP_{ex2.3}}{(T_3 + 460 \cdot F)} - C_{S316} \qquad a_{ex2.3} = 7.220$$

$$t_{r.ex2.3} := 1 \cdot hr (10)^{a_{ex2.3}} \qquad \boxed{t_{r.ex2.3} = 17 \times 10^6 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex2.1} := \frac{t_1}{t_{r.ex2.1}} = 0.001$$

$$\lambda_{ex2.2} := \frac{t_2}{t_{r.ex2.2}} = 0$$

$$\lambda_{ex2.3} := \frac{t_3}{t_{r.ex2.3}} = 0$$

STEP 7: Compute total life consumption, Λ:

$$\Lambda_{ex2} := \lambda_{ex2.1} + \lambda_{ex2.2} + \lambda_{ex2.3} = 0.001$$

acceptable when less than 1.000

A.1.3 Example 3 -- B31.3 Example with II-D Properties (SS 304)

Material SA-240; **S30400**, API-530 (FFS-1 is incorrect at 0.0)

$C_{S304} := 15$ LMP constant (from FFS-1; Table F.31)

$P_D = 250 \cdot psi$ design pressure

$T_D = 1050F$ design temperature

$t_{life} = 200000 \cdot hr$ total service life

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 = 178000 \cdot hr$ $t_2 = 20000 \cdot hr$ $t_3 = 2000 \cdot hr$

$T_1 = 1025F$ $T_2 = 1050F$ $T_3 = 1050F$

$\sigma_{eff.1} = 5100 \cdot psi$ $\sigma_{eff.2} = 5100 \cdot psi$ $\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex3.1} := 1235.7 \cdot F$ see Appendix B

$T_{D.ex3.2} := 1235.7 \cdot F$ see Appendix B

$T_{D.ex3.3} := 1180.3 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$LMP_{ex3.1} := (T_{D.ex3.1} + 460 \cdot F)(C_{S304} + \log(100000))$ $LMP_{ex3.1} = 33.914 \times 10^3 F$

$LMP_{ex3.2} := (T_{D.ex3.2} + 460 \cdot F)(C_{S304} + \log(100000))$ $LMP_{ex3.2} = 33.914 \times 10^3 F$

$LMP_{ex3.3} := (T_{D.ex3.3} + 460 \cdot F)(C_{S304} + \log(100000))$ $LMP_{ex3.3} = 32.806 \times 10^3 F$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex3.1} := \frac{LMP_{ex3.1}}{(T_1 + 460 \cdot F)} - C_{S304}$$ $$a_{ex3.1} = 7.838$$

$$t_{r.ex3.1} := 1 \cdot hr(10)^{a_{ex3.1}}$$ $$\boxed{t_{r.ex3.1} = 69 \times 10^6 \cdot hr}$$

$$a_{ex3.2} := \frac{LMP_{ex3.2}}{(T_2 + 460 \cdot F)} - C_{S304}$$ $$a_{ex3.2} = 7.460$$

$$t_{r.ex3.2} := 1 \cdot hr(10)^{a_{ex3.2}}$$ $$\boxed{t_{r.ex3.2} = 29 \times 10^6 \cdot hr}$$

$$a_{ex3.3} := \frac{LMP_{ex3.3}}{(T_3 + 460 \cdot F)} - C_{S304}$$ $$a_{ex3.3} = 6.726$$

$$t_{r.ex3.3} := 1 \cdot hr(10)^{a_{ex3.3}}$$ $$\boxed{t_{r.ex3.3} = 5 \times 10^6 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex3.1} := \frac{t_1}{t_{r.ex3.1}}$$ $$\boxed{\lambda_{ex3.1} = 0.003}$$

$$\lambda_{ex3.2} := \frac{t_2}{t_{r.ex3.2}}$$ $$\boxed{\lambda_{ex3.2} = 6.941 \times 10^{-4}}$$

$$\lambda_{ex3.3} := \frac{t_3}{t_{r.ex3.3}}$$ $$\boxed{\lambda_{ex3.3} = 0}$$

STEP 7: Compute total life consumption, Λ:

$$\Lambda_{ex3} := \lambda_{ex3.1} + \lambda_{ex3.2} + \lambda_{ex3.3}$$ $$\boxed{\Lambda_{ex3} = 3.657 \times 10^{-3}}$$

acceptable when less than 1.000

A.1.4 Example 4 -- B31.3 Example with II-D Properties (SS 347)

Material SA-240; **S34709**, Table 1A, pp 102-105 line 21

$C_{S347} := 15$ LMP constant (from FFS-1; Table F.31)

$P_D = 250 \cdot psi$ design pressure

$T_D = 1050F$ design temperature

$t_{life} = 200000 \cdot hr$ total service life

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 = 178000 \cdot hr$ $t_2 = 20000 \cdot hr$ $t_3 = 2000 \cdot hr$

$T_1 = 1025F$ $T_2 = 1050F$ $T_3 = 1050F$

$\sigma_{eff.1} = 5100 \cdot psi$ $\sigma_{eff.2} = 5100 \cdot psi$ $\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex4.1} := 1276.7 \cdot F$ see Appendix B

$T_{D.ex4.2} := 1276.7 \cdot F$ see Appendix B

$T_{D.ex4.3} := 1229.3 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$LMP_{ex4.1} := (T_{D.ex4.1} + 460 \cdot F)(C_{S347} + \log(100000))$ $LMP_{ex4.1} = 34.734 \times 10^3 F$

$LMP_{ex4.2} := (T_{D.ex4.2} + 460 \cdot F)(C_{S347} + \log(100000))$ $LMP_{ex4.2} = 34.734 \times 10^3 F$

$LMP_{ex4.3} := (T_{D.ex4.3} + 460 \cdot F)(C_{S347} + \log(100000))$ $LMP_{ex4.3} = 33.786 \times 10^3 F$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex4.1} := \frac{LMP_{ex4.1}}{(T_1 + 460 \cdot F)} - C_{S347} \qquad a_{ex4.1} = 8.39$$

$$t_{r.ex4.1} := 1 \cdot hr (10)^{a_{ex4.1}} \qquad \boxed{t_{r.ex4.1} = 245 \times 10^6 \cdot hr}$$

$$a_{ex4.2} := \frac{LMP_{ex4.2}}{(T_2 + 460 \cdot F)} - C_{S347} \qquad a_{ex4.2} = 8.003$$

$$t_{r.ex4.2} := 1 \cdot hr (10)^{a_{ex4.2}} \qquad \boxed{t_{r.ex4.2} = 101 \times 10^6 \cdot hr}$$

$$a_{ex4.3} := \frac{LMP_{ex4.3}}{(T_3 + 460 \cdot F)} - C_{S347} \qquad a_{ex4.3} = 7.375$$

$$t_{r.ex4.3} := 1 \cdot hr (10)^{a_{ex4.3}} \qquad \boxed{t_{r.ex4.3} = 24 \times 10^6 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex4.1} := \frac{t_1}{t_{r.ex4.1}} \qquad \boxed{\lambda_{ex4.1} = 0.001}$$

$$\lambda_{ex4.2} := \frac{t_2}{t_{r.ex4.2}} \qquad \boxed{\lambda_{ex4.2} = 1.988 \times 10^{-4}}$$

$$\lambda_{ex4.3} := \frac{t_3}{t_{r.ex4.3}} \qquad \boxed{\lambda_{ex4.3} = 0}$$

STEP 7: Compute total life consumption, Λ:

$$\Lambda_{ex4} := \lambda_{ex4.1} + \lambda_{ex4.2} + \lambda_{ex4.3} \qquad \boxed{\Lambda_{ex4} = 0.001}$$

acceptable when less than 1.000

A.1.5 Example 5 -- B31.3 Example with II-D Properties (1 Cr)

Material SA-387; **1 Cr** K11757, Table 1A, pp 30-33 line 34

$C_{1Cr} := 20$ LMP constant (from FFS-1; Table F.31 **using 0.5Cr**)

$P_D = 250 \cdot psi$ design pressure

$T_D = 1050 F$ design temperature

$t_{life} = 200000 \cdot hr$ total service life

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 = 178000 \cdot hr$ $t_2 = 20000 \cdot hr$ $t_3 = 2000 \cdot hr$

$T_1 = 1025 F$ $T_2 = 1050 F$ $T_3 = 1050 F$

$\sigma_{eff.1} = 5100 \cdot psi$ $\sigma_{eff.2} = 5100 \cdot psi$ $\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex5.1} := 1038.9 \cdot F$ see Appendix B

$T_{D.ex5.2} := 1038.9 \cdot F$ see Appendix B

$T_{D.ex5.3} := 1008.7 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$LMP_{ex5.1} := (T_{D.ex5.1} + 460 \cdot F)(C_{1Cr} + \log(100000))$ $LMP_{ex5.1} = 37.472 \times 10^3 F$

$LMP_{ex5.2} := (T_{D.ex5.2} + 460 \cdot F)(C_{1Cr} + \log(100000))$ $LMP_{ex5.2} = 37.472 \times 10^3 F$

$LMP_{ex5.3} := (T_{D.ex5.3} + 460 \cdot F)(C_{1Cr} + \log(100000))$ $LMP_{ex5.3} = 36.718 \times 10^3 F$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex5.1} := \frac{LMP_{ex5.1}}{\left(T_1 + 460 \cdot F\right)} - C_{1Cr} \qquad a_{ex5.1} = 5.234$$

$$t_{r.ex5.1} := 1 \cdot hr (10)^{a_{ex5.1}} \qquad \boxed{t_{r.ex5.1} = 171 \times 10^3 \cdot hr}$$

$$a_{ex5.2} := \frac{LMP_{ex5.2}}{\left(T_2 + 460 \cdot F\right)} - C_{1Cr} \qquad a_{ex5.2} = 4.816$$

$$t_{r.ex5.2} := 1 \cdot hr (10)^{a_{ex5.2}} \qquad \boxed{t_{r.ex5.2} = 65 \times 10^3 \cdot hr}$$

$$a_{ex5.3} := \frac{LMP_{ex5.3}}{\left(T_3 + 460 \cdot F\right)} - C_{1Cr} \qquad a_{ex5.3} = 4.316$$

$$t_{r.ex5.3} := 1 \cdot hr (10)^{a_{ex5.3}} \qquad \boxed{t_{r.ex5.3} = 21 \times 10^3 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex5.1} := \frac{t_1}{t_{r.ex5.1}} \qquad \boxed{\lambda_{ex5.1} = 1.039}$$

$$\lambda_{ex5.2} := \frac{t_2}{t_{r.ex5.2}} \qquad \boxed{\lambda_{ex5.2} = 0.305}$$

$$\lambda_{ex5.3} := \frac{t_3}{t_{r.ex5.3}} \qquad \boxed{\lambda_{ex5.3} = 0.097}$$

STEP 7: Compute total life consumption, Λ:

$$\Lambda_{ex5} := \lambda_{ex5.1} + \lambda_{ex5.2} + \lambda_{ex5.3} \qquad \boxed{\Lambda_{ex5} = 1.440}$$

acceptable when less than 1.000

A.1.6 Example 6 -- B31.3 Example with II-D Properties (800H)

Material SA-407; **Alloy 800H** N08810, Table 1B, pp 242-245 line 39

$C_{800H} := 15$ LMP constant (from FFS-1; Table F.31

$P_D = 250 \cdot psi$ design pressure

$T_D = 1050\,F$ design temperature

$t_{life} = 200000 \cdot hr$ total service life

STEPS 1, 2, 3: Information as given in this example for each elevated temperature case, i:

$t_1 = 178000 \cdot hr$	$t_2 = 20000 \cdot hr$	$t_3 = 2000 \cdot hr$
$T_1 = 1025\,F$	$T_2 = 1050\,F$	$T_3 = 1050\,F$
$\sigma_{eff.1} = 5100 \cdot psi$	$\sigma_{eff.2} = 5100 \cdot psi$	$\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Set T_D Temperatures for each stress level:

$T_{D.ex6.1} := 1283.3 \cdot F$ see Appendix B

$T_{D.ex6.2} := 1283.3 \cdot F$ see Appendix B

$T_{D.ex6.3} := 1222.3 \cdot F$ see Appendix B

STEP 4: Compute LMPs for each T_D using 100,000 hr.

$LMP_{ex6.1} := \left(T_{D.ex6.1} + 460 \cdot F\right)\left(C_{800H} + \log(100000)\right)$ $LMP_{ex6.1} = 34.866 \times 10^3\,F$

$LMP_{ex6.2} := \left(T_{D.ex6.2} + 460 \cdot F\right)\left(C_{800H} + \log(100000)\right)$ $LMP_{ex6.2} = 34.866 \times 10^3\,F$

$LMP_{ex6.3} := \left(T_{D.ex6.3} + 460 \cdot F\right)\left(C_{800H} + \log(100000)\right)$ $LMP_{ex6.3} = 33.646 \times 10^3\,F$

STEP 5: Compute rupture time for each case, $(t_r)_i$

$$a_{ex6.1} := \frac{LMP_{ex6.1}}{(T_1 + 460 \cdot F)} - C_{800H} \qquad a_{ex6.1} = 8.479$$

$$t_{r.ex6.1} := 1 \cdot hr\,(10)^{a_{ex6.1}} \qquad \boxed{t_{r.ex6.1} = 301 \times 10^6 \cdot hr}$$

$$a_{ex6.2} := \frac{LMP_{ex6.2}}{(T_2 + 460 \cdot F)} - C_{800H} \qquad a_{ex6.2} = 8.090$$

$$t_{r.ex6.2} := 1 \cdot hr\,(10)^{a_{ex6.2}} \qquad \boxed{t_{r.ex6.2} = 123 \times 10^6 \cdot hr}$$

$$a_{ex6.3} := \frac{LMP_{ex6.3}}{(T_3 + 460 \cdot F)} - C_{800H} \qquad a_{ex6.3} = 7.282$$

$$t_{r.ex6.3} := 1 \cdot hr\,(10)^{a_{ex6.3}} \qquad \boxed{t_{r.ex6.3} = 19 \times 10^6 \cdot hr}$$

STEP 6: Compute life consumption for each case, λ_i:

$$\lambda_{ex6.1} := \frac{t_1}{t_{r.ex6.1}} \qquad \boxed{\lambda_{ex6.1} = 0.001}$$

$$\lambda_{ex6.2} := \frac{t_2}{t_{r.ex6.2}} \qquad \boxed{\lambda_{ex6.2} = 0.000}$$

$$\lambda_{ex6.3} := \frac{t_3}{t_{r.ex6.3}} \qquad \boxed{\lambda_{ex6.3} = 0}$$

STEP 7: Compute life consumption, Λ:

$$\Lambda_{ex6} := \lambda_{ex6.1} + \lambda_{ex6.2} + \lambda_{ex6.3} \qquad \boxed{\Lambda_{ex6} = 0.001}$$

acceptable when less than 1.000

Summary of *life consumption* for each example (material)

Example	Total Life	t_1 Life	t_2 Life	t_3 Life
1. A335	$\Lambda_{ex1} = 0.518$	$\lambda_{ex1.1} = 0.363$	$\lambda_{ex1.2} = 0.109$	$\lambda_{ex1.3} = 0.046$
2. SS 316	$\Lambda_{ex2} = 0.001$	$\lambda_{ex2.1} = 0.001$	$\lambda_{ex2.2} = 0$	$\lambda_{ex2.3} = 0.000$
3. SS 304	$\Lambda_{ex3} = 0.004$	$\lambda_{ex3.1} = 0.003$	$\lambda_{ex3.2} = 0.001$	$\lambda_{ex3.3} = 0.000$
4. SS 347	$\Lambda_{ex4} = 0.001$	$\lambda_{ex4.1} = 0.001$	$\lambda_{ex4.2} = 0.000$	$\lambda_{ex4.3} = 0.000$
5. 1 Cr	$\Lambda_{ex5} = 1.44$	$\lambda_{ex5.1} = 1.039$	$\lambda_{ex5.2} = 0.305$	$\lambda_{ex5.3} = 0.097$
6. Alloy 800H	$\Lambda_{ex6} = 0.001$	$\lambda_{ex6.1} = 0.001$	$\lambda_{ex6.2} = 0.000$	$\lambda_{ex6.3} = 0.000$

A.2 Example 1 using ASME FFS-1 Level 1 Assessment

STEP 1: Determine maximum temperature, pressure and service time for each operating condition, j.

$t_1 = 178000 \cdot hr$ $t_2 = 20000 \cdot hr$ $t_3 = 2000 \cdot hr$

$T_1 = 1025\,F$ $T_2 = 1050\,F$ $T_3 = 1050\,F$

$P_D = 250 \cdot psi$

STEP 2: Determine the nominal stress.

$\sigma_{eff.1} = 5100 \cdot psi$ $\sigma_{eff.2} = 5100 \cdot psi$ $\sigma_{eff.3} = 6730 \cdot psi$

STEP 3: Determine material of construction and figure for damage curves.

Material   **<u>A335, *Grade 22*</u>** Pipe; 2.25Cr-1Mo (Annealed)

Curves: Figure 10.9 (b) for 2.25Cr-1M0 Annealed

STEP 4: Determine R_c^j and D_c^j

$R_{c.1} := \frac{1.6 \cdot 10^{-7}}{hr}$ $R_{c.2} := \frac{1.7 \cdot 10^{-7}}{hr}$ $R_{c.3} := \frac{1.4 \cdot 10^{-5}}{hr}$

$D_{c.1} := R_{c.1} \cdot t_1$ $D_{c.2} := R_{c.2} \cdot t_2$ $D_{c.3} := R_{c.3} \cdot t_3$

$D_{c.1} = 0.028$ $D_{c.2} = 0.003$ $D_{c.3} = 0.028$

STEP 5: Total Damage.

$D_{c.allow} := 0.25$

$D_c := D_{c.1} + D_{c.2} + D_{c.3}$ $\boxed{D_c = 0.06}$

$\frac{D_c}{D_{c.allow}} = 0.24$

VIII/B31.3 allowable stress method gives 0.363 + 0.109 + 0.046 = 0.518/1.00 = 0.518

A.3 Examples Part 2 -- Industrial Example

Four examples are presented, all using a 160-inch OD vessel (cylindrical shell) with two different materials and two different sets of elevated temperature operating conditions; one short-term (10,000 hr -or- 20,000 hr) and one long-term (100,000 hr -or- 200,000) hr. The examples and their variations are shown in Table Ex 7.1.

Table Ex 7.1
Example 7, 8, 9, 10 Variations

Example	Material	Time Variation
No.	Comp	t1 (hr) and t2 (hr)
7	1.25 Cr-1 Mo	10,000 & 100,000
8	1.25 Cr-1 Mo	20,000 & 200,000
9	2.25 Cr - 1 Mo	10,000 & 100,000
10	2.25 Cr - 1 Mo	20,000 & 200,000

Table Ex 7.2 shows two elevated temperature conditions ("1" and "2") that are applied to each of the four examples.

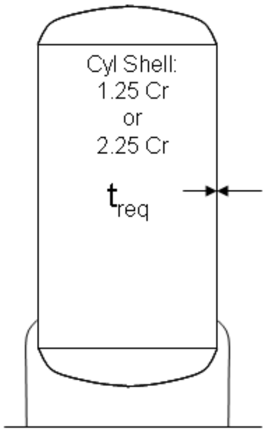
Table Ex 7.2
Example 7, 8, 9, 10 Design and Operating Conditions

	1	1	2	2	1	1	1	2	2	2
Example	Design Press., DP_1	Design Temp DT_1	Design Press., DP_2	Design Temp DT_2	Operating Pressure, p_1	Operating Temp., T_1	Operating Time t_1	Operating pressure p_2	Operating Temp., T_2	Operating Time t_2
No.	psi	°F	psi	°F	psi	°F	hr	psi	°F	hr
7	600	1075	650	1025	545	1025	10,000	590	975	100,000
8	600	1075	650	1025	545	1025	**20,000**	590	975	**200,000**
9	600	1075	650	1025	545	1025	10,000	590	975	100,000
10	600	1075	650	1025	545	1025	**20,000**	590	975	**200,000**

Two computational parts are used for each example. The first part, labeled "g", shows how the present VIII-1 rules could be used to set the shell thickness using most controlling of the two design conditions. The minimum required thickness is computed, a fabrication thickness is set to be slightly greater than the minimum required thickness, then the life consumption is calculated for the two operating conditions. The life consumption is calculated **for reference/information**; i.e., it is not part of the present code rules.

The second part, labeled "h", uses a design pressure and temperature based on the long-term operating condition. A modified minimum shell thickness is computed, a modified fabrication thickness is set, and a modified life consupmtions are calculated for the two operating conditions.

Examples 7, 8, 9, 10



Set DP and DT as a User of VIII-1 could specify.

DT = max OT + 50F
DP = max OP * 1.10

calculations part "g"

Calculate t_{req}"g" UG-27, with VIII-1 S for DT and DP
Set fabrication thickness > t_{req}"g"
Calculate stress for 2 op cases $(OT,OP)_{1\ and\ 2}$
Calculate life consumptions (λ_1 and λ_2)"g" – for REF/INFO
Calculate total life consumption, Λ"g" – for REF/INFO

calculations part "h"

modified DT = temperature of the long-term condition + 50F
Re-calculate t_{req}"h" based on DP for the long-term condition
Re-set fabrication thickness > t_{req}"h"
Re-calculate stress for 2 op cases
Re-calculate life consumptions (λ_1 and λ_2)"h"
Re-calculate total life consumption, Λ"h"
Show Λ"h" $\leq$ 1.00

Parameters applicable for all four examples. **NOTE: Green boxed items are INPUT**

$OD_{shell} := 160 \cdot in$ specified outside diameter of vessel cyclindrical shell

$f_{DP} := 1.1$ factor on operating pressure for design pressure (typically a user-specified issue).

$C_{LMP} := 20$ Larson-Miller parameter for both 1.25 and 2.25 Cr material from FFS-1, Table F.31 and API-530.

$DT_{marg.g} := 50 \cdot F$ Design Temperature Margin for "g" part (current rules)

$DT_{marg.h} := 50 \cdot F$ Design Temperature Margin for "h" part (proposed rules)

NOTE: For Examples 7, 8, 9, 10, interpolation of material data is done using the MATHCAD "linterp" function. The Section II-D data for 1.25Cr and 2.25Cr is entered into vectors, which are used in the "linterp" function.

Section VIII Allowable Stresses for Examples 7 and 8 (1.25 Cr)

Allowable stresses (from II-D) for interpolating for TEMPERATURE based on stress:

$ST_1 := 1200 \cdot F$ $\quad S_{viii_1} := 1200 \cdot psi$

$ST_2 := 1150 \cdot F$ $\quad S_{viii_2} := 1900 \cdot psi$

$ST_3 := 1100 \cdot F$ $\quad S_{viii_3} := 2800 \cdot psi$

$ST_4 := 1050 \cdot F$ $\quad S_{viii_4} := 4200 \cdot psi$

$ST_5 := 1000 \cdot F$ $\quad S_{viii_5} := 6300 \cdot psi$

$ST_6 := 950 \cdot F$ $\quad S_{viii_6} := 9300 \cdot psi$

$ST_7 := 900 \cdot F$ $\quad S_{viii_7} := 13700 \cdot psi$

Inverse for interpolating for STRESS based on temperature:

$ST'_1 := ST_7 = 900\,F$ $\quad S'_{viii_1} := S_{viii_7} = 13700\,psi$

$ST'_2 := ST_6 = 950\,F$ $\quad S'_{viii_2} := S_{viii_6} = 9300\,psi$

$ST'_3 := ST_5 = 1000\,F$ $\quad S'_{viii_3} := S_{viii_5} = 6300\,psi$

$ST'_4 := ST_4 = 1050\,F$ $\quad S'_{viii_4} := S_{viii_4} = 4200\,psi$

$ST'_5 := ST_3 = 1100\,F$ $\quad S'_{viii_5} := S_{viii_3} = 2800\,psi$

$ST'_6 := ST_2 = 1150\,F$ $\quad S'_{viii_6} := S_{viii_2} = 1900\,psi$

$ST'_7 := ST_1 = 1200\,F$ $\quad S'_{viii_7} := S_{viii_1} = 1200\,psi$

A.3.1 Example 7: Industrial Example with 1.25Cr-0.5Mo with 10,000/100,000 hrs

Operating Conditions 1

$OP_{ex7.1} := 545 \cdot psi$

$OT_{ex7.1} := 1025F$

$t_{ex7.1} := 10000 \cdot hr$

Operating Conditions 2

$OP_{ex7.2} := 590 \cdot psi$

$OT_{ex7.2} := 975F$

$t_{ex7.2} := 100000 \cdot hr$

Set design pressure based on specified margin on operating pressures:

$f_{DP} \cdot OP_{ex7.1} = 599.5\,psi$

set to a "hard value"

$DP_{ex7.1} := 600 \cdot psi$

$f_{DP} \cdot OP_{ex7.2} = 649\,psi$

set to a "hard value"

$DP_{ex7.2} := 650 \cdot psi$

The Design Pressure is the maximum of the two conditions:

$$DP_{ex7} := \max\left(DP_{ex7.1}, DP_{ex7.2}\right) = 650\,psi$$

Calculation part "g" FOR REFERENCE/INFO, VIII-1 current rules

Set design temperatures based on specified margin on operating temperatures:

Design temperature margin typically set by a User.

$DT_{marg.g} = 50\,F$ $OT_{ex7.1} = 1025\,F$ $OT_{ex7.2} = 975\,F$

$$\boxed{DT_{ex7.1} := OT_{ex7.1} + DT_{marg.g} = 1075\,F}$$

$$\boxed{DT_{ex7.2} := OT_{ex7.2} + DT_{marg.g} = 1025\,F}$$

Current rules design temperature condition "1":

$$DT_{ex7.1g} := DT_{ex7.1} = 1075\,F$$

Interpolate for allowable stress based on temperature from II-D data:

$$S_{DT.ex7.1g} := \mathrm{linterp}\left(ST', S'_{viii}, DT_{ex7.1g}\right) = 3500\,psi$$

EX. 7, Calculate the minimum required shell thickness for the design condition

$$t_{min.ex7.1g.eq1} := \frac{DP_{ex7} \cdot \frac{OD_{shell}}{2}}{\left(S_{DT.ex7.1g} \cdot 1.0 - 0.6 \cdot DP_{ex7}\right)} = 16.72 \cdot in$$ UG-27 (eq 1)

$$t_{min.ex7.1g.eq2} := \frac{DP_{ex7} \cdot \frac{OD_{shell}}{2}}{\left(2 S_{DT.ex7.1g} \cdot 1.0 + 0.4 \cdot DP_{ex7}\right)} = 7.163 \cdot in$$ UG-27 (eq 2)

Find minimum shell thickness:

$$t_{min.7g} := \max\left(t_{min.ex7.1g.eq1}, t_{min.ex7.1g.eq2}\right) = 16.72 \cdot in$$

Set shell thickness for fabrication

$$\boxed{t_{shell.7g} := 17.00 \cdot in}$$

Compute maximum principal stresses, "P(r')/t":

$$r'_{7g} := 0.6 \cdot t_{shell.7g} + \frac{\left(OD_{shell} - t_{shell.7g}\right)}{2} = 81.7 \cdot in$$

$$\boxed{\sigma_{ex7.1g} := OP_{ex7.1} \cdot \frac{r'_{7g}}{t_{shell.7g}} = 2.619 \times 10^{3} \cdot psi}$$

$$\boxed{\sigma_{ex7.2g} := OP_{ex7.2} \cdot \frac{r'_{7g}}{t_{shell.7g}} = 2.835 \times 10^{3} \cdot psi}$$

Life consumption part "g" (FOR REF/INFO):

EX. 7, STEP 3 "part g": Set T_D Temperatures for each stress level:

Interpolate for temperature based on stress from II D data:

$$T_{D.ex7.1g} := \text{linterp}\left(S_{viii}, ST, \sigma_{ex7.1g}\right) = 1110.044\,F$$

$$T_{D.ex7.2g} := \text{linterp}\left(S_{viii}, ST, \sigma_{ex7.2g}\right) = 1098.733\,F$$

EX. 7, STEP 4 "part g": Compute LMPs for each T_D using 100,000 hr.

$$LMP_{ex7.1g} := \left(T_{D.ex7.1g} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 39.251 \times 10^3 F$$

$$LMP_{ex7.2g} := \left(T_{D.ex7.2g} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 38.968 \times 10^3 F$$

EX. 7, STEP 5 "part g": Compute rupture time for each case, $(t_r)_i$

$$a_{ex7.1g} := \frac{LMP_{ex7.1g}}{\left(OT_{ex7.1} + 460 \cdot F\right)} - C_{LMP} = 6.432$$

$$\boxed{t_{r.ex7.1g} := 1 \cdot hr(10)^{a_{ex7.1g}} = 2702210.345 \cdot hr}$$

$$a_{ex7.2g} := \frac{LMP_{ex7.2g}}{\left(OT_{ex7.2} + 460 \cdot F\right)} - C_{LMP} = 7.156$$

$$\boxed{t_{r.ex7.2g} := 1 \cdot hr(10)^{a_{ex7.2g}} = 14309700.525 \cdot hr}$$

EX. 7, STEP 6 ("part g"): Compute life consumption for each case, λ_i:

$$\boxed{\lambda_{ex7.1g} := \frac{t_{ex7.1}}{t_{r.ex7.1g}} = 0.004}$$

$$\boxed{\lambda_{ex7.2g} := \frac{t_{ex7.2}}{t_{r.ex7.2g}} = 0.007}$$

EX. 7, STEP 7 ("part g"): Compute total life consumption, λ:

$$\boxed{\Lambda_{ex7g} := \lambda_{ex7.1g} + \lambda_{ex7.2g} = 0.011}$$

<<< **REF/INFO**

Part "h" of the example:

Set the design temperature based on the operating pressure for the long-term condition ("2").

$t_{ex7.2} = 100000 \cdot hr$ $\quad OT_{ex7.2} = 975\,F$ $\quad DT_{marg.h} = 50\,F$

$$DT_{ex7.h} := OT_{ex7.2} + DT_{marg.h} = 1025\,F$$

Interpolate for stress based on temperature from II D data.

$$S_{DT.ex7.h} := \mathrm{linterp}\left(ST', S'_{viii}, DT_{ex7.h}\right) = 5250\,psi$$

EX. 7, Calculate the minimum required shell thickness for the proposed rules.

(based on the long-term design pressure condition, "2")

$$DP_{ex7.h} := DP_{ex7.2} = 650\,psi$$

$$t_{min.7h.eq1} := \frac{DP_{ex7.h} \cdot \frac{OD_{shell}}{2}}{\left(S_{DT.ex7.h} \cdot 1.0 - 0.6 \cdot DP_{ex7.h}\right)} = 10.700 \cdot in$$

UG-27 (eq 1)

$$t_{min.7h.eq2} := \frac{DP_{ex7.h} \cdot \frac{OD_{shell}}{2}}{\left(2 S_{DT.ex7.h} \cdot 1.0 + 0.4 \cdot DP_{ex7.h}\right)} = 4.833 \cdot in$$

UG-27 (eq 2)

$$t_{min.7h} := \max\left(t_{min.7h.eq1}, t_{min.7h.eq2}\right) = 10.700 \cdot in$$

minimum modified design shell thickness

$$t_{shell.7h} := 10.875 \cdot in$$

set modified shell thickness for fabrication

Compute the maximum principal stresses, "P(r')/t":

$$r'_h := 0.6 \cdot t_{shell.7h} + \frac{\left(OD_{shell} - t_{shell.7h}\right)}{2} = 81.088 \cdot in$$

$$\boxed{\sigma_{ex7.1h} := OP_{ex7.1} \cdot \frac{r'_h}{t_{shell.7h}} = 4064 \cdot psi}$$

$$\boxed{\sigma_{ex7.2h} := OP_{ex7.2} \cdot \frac{r'_h}{t_{shell.7h}} = 4399 \cdot psi}$$

Using $\sigma_{ex7.1h}$ and $\sigma_{ex7.2h}$, **check the two elevated temperature and specified time operating conditions for the proposed life consumption requirement.**

EX. 7, STEP 3 ("part h"): Set T_D Temperatures for each stress level:

(interpolate for temperature based on stress from II D data)

$$T_{D.ex7.1h} := \text{linterp}\left(S_{viii}, ST, \sigma_{ex7.1h}\right) = 1054.868\,F$$

$$T_{D.ex7.2h} := \text{linterp}\left(S_{viii}, ST, \sigma_{ex7.2h}\right) = 1045.256\,F$$

EX. 7, STEP 4 ("part h"): Compute LMPs for each T_D using 100,000 hr.

$$LMP_{ex7.1h} := \left(T_{D.ex7.1h} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 37.872 \times 10^3\,F$$

$$LMP_{ex7.2h} := \left(T_{D.ex7.2h} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 37.631 \times 10^3\,F$$

EX. 7, STEP 5 ("part h"): Compute rupture time for each case, $(t_r)_i$

$$a_{ex7.1h} := \frac{LMP_{ex7.1h}}{\left(OT_{ex7.1} + 460 \cdot F\right)} - C_{LMP} = 5.503$$

$$\boxed{t_{r.ex7.1h} := 1 \cdot hr (10)^{a_{ex7.1h}} = 318294.139 \cdot hr}$$

$$a_{ex7.2h} := \frac{LMP_{ex7.2h}}{\left(OT_{ex7.2} + 460 \cdot F\right)} - C_{LMP} = 6.224$$

$$\boxed{t_{r.ex7.2h} := 1 \cdot hr (10)^{a_{ex7.2h}} = 1674864.354 \cdot hr}$$

EX. 7, STEP 6 ("part h"): Compute life consumption for each case, λ_i:

$$\boxed{\lambda_{ex7.1h} := \frac{t_{ex7.1}}{t_{r.ex7.1h}} = 0.031}$$

$$\boxed{\lambda_{ex7.2h} := \frac{t_{ex7.2}}{t_{r.ex7.2h}} = 0.06}$$

EX. 7, STEP 7 ("part h"): Compute total life consumption, λ:

$$\boxed{\Lambda_{ex7h} := \lambda_{ex7.1h} + \lambda_{ex7.2h} = 0.091}$$

<<< acceptable when $\leq$ 1.000

EX. 7, Summary of the two parts to illustrate advantage of proposed rules for setting shell thickness.

	Present Rules ("g")	Proposed Rules ("h")
Sesign Temperature Margins	$DT_{marg.g} = 50 F$	$DT_{marg.h} = 50 F$
Design Temperatures	$DT_{ex7.1} = 1075 F$ $DT_{ex7.2} = 1025 F$	$DT_{ex7.h} = 1025 F$
Design Pressures	$DP_{ex7.1} = 600 psi$ $DP_{ex7.2} = 650 psi$	$DP_{ex7.h} = 650 psi$
Design Allowable Stress	$S_{DT.ex7.1g} = 3500 psi$	$S_{DT.ex7.h} = 5250 psi$
Required shell thickness	$t_{min.7g} = 16.72 \cdot in$	$t_{min.7h} = 10.7 \cdot in$
Fabrication thickness	$t_{shell.7g} = 17 \cdot in$	$t_{shell.7h} = 10.875 \cdot in$
Stress Op Cond 1	$\sigma_{ex7.1g} = 2619 psi$	$\sigma_{ex7.1h} = 4064 psi$
Stress Op Cond 2	$\sigma_{ex7.2g} = 2835 psi$	$\sigma_{ex7.2h} = 4399 psi$
Op Cond 1 T_D	$T_{D.ex7.1g} = 1110 F$	$T_{D.ex7.1h} = 1055 F$
Op Cond 2 T_D	$T_{D.ex7.2g} = 1099 F$	$T_{D.ex7.2h} = 1045 F$
LMP Cond 1	$LMP_{ex7.1g} = 39251.103 F$	$LMP_{ex7.1h} = 37871.701 F$
LMP Cond 2	$LMP_{ex7.2g} = 38968.33 F$	$LMP_{ex7.2h} = 37631.411 F$
Max time Op Cond 1	$t_{r.ex7.1g} = 2702210.345 \cdot hr$	$t_{r.ex7.1h} = 318294.139 \cdot hr$
Max time Op Cond 2	$t_{r.ex7.2g} = 14309700.525 \cdot hr$	$t_{r.ex7.2h} = 1674864.354 \cdot hr$
Life Consum Cond 1	$\lambda_{ex7.1g} = 0.004$	$\lambda_{ex7.1h} = 0.031$
Life Consum Cond 2	$\lambda_{ex7.2g} = 0.007$	$\lambda_{ex7.2h} = 0.06$
Total Life Consumption	$\boxed{\Lambda_{ex7g} = 0.011}$	$\boxed{\Lambda_{ex7h} = 0.091}$

$$\frac{\Lambda_{ex7h}}{\Lambda_{ex7g}} = 8.525$$

A.3.2 Example 8: Industrial Example with 2.25Cr-1Mo with 20,000/200,000 hrs

NOTE: The only difference between Example 7 and Example 8 is the times of load duration for the two operating conditions. This means that calculations for STEPS 3 through 5 are identical to those for Example 7. Therefore, only STEPS 6 and 7 involving the life consumption calculations are shown.

Operating Conditions 1

$DP_{ex8.1} := DP_{ex7.1} = 600\,psi$

$OT_{ex8.1} := OT_{ex7.1} = 1025\,F$

$t_{ex8.1} := 20000 \cdot hr$

$t_{r.ex8.1g} := t_{r.ex7.1g} = 2.702 \times 10^{6} \cdot hr$

Operating Conditions 2

$DP_{ex8.2} := DP_{ex7.2} = 650\,psi$

$OT_{ex8.2} := OT_{ex7.2} = 975\,F$

$t_{ex8.2} := 200000 \cdot hr$

$t_{r.ex8.2g} := t_{r.ex7.2g} = 14.31 \times 10^{6} \cdot hr$

EX. 8, STEP 6 ("part g"): Compute life consumption for each case, λ_i:

$$\lambda_{ex8.1g} := \frac{t_{ex8.1}}{t_{r.ex8.1g}} = 0.007$$

$$\lambda_{ex8.2g} := \frac{t_{ex8.2}}{t_{r.ex8.2g}} = 0.014$$

EX. 8, STEP 7 ("part g"): Compute total life consumption, λ:

$\Lambda_{ex8g} := \lambda_{ex8.1g} + \lambda_{ex8.2g} = 0.021$ <<< acceptable when $\leq$ 1.000

EX. 8, STEP 6 ("part h"): Compute life consumption for each case, λ_i:

$t_{r.ex8.1h} := t_{r.ex7.1h} = 318.294 \times 10^3 \cdot hr$

$t_{r.ex8.2h} := t_{r.ex7.2h} = 1.675 \times 10^6 \cdot hr$

$$\boxed{\lambda_{ex8.1h} := \frac{t_{ex8.1}}{t_{r.ex8.1h}} = 0.063}$$

$$\boxed{\lambda_{ex8.2h} := \frac{t_{ex8.2}}{t_{r.ex8.2h}} = 0.119}$$

EX. 8, STEP 7 ("part h"): Compute total life consumption, Λ:

$\boxed{\Lambda_{ex8h} := \lambda_{ex8.1h} + \lambda_{ex8.2h} = 0.182}$ <<< acceptable when $\leq$ 1.000

Summary of the two parts to illustrate advantage of proposed rules for setting shell thickness.

	Present Rules ("g")	Proposed Rules ("h")
Max time Op Cond 1	$t_{r.ex8.1g} = 2.702 \times 10^6 \cdot hr$	$t_{r.ex8.1h} = 318.294 \times 10^3 \cdot hr$
Max time Op Cond 2	$t_{r.ex8.2g} = 14.31 \times 10^6 \cdot hr$	$t_{r.ex8.2h} = 1.675 \times 10^6 \cdot hr$
Life Consum Cond 1	$\lambda_{ex8.1g} = 0.007$	$\lambda_{ex8.1h} = 0.063$
Life Consum Cond 2	$\lambda_{ex8.2g} = 0.014$	$\lambda_{ex8.2h} = 0.119$
Total Life Consumption	$\boxed{\Lambda_{ex8g} = 0.021}$	$\boxed{\Lambda_{ex8h} = 0.182}$

$$\frac{\Lambda_{ex8h}}{\Lambda_{ex8g}} = 8.525$$

Section VIII Allowable Stresses for Examples 9 and 10 (2.25 Cr)

Allowable stresses (from II-D) for interpolating for TEMPERATURE based on stress:

$ST225_1 := 1200 \cdot F$ $S_{viii.225_1} := 1400 \cdot psi$

$ST225_2 := 1150 \cdot F$ $S_{viii.225_2} := 2400 \cdot psi$

$ST225_3 := 1100 \cdot F$ $S_{viii.225_3} := 3800 \cdot psi$

$ST225_4 := 1050 \cdot F$ $S_{viii.225_4} := 5700 \cdot psi$

$ST225_5 := 1000 \cdot F$ $S_{viii.225_5} := 8000 \cdot psi$

$ST225_6 := 950 \cdot F$ $S_{viii.225_6} := 10800 \cdot psi$

$ST225_7 := 900 \cdot F$ $S_{viii.225_7} := 13600 \cdot psi$

Inverse for interpolating for STRESS based on temperature:

$ST'225_1 := ST225_7 = 900\,F$ $S'_{viii.225_1} := S_{viii.225_7} = 13600\,psi$

$ST'225_2 := ST225_6 = 950\,F$ $S'_{viii.225_2} := S_{viii.225_6} = 10800\,psi$

$ST'225_3 := ST225_5 = 1000\,F$ $S'_{viii.225_3} := S_{viii.225_5} = 8000\,psi$

$ST'225_4 := ST225_4 = 1050\,F$ $S'_{viii.225_4} := S_{viii.225_4} = 5700\,psi$

$ST'225_5 := ST225_3 = 1100\,F$ $S'_{viii.225_5} := S_{viii.225_3} = 3800\,psi$

$ST'225_6 := ST225_2 = 1150\,F$ $S'_{viii.225_6} := S_{viii.225_2} = 2400\,psi$

$ST'225_7 := ST225_1 = 1200\,F$ $S'_{viii.225_7} := S_{viii.225_1} = 1400\,psi$

A.3.3 Example 9: Industrial Example with 2.25Cr-0.5Mo with 10,000/100,000 hrs

Operating Conditions 1

$OP_{ex9.1} := 545 \cdot psi$

$OT_{ex9.1} := 1025F$

$t_{ex9.1} := 10000 \cdot hr$

Operating Conditions 2

$OP_{ex9.2} := 590 \cdot psi$

$OT_{ex9.2} := 975F$

$t_{ex9.2} := 100000 \cdot hr$

EX. 9, Set design pressure based on specified margin on operating pressures:

$f_{DP} \cdot OP_{ex9.1} = 599.5\,psi$

set to a "hard value"

$DP_{ex9.1} := 600 \cdot psi$

$f_{DP} \cdot OP_{ex9.2} = 649\,psi$

set to a "hard value"

$DP_{ex9.2} := 650 \cdot psi$

The Design Pressure is the maximum of the two conditions:

$$DP_{ex9} := \max\left(DP_{ex9.1}, DP_{ex9.2}\right) = 650\,psi$$

Calculation part "g" FOR REFERENCE/INFO, VIII-1 current rules

Set design temperatures based on specified margin on operating temperatures:

Design temperature margin typically set by a User.

$DT_{marg.g} = 50\,F$ $\quad OT_{ex9.1} = 1025\,F$ $\quad OT_{ex9.2} = 975\,F$

$$\boxed{DT_{ex9.1} := OT_{ex9.1} + DT_{marg.g} = 1075\,F}$$

$$\boxed{DT_{ex9.2} := OT_{ex9.2} + DT_{marg.g} = 1025\,F}$$

Current rules design temperature condition "1":

$$DT_{ex9.1g} := DT_{ex9.1} = 1075\,F$$

Interpolate for allowable stress based on temperature from II-D data:

$$S_{DT.ex9.1g} := \mathrm{linterp}\left(ST'_{225}, S'_{viii.225}, DT_{ex9.1g}\right) = 4750\,psi$$

EX. 9, Calculate the minimum required shell thickness for the design condition

$$t_{min.ex9.1g.eq1} := \frac{DP_{ex9} \cdot \frac{OD_{shell}}{2}}{\left(S_{DT.ex9.1g} \cdot 1.0 - 0.6 \cdot DP_{ex9}\right)} = 11.927 \cdot in$$ UG-27 (eq 1)

$$t_{min.ex9.1g.eq2} := \frac{DP_{ex9} \cdot \frac{OD_{shell}}{2}}{\left(2S_{DT.ex9.1g} \cdot 1.0 + 0.4 \cdot DP_{ex9}\right)} = 5.328 \cdot in$$ UG-27 (eq 2)

EX. 9, Find minimum shell thickness:

$$t_{min.9g} := \max\left(t_{min.ex9.1g.eq1}, t_{min.ex9.1g.eq2}\right) = 11.927 \cdot in$$

EX. 9, Set shell thickness for fabrication

$$t_{shell.9g} := 12.250 \cdot in$$

Compute maximum principal stresses, "P(r')/t":

$$r'_{9g} := 0.6 \cdot t_{shell.9g} + \frac{\left(OD_{shell} - t_{shell.9g}\right)}{2} = 81.225 \cdot in$$

$$\boxed{\sigma_{ex9.1g} := OP_{ex9.1} \cdot \frac{r'_{9g}}{t_{shell.9g}} = 3.614 \times 10^{3} \cdot psi}$$

$$\boxed{\sigma_{ex9.2g} := OP_{ex9.2} \cdot \frac{r'_{9g}}{t_{shell.9g}} = 3.912 \times 10^{3} \cdot psi}$$

Life consumption part "g" (FOR REF/INFO):

EX. 9, STEP 3 "part g": Set T_D Temperatures for each stress level:

Interpolate for temperature based on stress from II D data:

$$T_{D.ex9.1g} := \text{linterp}\left(S_{viii.225}, ST_{225}, \sigma_{ex9.1g}\right) = 1106.654\,F$$

$$T_{D.ex9.2g} := \text{linterp}\left(S_{viii.225}, ST_{225}, \sigma_{ex9.2g}\right) = 1097.051\,F$$

EX. 9, STEP 4 "part g": Compute LMPs for each T_D using 100,000 hr.

$$LMP_{ex9.1g} := \left(T_{D.ex9.1g} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 39.166 \times 10^3 F$$

$$LMP_{ex9.2g} := \left(T_{D.ex9.2g} + 460 \cdot F\right)\left(C_{LMP} + \log(100000)\right) = 38.926 \times 10^3 F$$

EX. 9, STEP 5 "part g": Compute rupture time for each case, $(t_r)_i$

$$a_{ex9.1g} := \frac{LMP_{ex9.1g}}{\left(OT_{ex9.1} + 460 \cdot F\right)} - C_{LMP} = 6.375$$

$$\boxed{t_{r.ex9.1g} := 1 \cdot hr(10)^{a_{ex9.1g}} = 2369458.278 \cdot hr}$$

$$a_{ex9.2g} := \frac{LMP_{ex9.2g}}{\left(OT_{ex9.2} + 460 \cdot F\right)} - C_{LMP} = 7.126$$

$$\boxed{t_{r.ex9.2g} := 1 \cdot hr(10)^{a_{ex9.2g}} = 13375942.629 \cdot hr}$$

EX. 9, STEP 6 ("part g"): Compute life consumption for each case, λ_i:

$$\boxed{\lambda_{ex9.1g} := \frac{t_{ex9.1}}{t_{r.ex9.1g}} = 0.004}$$

$$\boxed{\lambda_{ex9.2g} := \frac{t_{ex9.2}}{t_{r.ex9.2g}} = 0.007}$$

EX. 9, STEP 7 ("part g"): Compute total life consumption, λ:

$$\boxed{\Lambda_{ex9g} := \lambda_{ex9.1g} + \lambda_{ex9.2g} = 0.012}$$

<<< **REF/INFO**

Part "h" of the example:

Set the design temperature based on the operating pressure for the long-term condition ("2").

$t_{ex9.2} = 100000 \cdot hr$ $OT_{ex9.2} = 975\,F$ $DT_{marg.h} = 50\,F$

$$DT_{ex9.h} := OT_{ex9.2} + DT_{marg.h} = 1025\,F$$

Interpolate for stress based on temperature from II D data.

$$S_{DT.ex9.h} := \mathrm{linterp}\left(ST'_{225}, S'_{viii.225}, DT_{ex9.h}\right) = 6850\,psi$$

EX. 9, Calculate the minimum required shell thickness for the proposed rules.

(based on the long-term design pressure condition, "2")

$$DP_{ex9.h} := DP_{ex9.2} = 650\,psi$$

$$t_{min.9h.eq1} := \frac{DP_{ex9.h} \cdot \frac{OD_{shell}}{2}}{\left(S_{DT.ex9.h} \cdot 1.0 - 0.6 \cdot DP_{ex9.h}\right)} = 8.050 \cdot in$$ UG-27 (eq 1)

$$t_{min.9h.eq2} := \frac{DP_{ex9.h} \cdot \frac{OD_{shell}}{2}}{\left(2S_{DT.ex9.h} \cdot 1.0 + 0.4 \cdot DP_{ex9.h}\right)} = 3.725 \cdot in$$ UG-27 (eq 2)

$$t_{min.9h} := \max\left(t_{min.9h.eq1}, t_{min.9h.eq2}\right) = 8.050 \cdot in$$ minimum modified design shell thickness

$$t_{shell.9h} := 8.25 \cdot in$$ set modified shell thickness for fabrication

Compute the maximum principal stresses, "P(r')/t":

$$r'_{9h} := 0.6 \cdot t_{shell.9h} + \frac{\left(OD_{shell} - t_{shell.9h}\right)}{2} = 80.825 \cdot in$$

$$\boxed{\sigma_{ex9.1h} := OP_{ex9.1} \cdot \frac{r'_{9h}}{t_{shell.9h}} = 5339 \cdot psi}$$

$$\boxed{\sigma_{ex9.2h} := OP_{ex9.2} \cdot \frac{r'_{9h}}{t_{shell.9h}} = 5780 \cdot psi}$$

Using $\sigma_{ex9.1h}$ and $\sigma_{ex9.2h}$, check the two elevated temperature and specified time operating conditions for the proposed life consumption requirement.

EX. 9, STEP 3 ("part h"): Set T_D Temperatures for each stress level:

(interpolate for temperature based on stress from II D data)

$$T_{D.ex9.1h} := \mathrm{linterp}\left(S_{viii.225}, ST_{225}, \sigma_{ex9.1h}\right) = 1059.5\,F$$

$$T_{D.ex9.2h} := \mathrm{linterp}\left(S_{viii.225}, ST_{225}, \sigma_{ex9.2h}\right) = 1048.3\,F$$

EX. 9, STEP 4 ("part h"): Compute LMPs for each T_D using 100,000 hr.

$$LMP_{ex9.1h} := \left(T_{D.ex9.1h} + 460\cdot F\right)\left(C_{LMP} + \log(100000)\right) = 37.987 \times 10^{3}\,F$$

$$LMP_{ex9.2h} := \left(T_{D.ex9.2h} + 460\cdot F\right)\left(C_{LMP} + \log(100000)\right) = 37.706 \times 10^{3}\,F$$

EX. 9, STEP 5 ("part h"): Compute rupture time for each case, $(t_r)_i$

$$a_{ex9.1h} := \frac{LMP_{ex9.1h}}{\left(OT_{ex9.1} + 460\cdot F\right)} - C_{LMP} = 5.581$$

$$t_{r.ex9.1h} := 1\cdot hr\,(10)^{a_{ex9.1h}} = 380.762 \times 10^{3}\cdot hr$$

$$a_{ex9.2h} := \frac{LMP_{ex9.2h}}{\left(OT_{ex9.2} + 460\cdot F\right)} - C_{LMP} = 6.276$$

$$t_{r.ex9.2h} := 1\cdot hr\,(10)^{a_{ex9.2h}} = 1.889 \times 10^{6}\cdot hr$$

EX. 9, STEP 6 ("part h"): Compute life consumption for each case, λ_i:

$$\lambda_{ex9.1h} := \frac{t_{ex9.1}}{t_{r.ex9.1h}} = 0.026$$

$$\lambda_{ex9.2h} := \frac{t_{ex9.2}}{t_{r.ex9.2h}} = 0.053$$

EX. 9, STEP 7 ("part h"): Compute total life consumption, λ:

$$\Lambda_{ex9h} := \lambda_{ex9.1h} + \lambda_{ex9.2h} = 0.079$$

<<< acceptable when $\leq$ 1.000