FINAL

A REVIEW OF CURRENT OPERATING CONDITIONS ALLOWABLE STRESSES IN ASME SECTION III SUBSECTION NH

AND

OVERVIEW OF THE AVAILABILITY OF THE ORIGINAL AND AUGMENTED DATABASES NEEDED TO ESTABLISH S_o, S_t, and S_r

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ABSTRACT

The current operating condition allowable stresses provided in ASME Section III, Subsection NH were reviewed for consistency with the criteria used to establish the stress allowables and with the allowable stresses provided in ASME Section II, Part D. It was found that the S_o values in ASME III-NH were consistent with the S values in ASME II-D for the five materials of interest. However, it was found that $0.80S_r$ was less than S_o for some temperatures for four of the materials. Only values for alloy 800H appeared to be consistent with the criteria on which S_o values are established. With the intent of undertaking a more detailed evaluation of issues related to the allowable stresses in ASME III-NH, the availabilities of databases for the five materials were reviewed and augmented databases were assembled.

INTRODUCTION

In ASME Section II Part D, the criteria for setting *S* of wrought products above room temperature are provided in Appendix 1 Table I-100 and include:

(i) $S_T/3.5$, where S_T is the "specified minimum specified tensile strength at room temperature,"

(ii) $1.1S_TR_T/3.5$, where "R_T is the ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength,"

(iii) $2S_Y/3$, where S_Y is the "specified minimum yield strength at room temperature,"

(iv) $2S_YR_Y/3$ or $0.9\ S_YR_Y$ where R_Y is the "ratio of the average temperature dependent trend curve value of yield strength to room temperature yield strength,"

(v) $F_{\text{avg}}S_{R\text{avg}}$, where $S_{R\text{avg}}$ is the "average stress to cause rupture at the end of 100,000 hr" and F_{avg} is a "multiplier applied to $S_{R\text{avg}}$" that has a value of 0.67 for temperatures of 1500°F and below,

(vi) $0.80S_{R\text{min}}$, where $S_{R\text{min}}$ is the "minimum stress to cause rupture at the end of 100,000 hr," and

(vii) $1.0S_c$, where S_c is the "average stress to produce a creep rate of 0.01%/1,000 hr."

In ASME III-NH, the criteria for setting S_m, "the lowest stress intensity value at a given temperature among the time-independent strength properties" for wrought metal are provided in ASME Section II Part D Appendix 2 and Table 2-100(a). These include:

(i) $S_T/3$, where S_T is the "specified minimum specified tensile strength at room temperature,"

(ii) $1.1S_TR_T/3$, where "R_T is the ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength,"

(iii) $2S_Y/3$, where S_Y is the "specified minimum yield strength at room temperature," and

(iv) $2S_YR_Y/3$ or $0.9\ S_YR_Y$ where R_Y is the "ratio of the average temperature dependent trend curve value of yield strength to room temperature yield strength,"

The criteria for setting S_o, the "maximum allowable value of general primary membrane stress intensity to be used as a reference for stress calculation under Design Loadings" above room temperature, are identical to the criteria of Section II-D Appendix 1 for wrought products and S_o is intended to be equivalent to *S*, "except for a few cases at lower temperatures" as defined in NH-3221. This exception sometimes appears as a lower value than S_m or greater value than S_t at the temperature where S_o transitions from the time-independent criteria to time-dependent criteria.

The criteria in ASME III-NH for setting S_t, "the temperature and time-dependent stress intensity limit," include:

(i) "100% of the average stress required to obtain a total strain (elastic, plastic, and creep) of 1%,"

(ii) "80% of the minimum stress to cause initiation of tertiary creep," and

(iii) "67% of the minimum stress to cause rupture."

The criteria for S_t, therefore, differ from the criteria for setting S and S_o in the sense that they need to cover a range of times from 1 to 300,000 hr, whereas S and S_o only pertain to 100,000 hr.

The value of S_{mt} is defined as "the lower of two stress intensity values, S_m (time-independent) and S_t (time-dependent)."

Finally, the stress S_r is defined as the "expected minimum stress-to-rupture strength" and pertains to base metal, although the definition is provided in the paragraphs of NH-3221 dealing with criteria for weldments. At 100,000 hr, $S_{R\text{min}}$ and S_r should be equivalent.

With respect to the assessment of the consistency in the current operating condition allowable stresses, the current *S* values in ASME II-D Tables 1A and 1B should agree with the S_o values in ASME III-NH Table I-14.2, as mentioned above, since they are intended to be identical. However, no direct comparisons are possible between the stresses based on the criteria in ASME Section II-D and Section III-NH without knowing the criteria that controls the stress allowables for specific temperatures and times in the two Codes. Both Codes include the minimum stress-to-rupture strength criterion, although ASME II-D Tables 1A and 1B call for a factor of 0.80 on stress while ASME III-NH calls for a factor of 0.67 on stress. On the other hand, if 0.80 $S_{R\text{min}}$ controls the *S* values in the II-D tables, then 0.80 S_r for 100,000 hr in ASME III-NH Table I-14.6 should agree with the *S* and S_o values. If $F_{\text{avg}}S_{R\text{avg}}$ controls the *S* values in the II-D tables and the S_o values in ASME III-NH, then 0.80 S_r for 100,000 hr in ASME III-NH Table I-14.6 should be greater than the *S* and S_o values.

This report (1) provides an evaluation of the consistency of the stress allowable in ASME III-NH with the ASME II-D values for each of the five materials currently covered by ASME III-NH; (2) briefly reviews the databases that were used to establish or recommend stress allowables; and (3) reviews the expansion of the databases for the materials.

EVALUATION OF CONSISTENCIES IN THE CURRENT VALUES

304H Stainless Steel

In Table 1, the stress allowables for 304H stainless steel are compared for temperatures in the time-dependent range covered by ASME Section III-NH (800 to 1500°F). These stress allowables include S, S_o, S_t, and S_r. To the right of these columns are values produced by the application of two of the criteria for setting the time-dependent allowables. The 0.80 S_r column applies to S and S_o and the 0.67 S_r column applies to S_t at 100,000 h. Of course, these two columns do not necessarily represent the controlling criterion. Values are shown to two decimal places to examine round-off or truncation effects. The S, S_o, or S_t value cannot exceed the stress estimated from the applicable criterion. The values corresponding to the time-dependent behavior are in italics. Table 1 shows two inconsistencies between S and S_o in the time-independent range that may be due to rounding errors. More importantly, the time-dependent S values are greater than the 0.80 S_r values, which is inconsistent with the criteria for setting the S values. The time-dependent S_o values are consistent with the S values and the S_t values are more-or-less consistent with the 0.67 S_r criterion, if one assumes that the small differences are due to rounding errors. The issue to be resolved is whether the S_r values in ASME III-NH need to be revised or the 0.80 S_r criterion was not considered in setting the S values.

Table 1. Comparison of allowable stresses for 304H in ASME Section III, Subsection NH

Temp (°F)	S (ksi)	S_o (ksi)	S_t (ksi)	S_r (ksi)	0.80 S_r (ksi)	0.67 S_r (ksi)
800	15.2	15.2	*20.4*	*44.3*	*35.44*	*29.68*
850	14.9	14.8	*19.8*	*34.7*	*27.76*	*23.25*
900	14.6	14.6	*17.7*	*27.2*	*21.76*	*18.22*
950	14.3	14.2	*14.2*	*21.2*	*16.96*	*14.20*
1000	14.0	*11.1*	*11.1*	*16.6*	*13.28*	*11.12*
1050	*12.4*	*10.1*	*8.7*	*13.0*	*10.40*	*8.71*
1100	*9.8*	*9.8*	*6.8*	*10.2*	*8.16**	*6.83*
1150	*7.7*	*7.7*	*5.3*	*8.0*	*6.40**	*5.36*
1200	*6.1*	*6.1*	*4.1*	*6.2*	*4.96**	*4.15*
1250	*4.7*	*4.7*	*3.2*	*4.9*	*3.92**	*3.28*
1300	*3.7*	*3.7*	*2.5*	*3.8*	*3.04**	*2.55*
1350	*2.9*	*2.9*	*2.0*	*3.0*	*2.40**	*2.01*
1400	*2.3*	*2.3*	*1.6*	*2.3*	*1.84**	*1.54*
1450	*1.8*	*1.8*	*1.2*	*1.8*	*1.44**	*1.21*
1500	*1.4*	*1.4*	*0.8*	*1.4*	*1.12**	*0.94*

* Less than S_o

316H Stainless Steel

In Table 2, the stress allowables for 316H stainless steel are compared for temperatures in the time-dependent range covered by ASME Section III-NH (800 to 1500°F). As for Table 1 on 304H stainless steel, these stress allowables include S, S_o, S_t, and S_r. Table 2 shows one inconsistency between S and S_o in the time-independent range at 950°F that may be due to a rounding error. The value for S_o at 1000°F is consistent with the value of S_{mt} at 300,00 hr (NH-3221) but the values for 1050 and 1100°F need further examination. Several of the time-dependent S values are significantly greater than the 0.80 S_r values, which is inconsistent with the criteria for setting the S values. The time-dependent S_o values are consistent with the S values. Some S_t values are more-or-less consistent with the 0.67 S_r criterion, if one assumes that small differences are due to rounding errors, yet other S_t values do not appear to be based on the 0.67 S_r criterion. Similar to the case for 304H stainless steel, one issue to be resolved is whether the S_r values in ASME III-NH for 316H stainless steel need to be revised or the 0.80 S_r criterion was not considered in setting the S values. A second issue to be resolved is which criterion was used to determine the S_t values.

Table 2. Comparison of allowable stresses for 316H in ASME Section III, Subsection NH

Temp (°F)	S (ksi)	S_o (ksi)	S_t (ksi)	S_r (ksi)	0.80 S_r (ksi)	0.67 S_r (ksi)
800	15.9	15.9	*20.8*	*64.5*	*51.60*	*43.22*
850	15.7	15.7	*20.6*	*56.0*	*44.80*	*37.52*
900	15.6	15.6	*19.9*	*42.6*	*34.08*	*28.54*
950	15.4	15.5	*18.4*	*32.4*	*25.92*	*21.71*
1000	15.3	*14.0*	*16.2*	*24.6*	*19.68*	*16.48*
1050	15.1	*11.2*	*12.5*	*18.8*	*15.04*	*12.60*
1100	*12.4*	*11.1*	*9.5*	*14.3*	*11.44*	*9.58*
1150	*9.8*	*9.8*	*7.2*	*10.9*	*8.72**	*7.30*
1200	*7.4*	*7.4*	*5.5*	*8.3*	*6.64**	*5.56*
1250	*5.5*	*5.5*	*4.2*	*6.3*	*5.04**	*4.22*
1300	*4.1*	*4.1*	*3.1*	*4.8*	*3.84**	*3.22*
1350	*3.1*	*3.1*	*2.1*	*3.6*	*2.88**	*2.41*
1400	*2.3*	*2.3*	*1.5*	*2.8*	*2.24**	*1.88*
1450	*1.7*	*1.7*	*1.0*	*2.1*	*1.68*	*1.41*
1500	*1.3*	*1.3*	*0.65*	*1.6*	*1.28*	*1.07*

* Less than S_o

Alloy 800H

In Table 3, the stress allowables for alloy 800H are compared for temperatures in the time-dependent range covered by ASME Section III-NH (800 to 1400°F). In the time-independent range for S, the S_o values are different because they are based on the S_{mt} for 300,000 hr (NH-3221). In the time-dependent temperature range, the S and S_o values are consistent. The S values are less than values based on 0.80 S_r and the S_t values are equivalent to or less than the 0.67 S_r values. It does not appear that any corrections are needed to the S_o, S_t, or S_r values for alloy 800H.

Table 3. Comparison of allowable stresses for alloy 800H in ASME Section III, Subsection NH

Temp (°F)	S (ksi)	S_o (ksi)	S_t (ksi)	S_r (ksi)	0.80 S_r (ksi)	0.67 S_r (ksi)
800	15.0	*15.3*	*19.1*	*56.2*	*45.96*	*37.65*
850	14.7	*15.1*	*18.8*	*47.7*	*38.16*	*31.96*
900	14.5	*14.8*	*18.5*	*38.0*	*30.40*	*25.46*
950	14.2	*14.6*	*18.0*	*30.3*	*24.24*	*20.30*
1000	14.0	*14.1*	*16.5*	*24.2*	*19.36*	*16.21*
1050	13.8	*11.2*	*12.0*	*19.3*	*15.44*	*12.93*
1100	*11.6*	*10.0*	*10.3*	*15.4*	*12.32*	*10.32*
1150	*9.3*	*9.3*	*8.1*	*12.2*	*9.76*	*8.17*
1200	*7.4*	*7.4*	*6.5*	*9.8*	*7.84*	*6.57*
1250	*5.9*	*5.9*	*5.2*	*7.8*	*6.24*	*5.23*
1300	*4.7*	*4.7*	*4.1*	*6.2*	*4.96*	*4.15*
1350	*3.8*	*3.8*	*3.3*	*4.9*	*3.92*	*3.28*
1400	*3.0*	*3.0*	*2.6*	*3.9*	*3.12*	*2.61*

2 1/4Cr-1Mo Steel

In Table 4, the stress allowables for 2 1/4Cr-1Mo steel are compared for temperatures in the time-dependent range covered by ASME Section III-NH (700 to 1100°F). As for Table 1 on 304H stainless steel, these stress allowables include S, S_o, S_t, and S_r. With respect to the comparison of S and S_o, the values for S_o at 700 and 750°F correspond the S_{mt} values at 300,000 hr (NH-3221). Other than this difference, S and S_o are identical. However, the S values for 900, 950, 1000, and 1050°F are greater than the values in the 0.80 S_r column. This inconsistency should be resolved. On the other hand, the values for S_t are more-or-less equal to or less than the values of 0.67 S_r. This trend suggests that the minimum rupture strength at 100,000 h controls S_t.

Table 4. Comparison of allowable stresses for 2 1/4Cr-1Mo steel in ASME Section III, Subsection NH

Temp (°F)	S (ksi)	S_o (ksi)	S_t (ksi)	S_r (ksi)	0.8 S_r (ksi)	0.67 S_r (ksi)
700	16.6	*17.9*	*35.5*	*54.0*	*28.40*	*36.18*
750	16.6	*17.9*	*25.0*	*37.5*	*20.00*	*25.13*
800	16.6	16.6	*18.0*	*27.0*	*14.40*	*18.09*
850	16.6	16.6	*14.0*	*21.0*	*16.80*	*14.07*
900	*13.6*	*13.6*	*10.9*	*16.4*	*13.12**	*10.99*
950	*10.8*	*10.8*	*8.4*	*12.6*	*10.08**	*8.44*
1000	*8.0*	*8.0*	*6.3*	*9.4*	*7.52**	*6.30*
1050	*5.7*	*5.7*	*4.7*	*7.0*	*5.60**	*4.69*
1100	*3.8*	*3.8*	*3.3*	*5.0*	*4.00*	*3.35*

* Less than S_o

9Cr-1Mo-V Steel

In Table 5, the stress allowables for 9Cr-1Mo-V steel are compared for temperatures in the time-dependent range covered by ASME Section III-NH (700 to 1200°F). As for Table 1 on 304H stainless steel, these stress allowables include S, S_o, S_t, and S_r. With respect to the comparison of S and S_o, the values for S_o at 700 and 900°F correspond the S_{mt} values at 300,000 hr (NH-3221). Other than this difference, S and S_o are identical. However, the S values for 1150 and 1200°F are greater than the values in the 0.80 S_r column. This inconsistency should be resolved. On the other hand, the values for S_t are more-or-less equal to or less than the values of 0.67 S_r. This trend suggests that the minimum rupture strength at 100,000 hr controls S_t. It is not clear that the S_r values in the ASME Section III-NH pertain to products thicker than 3 inches. It is known, however, that the S_o values represent the thick product stress line and that the difference in the allowable stresses for the product size difference only occurs at 1100 and 1150°F.

Table 5. Comparison of allowable stresses for 9Cr-1Mo-V steel in ASME Section III, Subsection NH

Temp (°F)	S (ksi)	S_o (ksi)	S_t (ksi)	S_r (ksi)	0.8 S_r (ksi)	0.67 S_r (ksi)
700	22.9	*26.7*	*47.3*	*71.0*	*56.80*	*47.57*
750	22.2	*25.9*	*42.3*	*63.5*	*50.80*	*42.54*
800	21.3	*24.9*	*35.1*	*52.7*	*42.16*	*35.31*
850	20.3	*23.7*	*28.9*	*43.3*	*34.64*	*29.01*
900	19.1	*21.9*	*23.5*	*35.2*	*28.16*	*23.58*
950	*17.8*	*17.8*	*18.8*	*28.2*	*22.56*	*18.89*
1000	*16.3*	*16.3*	*14.9*	*22.3*	*17.84*	*14.94*
1050	*12.9*	*12.9*	*11.5*	*17.3*	*13.84*	*11.59*
1100	*9.6*	*9.6*	*8.7*	*13.1*	*10.48*	*8.78*
1150	*7.0*	*7.0*	*5.5*	*8.2*	*6.56**	*5.49*
1200	*4.3*	*4.3*	*3.3*	*4.9*	*3.92**	*3.28*

* Less than S_o

Summary of the Evaluations

In summary, S_o values in ASME III-NH are consistent with S values in ASME II- Part D for all five materials which have values in ASME III-NH. However, relative to the use of S_{min} or S_r as a criterion for setting the stress allowables, there are inconsistencies for four of the five materials which need further examination. Here, the 0.80 S_r values reported in Table I-14.6 for 100,000 hr were found to be less than the S_o values in many instances.

AVAILABILITY OF THE ORIGINAL AND AUGMENTED DATABASES NEEDED TO ESTABLISH S_o, S_t, and S_r

In 1963, Brister and Leyda, outlined the early work that was undertaken to establish allowable stresses for boilers and pressure vessels at elevated temperature [1]. At that time, the criteria for unfired pressure vessels differed from the criteria for boilers but both construction codes made use of the stress to produce a creep rate of 1% in 100,000 hr, the average rupture strength at 100,000 hr, and the minimum rupture strength at 100,000 hr. Data were meager but analysis methods began to emerge [2, 3]. It was recognized that data for the different products covered by materials specification were needed. In the period 1963 to 1967, Smith, working with the ASTM-ASME Joint Committee on the Effect of Temperature on the Properties of Metals and the Metals Properties Council (MPC), undertook the responsibility for obtaining strength data requested by the Code [4]. The data were summarized in a series of reports published by the American Society for Testing and Materials (ASTM), and the evaluation and analysis procedures developed by Smith were published, as well [5-8]. Materials included in this work were 304H stainless steel [5], 316H stainless steel [5], and 2 1/4Cr-1Mo steel [6].

Alloy 800 and alloy 800H data were not included but a separate collection and analysis effort was undertaken by the International Nickel Company (INCO), the Westinghouse Electric Company, and Gulf General Atomics (GA) to support work on nuclear components for the gas cooled reactors [9]. In contrast to the availability of the ASTM STP series reports, the database for alloy 800 and 800H was not readily available in the open literature or as company reports at the time that the original code work was undertaken. Data had to be extracted from letter reports and minutes of meetings for this assembly and augmentation.

The criteria for setting the allowable stresses for construction of Class 1 nuclear components first appeared in ASME Section III Code Case 1331-5 in 1971 and were developed for application to the Fast Flux Test Facility (FFTF). These criteria, identified by Snow and Jakub in 1982, were essentially the same as those currently utilized in ASME III-NH [10]. Only 304H and 316H stainless steels were included in Code Case 1331-5, but a year later alloy 800 was introduced into Code Case 1331-6 and later in that year 2 1/4Cr-1Mo steel was incorporated into Code Case 1331-8. There was interest in the fine-grained higher strength alloy 800 (UNS 08800) for use in heat exchangers at temperatures below 1200°F, and much of the data accumulated was on alloy 800 rather than alloy 800H (UND 08810). Subsequent changes to Code Case 1331-5 which led to Code Case 1592 and eventually to Code Case N-47-19 in 1979 were outlined by Snow and Jakub in 1982 [10]. The databases used to set the stress allowables in the code cases were the same as those used by Smith for non-nuclear construction codes.

In the late 1960's and early 1970s, work to expand the databases was undertaken. Efforts included testing sponsored by the Metals Properties Council and the U.S. Atomic Energy Commission for all of the materials in the Class 1 components nuclear construction code cases. Further, collection of data from overseas sources was undertaken by Booker and co-workers, among others [11, 12]. Booker performed an evaluation of newer data for 304H stainless steel, 316 stainless steel, and alloy 800H [12]. He produced a table that summarized the database that produced the ASME III Code Case N-47 stress allowables and compared the database with a new database as shown in Table 6. Booker found that the stress allowables provided in ASME III Code Case N-47 for 304H stainless steel were appropriate and no changes were needed. Examination of the allowable stresses provided in the code cases of the 1970s for 304H and 316H stainless steels revealed that stresses are identical to those currently in ASME Section III-NH.

Table 6. Comparison of the data that produced the N-47 Code Case
with new data for re-evaluation by Booker [12]

Item	Material	No. Lots	No. Data	Temp Range (°F)	Longest Life (hr)
N-47	304H	22	225	1000-1500	46,000
N-47	316H	21	348	1000-1600	26,000
N-47	800H	15	241	1000-1800	22,000
New data	304H	26	255	900-1400	60,000
New data	316H	106	1269	932-1600	72,000
New data	800H	21	209	1000-1500	24,000

Booker found that the long-time (100,000 hr) stress allowables in ASME III Code Case N-47 for 316H stainless steel and alloy 800H were high relative to his analysis. Further, he found that the tertiary creep criterion controlled the stress allowables for alloy 800H for some combinations of time and temperature. The analyses of Booker and earlier work by Roberts of GA contributed to changes in the stress allowables for alloy 800H, which were lowered in a subsequent revision to ASME III Code Case N-47 [13]. Booker did not look for any inconsistency between S_o and $0.80S_{min}$.

Booker did not examine the 2 1/4Cr-1Mo steel database in his re-evaluation of the allowable stresses in ASME III Code Case N-47, stating that the available data were "…judged to be insufficient to draw conclusions…" Although the new data for 2 1/4Cr-1Mo steel produced by the USAEC-funded research were not included in re-evaluation of stress allowables for ASME III Code Case N-47, a re-analysis of other available data in an expanded database was undertaken by Roberts for the ASME Section II Subgroup Strength of Ferrous Alloys (SG SFA) at a later time [14]. This work, completed in 1990, involved the analysis of 88 heats and 658 data extracted from the ASTM database, the British Steelmakers Creep Committee (BSCC) [15], and the National Research Institute for Metals (NIMS) [16]. The database was not included in the Roberts report but a reasonable re-assembly is possible from the references that were provided. The Roberts effort produced the stress allowables that are currently listed in ASME II Part D Table 1A. The new values for the minimum stress to rupture were provided for consideration by the ASME Subgroup on Elevated Temperature Design for developing S_{min} and S_t tables in ASME III Code Case N-47 in May of 1993. However, it was concluded that ASME III N-47 minimum stress-rupture values were conservative relative to the Roberts analysis, so no changes were made.

Data accumulated on alloy 800H were provided by McCoy in 1993 [17]. The tabulation included data from several "new" sources and greatly expanded the original database used to establish the stress allowables in ASME III Code Case N-47. Information is provided in Table 7. This compilation included many lots of Sandvik steels that did not meet the specifications for the 800H grade (chemistry or grain size) and some lots that did not meet the special ASME III Code Case N-47 minimum requirements for aluminum plus titanium content. From the database, McCoy selected 708 data from 66 lots that seemed to meet the requirements for alloy 800H specified by ASME III Code Case N-47. Analyses of these data produced minimum strength to rupture values for 100,000 hr that were fairly close to values listed in current edition of ASME III-NH for alloy 800H.

Table 7. Comparison of the data that produced the N-47 Code Case with data for re-evaluation by McCoy for alloy 800H in ASME III Code Case N-47 [17]

Item	Source	No. Lots	No. Data	Temp Range (°F)	Longest Life (hr)
N-47	INCO	15	241	1000-1800	22,000
New data	Sandvik	32	360	1020-1500	83,000
New data	NIMS	12	120	1112-1472	33,000
New data	British	13	47	932-1472	46,000
New data	Other	8	68	1200-1500	24,000
"Censored"	INCO	14	167	1000-1500	34,000

The original database for 9Cr-1Mo-V steel was well documented at the time of the submittal for inclusion in ASME Section III and III-N-47 and consisted of data largely produced at Combustion Engineering (CE), the Oak Ridge National Laboratory, and Westinghouse Electric Company [18, 19, 20]. The steel was approved quickly for construction under the rules of ASME Section I and Section VIII and values for S_o were submitted for inclusion in ASME III-N-47 in 1989. In the early 1990s, however, European producers became concerned about the stress allowables in ASME for Section I and Section VIII construction. A new database was assembled by the MPC which included an up-date of the ORNL data, some European data, and some Japanese data. The expanded database produced modifications of ASME Section II Part D Table 1A stresses including a separate stress line for products thicker than 3 inches. Eventually, the "thick product" stress line was provided as a singular set of S_o values when 9Cr-1Mo-V steel was incorporated into ASME III-N-47.

Because of its world-wide usage in Section I and VIII components, the 9Cr-1Mo-V steel database has grown substantially in the last fifteen years. Most new data were restricted to stress-rupture but some additional information on creep behavior was accumulated [21, 22]. Unfortunately, most of the "new" data are not freely available. Nevertheless, the data have been used to assess the adequacy of the stress allowables in the ASME and overseas construction codes for boilers, pressure vessels, and piping. Table 8 provides a summary of the development of the current database.

Table 8. Comparison of data that produced the ASME III-NH stress allowables for 9Cr-1Mo-V steel with data that could be used for re-evaluation

Item	Source	No. Lots	No. Data	Temp Range (°F)	Longest Life (hr)
US- 1984	US-1984	17	222	900-1250	39,000
ALL-1994	US	21	210	1000-1200	30,700
ALL-1994	German	12	96	1022-1292	33,000
ALL-1994	Japanese	39	605	1022-1292	66,200
Current	US	23	315	850-1300	120,000
Current	European	32	568	1022-1310	110,300
Current	Japanese	55	906	842-1292	66,200

An overview of stress-rupture databases by means of the Larson-Miller parameter

It is clear that the stress-rupture databases for the ASME III-NH materials are quite large. There exists data from a range of data sources, chemistries, product forms, heat treatments, and specimen configurations. Testing variables include a broad range of temperatures, stress levels, and procedures based on ASTM, British, German, and Japanese standards. Nevertheless, the overall character of the databases for the materials may be captured in the form of the Larson Miller parameter (LMP) for stress-rupture. These parametric plots for the five materials are shown in Figures 1 through 5. The correlations are based on an "average" Larson Miller parametric constant C_{ave} that was produced by a lot-centered regression analysis of the data to the LMP relation written in the form [24, 25, 26]:

$$\log(t_r) = \{[a_0 + a_1 \log S + a_2 (\log S)^2 + a_3 (\log S)^3] / T_k\} - C_{ave}$$

where: t_r is rupture life in hours, S is stress in MPa, T_k is temperature in Kelvins, and a_0, a_1, a_2, and a_3 are coefficients determined in the regression analysis. Details of the databases for alloy 800H and Gr 91 were covered to some extent in the reports of the Task 1 effort [25, 26]. Details of the database for the other materials will be covered in Part 2 of this task.

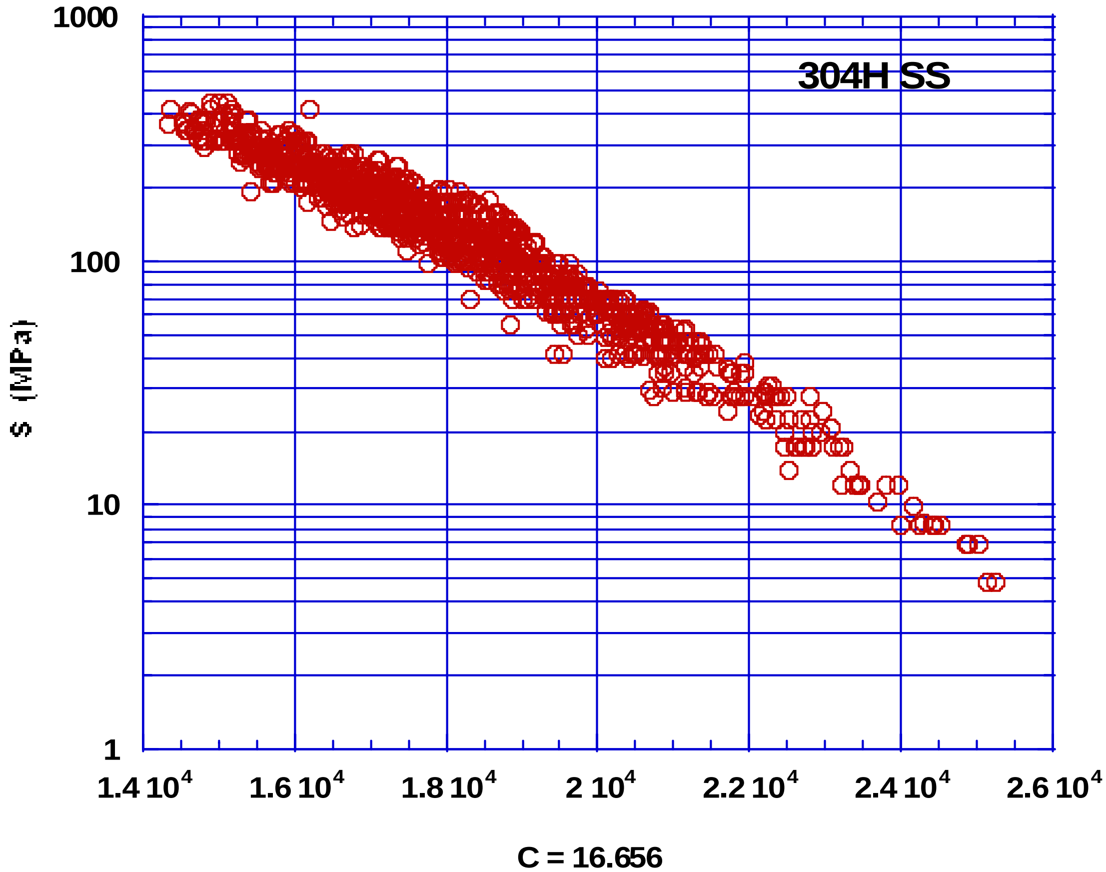

Fig. 1. Stress versus the Larson Miller parameter for the combined 304H stainless steel rupture database- 75 lots, 1170 data, 179,000 longest life.

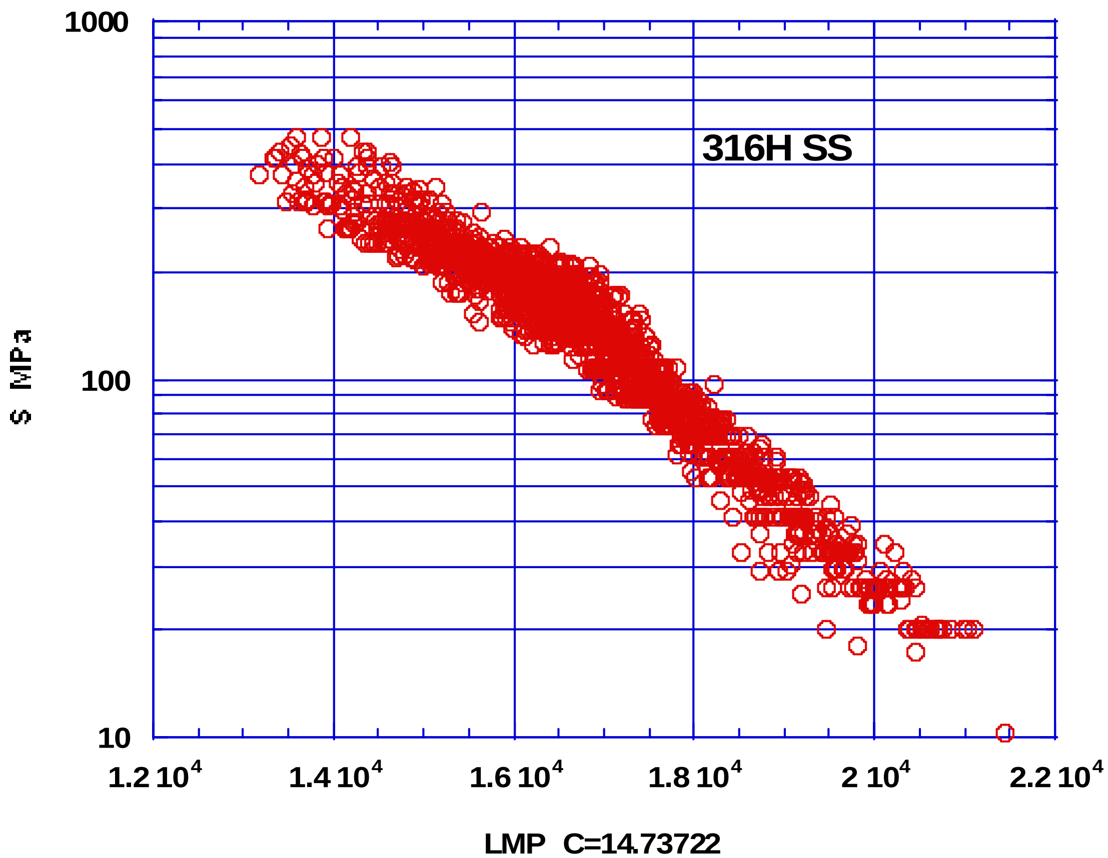

Fig. 2. Stress versus the Larson Miller parameter for the combined 316H stainless steel rupture database- 106 lots, 1940 data, 222,000 h longest life..

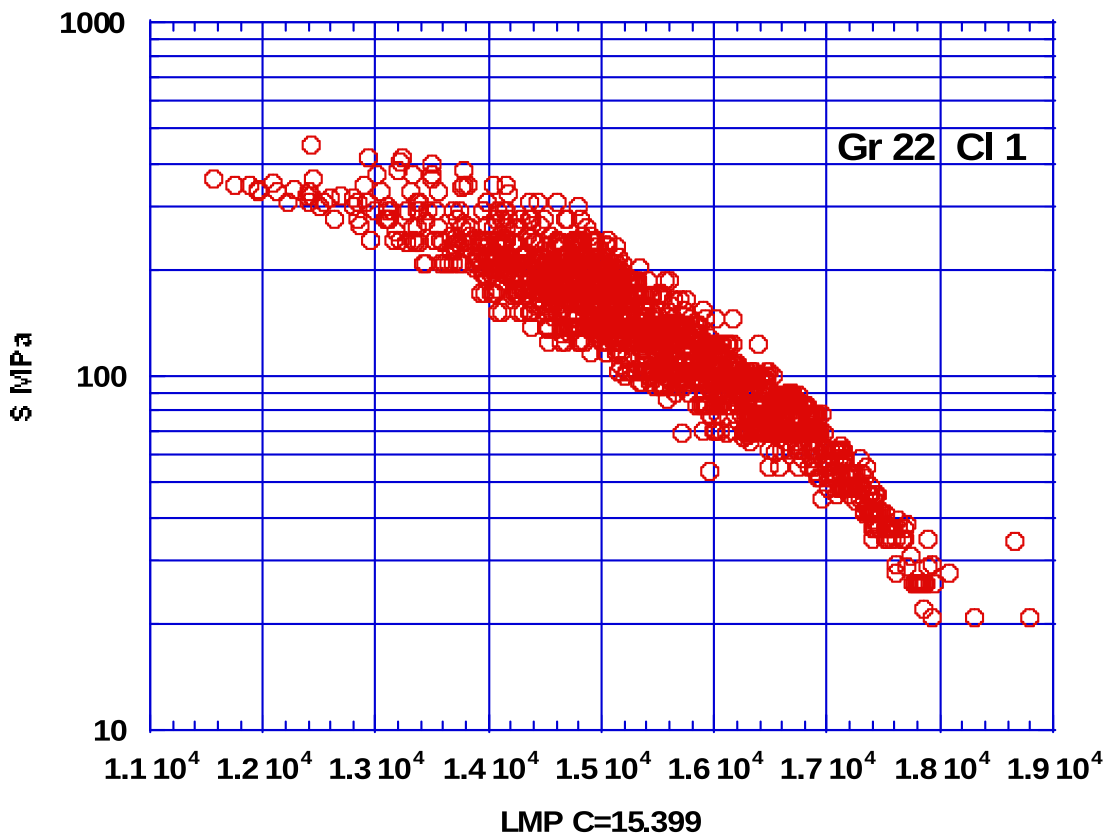

Fig. 3. Stress versus the Larson Miller parameter for the combined 2 ¼ Cr – 1Mo steel (Gr 22 Class 1) rupture database- 189 lots, 1623 data, 213,000 longest life.

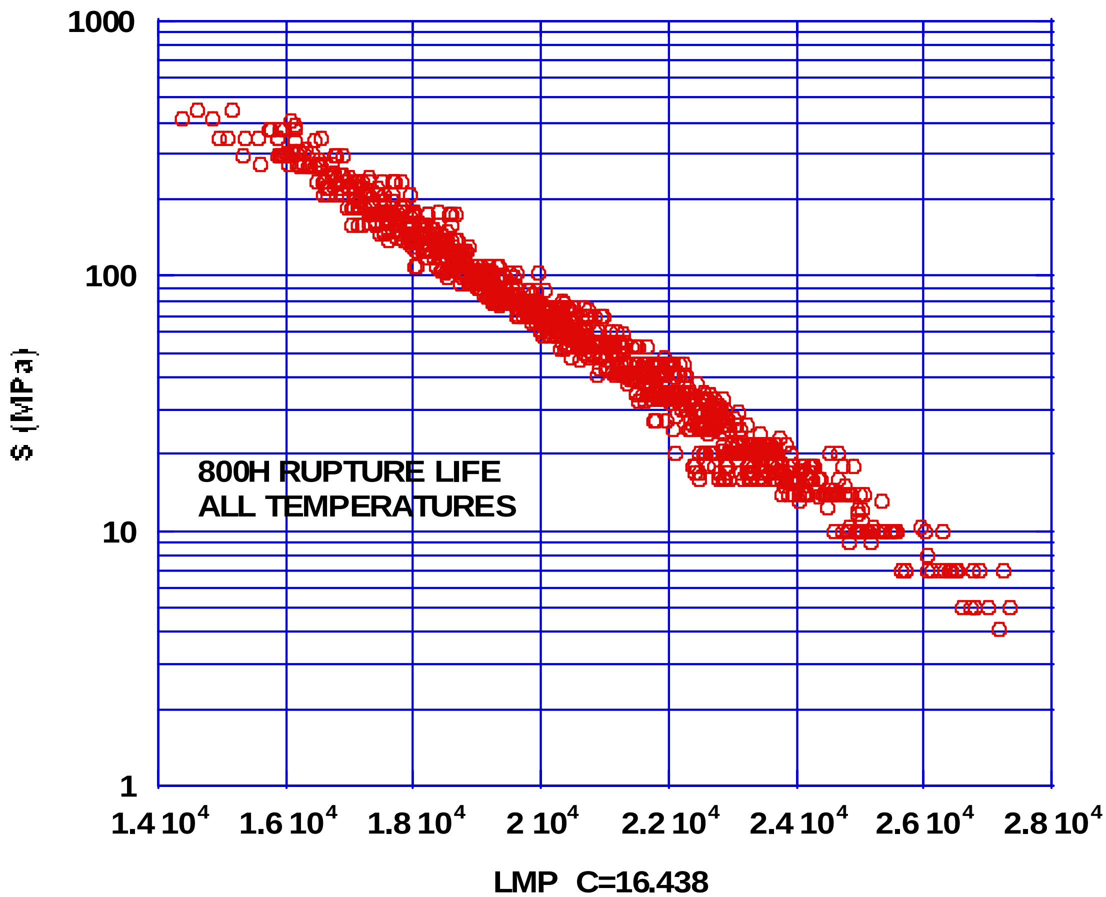

Fig. 4. Stress versus the Larson Miller parameter for the combined alloy 800H rupture database- 83 lots, 1170 data, 194,000 longest life.

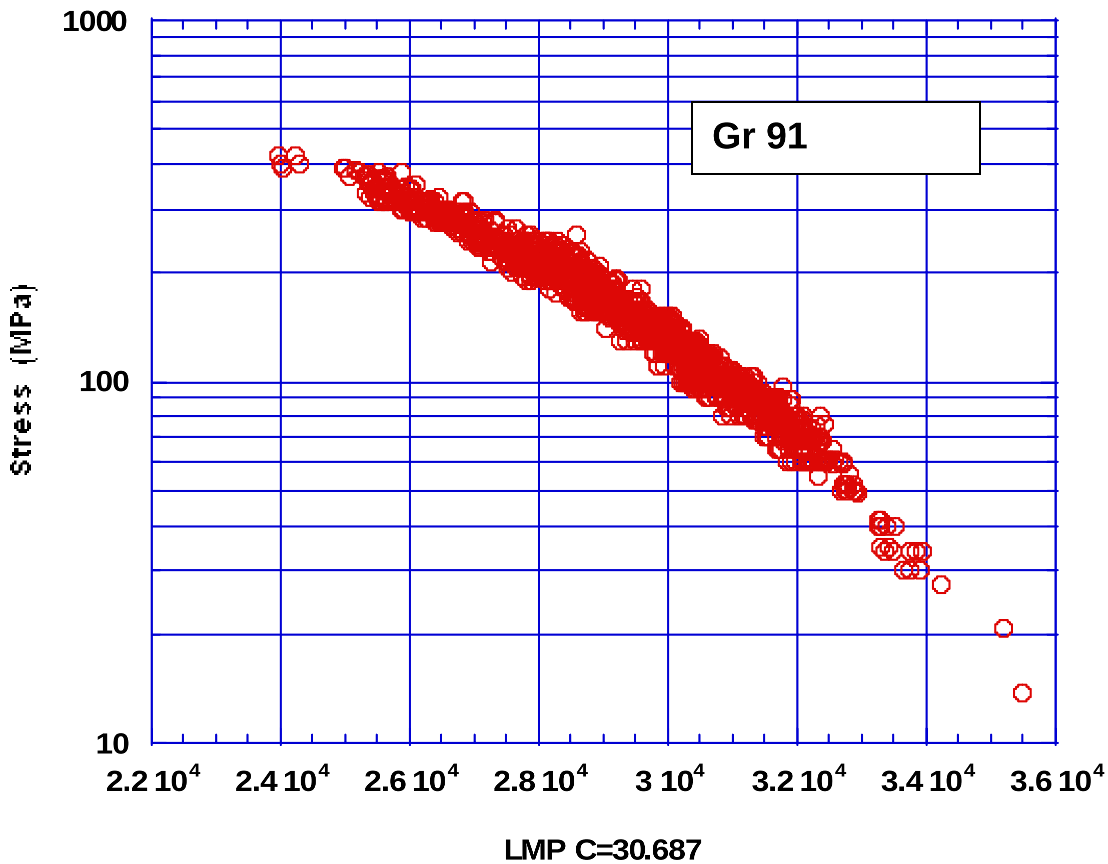

Fig. 5. Stress versus the Larson Miller parameter for the combined 9Cr – 1Mo -V steel (Gr 91) rupture database- 104 lots, 1600 data, 110,000 longest life.

SUMMARY

The current operating condition allowable stresses provided in ASME Section III, Subsection NH were reviewed for consistency with the criteria used to establish the stress allowables and with the allowable stresses provided in ASME Section II, Part D.

The materials included 304H stainless steel, 316H stainless steel, alloy 800H, 2 1/4Cr-1Mo steel, and 9Cr-1Mo-V steel.

The S_o values in ASME III-NH were found to be consistent with the *S* values in ASME II-D for the five materials of interest.

The stress values based on the criterion of 80% of the minimum rupture strength at 100,000 hr ($0.80S_r$) were less than S_o for some temperatures for 304H stainless steel, 316H stainless steel, 2 1/4Cr-1Mo steel, and 9Cr-1Mo-V steel.

Stress values for alloy 800H appeared to be consistent with the criteria on which S_o values were established for all temperatures.

The databases which formed the basis for the current stress allowables in ASME III-NH were significantly smaller in size and scope than the databases currently available.

ACKNOWLEDGEMENTS

This work was supported by ASME ST-LLC and managed by J. Ramirez. Technical oversight was provided by R. I. Jetter, C. Hoffmann, and Sam Sham. Blaine Roberts provided guidance and background information on the development of the code allowables for all of the materials covered by the report and was the author of the background document that supported the current design allowables for 2 1/4Cr-1Mo steel. Important minutes of the meetings of the describing the development of the stress tables for the high-temperature Section III code cases were supplied by Richard Moen through Noel Lobo of the ASME staff. The author was assisted by Elizabeth A. Cantrell in assembling several of the databases.

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FINAL

OPERATING CONDITION ALLOWABLE STRESS VALUES

ASSESSMENT OF THE DATABASES LEADING TO THE ESTABLISHMENT OF ALLOWABLE STRESSES IN ASME SECTION III SUBSECTION NH

AND

RECOMMENDED ACTION FOR THE CORRECTION OF CURRENTLY LISTED VALUES FOR S_o, S_t, and S_r

Submitted to ASME ST-LLC

ASME/DOE Gen-IV Materials Project
Task 6, Part II and Part III

Revision 3

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December 15, 2009

FINAL

OPERATING CONDITION ALLOWABLE STRESS VALUES

ASSESSMENT OF THE DATABASES LEADING TO THE ESTABLISHMENT OF ALLOWABLE STRESSES IN ASME SECTION III SUBSECTION NH

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ABSTRACT

Based on a review of the current operating condition allowable stresses provided in ASME BPV Section III, Subsection NH and the finding of inconsistencies between the *S* values in ASME BPV Section II, Part D and the S_o values in ASME BPV III-NH for the five materials included in ASME BPV III-NH, expanded databases for stress-rupture, tertiary creep, and time to 1% strain were assembled for use estimating and possibly revising the stress allowables in ASME BPV III-NH. A preliminary evaluation showed that, in spite of the substantially larger databases, the stress allowables S_t and S_r for some materials were within 5% of the existing values. It was judged that the existing values in ASME BPV III-NH for alloy 800H and 9Cr-1Mo-V steel were conservative and adequate for use in the temperature range of interest to the Generation IV reactor design. A number of issues were identified in using the databases to estimate the stresses based on tertiary creep and time to 1% strain criteria. Some actions were suggested to resolve the issues. The greatly expanded times for the databases were expected to help in extending allowable stresses to at least 500,000 hours

INTRODUCTION

In Part I of Task 6 addressing the ***OPERATING CONDITION ALLOWABLE STRESS VALUES*** in ASME BPV Section III-NH (BPV III-NH), it was found that the S_o values in III-NH were consistent with the *S* values in ASME BPV II-D Tables 1A or 1B (BPV II-D) for the five materials covered by BPV III-NH, namely 304H stainless steel, 316H stainless steel, alloy 800H, 2 1/4Cr-1Mo steel, and 9Cr-1Mo-V steel [1]. However, the stress values based on the criterion of 80% of the minimum rupture strength at 100,000 hr ($0.80S_r$) were less than S_o for some temperatures for 304H stainless steel, 316H stainless steel, 2 1/4Cr-1Mo steel, and 9Cr-1Mo-V steel. The stress values for alloy 800H appeared to be consistent with the criteria on which S_o values were established for all temperatures. The development of the stress allowables in BPV III-NH was traced for the five materials and it was found that the databases which formed the basis for the current stress allowables in BPV III-NH were significantly smaller in size and scope than the databases currently available. Several different analysis procedures were used to produce these stresses over the years and the allowable stresses were revised for some of the materials in BPV III-NH and not revised for other materials. In view of the need to extend the time limits and, in some cases, the temperature limits for use in the Generation IV reactor concepts, an exploratory re-evaluation of the databases and analyses methods was undertaken.

In Part II of Task 6 reported here, the expanded databases are analyzed using a procedure that is typical of the current procedure used by consultants assigned by the ASME to recommend the stress allowables for BPV II-D. In Part III the results from Part II are used to recommend actions to meet the needs for setting allowables over the range of temperatures and times of interest to the Generation IV reactor concepts.

In the databases collected in Task 6 Part I reported earlier, data from a range of sources, chemistries, product forms, heat treatments, and specimen configurations were included. Data covered a broad range of temperatures, stress levels, and testing procedures based on ASTM, British, German, and Japanese standards. It was expected that significant variations in the results that could be attributed to specific products, heat treatments, or sources could be identified by means of a characteristic “Lot Constant” (or Heat Constant) associated with that source. The Lot Constant and average materials constants were a direct product of the Larson Miller parametric (LMP) analysis that is generally employed by consultants to develop the recommended time-dependent stress allowables in BPV II-D. Here, the correlations are based on an “average” Larson-Miller parametric constant, C, that was produced by a lot-centered regression analysis of the data to the LMP relation written in the form [2, 3, 4]:

$$\text{Log}\,(t_r) = \{[a_0 + a_1 \log S + a_2 (\log S)^2 + a_3 (\log S)^3] / T_k\} - C \qquad (1)$$

where: t_r is rupture life in hours, S is stress in MPa, T_k is temperature in Kelvin, and a_0, a_1, a_2, and a_3 are coefficients determined in the regression analysis.

EVALUATION OF THE 304H STAINLESS STEEL DATABASE

The database for 304/304H stainless steel consisted of more than 1600 lines covering temperatures from 427 to 1093°C (800 to 2000°F) and times to 120,000 hours. Not all lines included rupture points and relatively few lines provided the time to tertiary creep and the time to 1% creep strain.

Expected minimum stress-to-rupture for 304H stainless steel:

With respect to the rupture life, it is policy of consultants for BPV II-D in their analysis of time-dependent allowable stress values for BPV II-D to delete or "censor" data that are short of 100 hours. However, the criteria for setting *S* values for BPV II-D Tables 1A and 1B require only values for 100,000 h whereas BPV III-NH Tables I-14.3, I-14.4, and I-14.6 currently require S_{mt}, S_t, or S_r values ranging from 1 h to 300,000 h. To explore the effect of censoring, the analyses for rupture data were performed for all times, 10-h censor, 100-h censor, and 1000-h censor. The effect of the censoring on the average lot constant, C, is shown below. Here, it may be seen that the number of lots, the number of data, the value of the parametric constant, and the average strength at 10^5 h decreased as shorter time data were discarded. However, the average strength decreased by less than 2% when the data below 100 h were discarded. Further, discarding data below 1000 h decreased the average strength at 10^5 h by ~4.4% and the minimum strength by 6%. The value for the expected minimum stress-to-rupture provided in BPV III-NH Table I-14.6 for 304H stainless steel at 649°C (1200°F) is 42.7 MPa (6.2 ksi) which is the same as the value calculated from the 1000-h censor database.

Table 1. Effect of censoring on the Larson-Miller Lot Constant, C, and strength at 10^5 h and 649°C (1200°F) for 304 stainless steel

Censor time (h)	No. of Lots	No. of Data	C	Strength (MPa) at 10^5 h (avg)	(min)
None	76	1295	17.13985	63.1	45.5
10 h	76	1183	16.81973	62.9	45.5
100 h	73	956	15.70056	62.3	44.8
1000 h	63	579	13.15619	60.3	42.7

With respect to the statistics, all fits were similar. Figure 1 compares the data distribution to the calculated stress function of the Larson-Miller parameter for the total database. A gradual downward curvature is evident. Figure 2 shows the distribution of the residuals, $\log(t_{observed}/t_{calculated})$, as a frequency plot. Figure 3 shows a histogram of the Lot Constants in which the data sources are identified, and Figure 4 shows a histogram of the lot constants in which the product forms are identified. Table 2 summarizes the information on the Lot Constants in terms of the sources and products. Here, it may be seen that the largest number of lots were collected from U.S. sources and the smallest from Japan. Bars and forging comprised the largest number of lots with respect to products. The Lot Constants were the smallest for the Japanese lots and for tubes and pipes. The standard deviation for the lots of data sources was the smallest for the Japanese lots which were mostly tubes. The standard deviation for the lots of products was smallest for the plates. Because the stress function in the Larson-Miller model is the same for all lots, and the Lot Constant represents the intercept of the log rupture life versus reciprocal temperature at zero, smaller Lot Constants imply greater rupture strength.

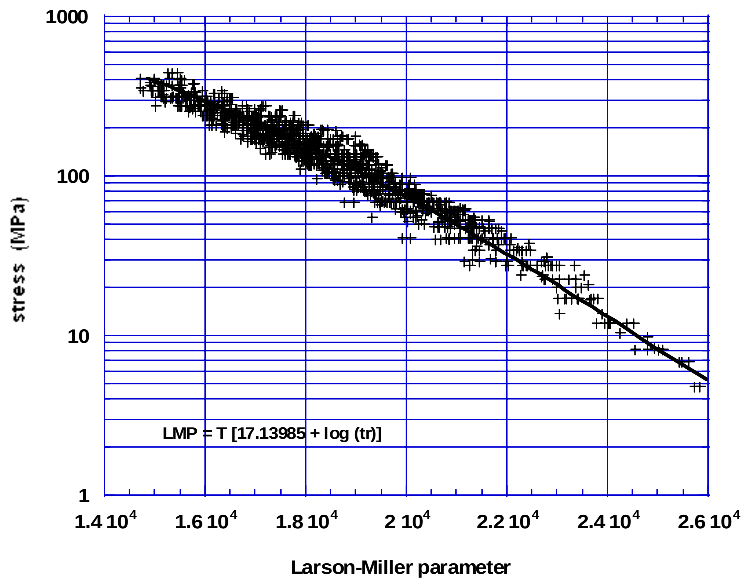

Figure 1. Stress versus the Larson-Miller parameter for rupture of 304H stainless steel

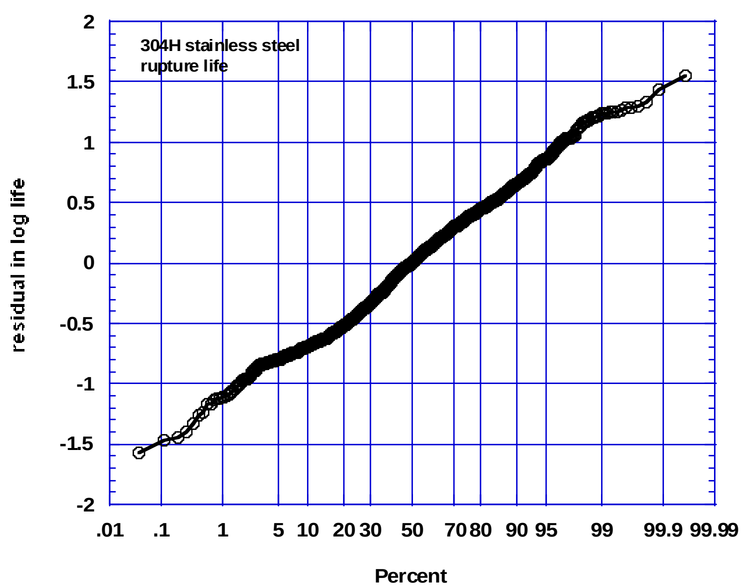

Figure 2. Distribution of residuals from the fit of the Larson-Miller parameter to rupture life data for 304H stainless steel

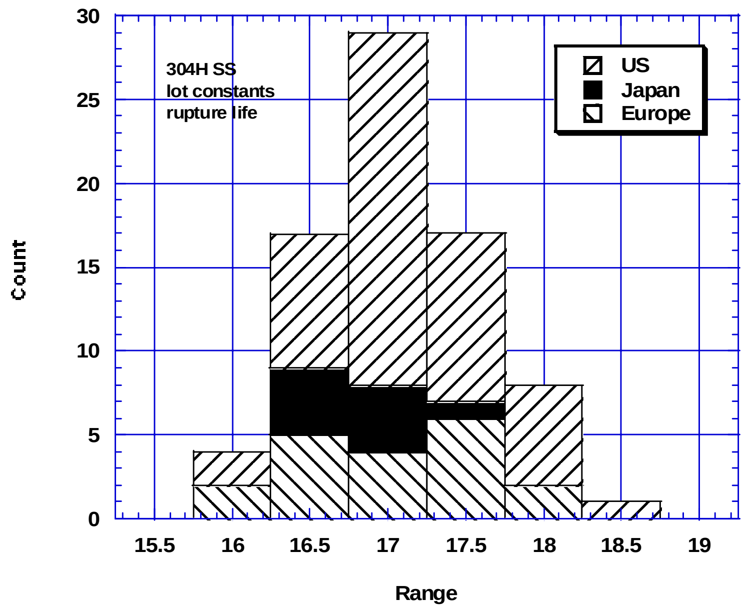

Figure 3. Distribution of the lot constants for the rupture life of 304H stainless steel according to the source of the rupture data

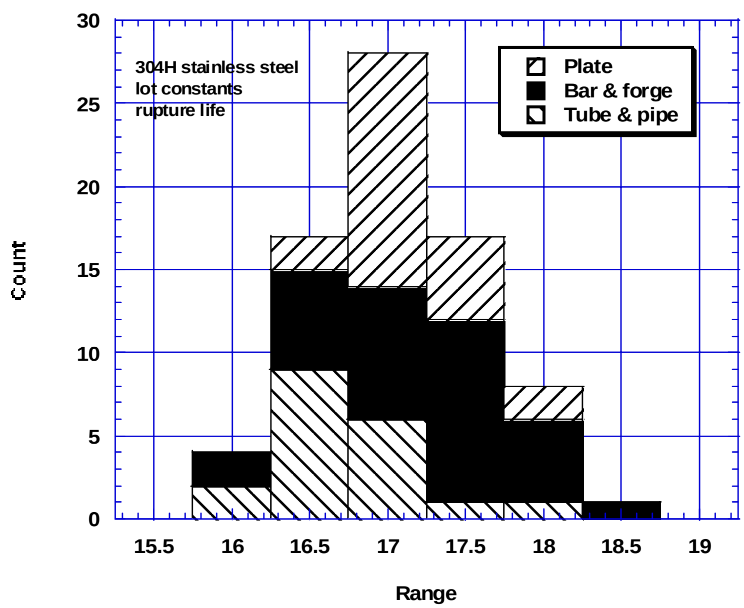

Figure 4. Distribution of the lot constants for the rupture life of 304H stainless steel according to the product

Table 2. Summary of the Larson-Miller Lot Constants for the rupture life of 304H stainless steel in terms of the data sources and products.

Source or Product	No. of Lots	Avg of Lot Constants	Standard Deviation
U. S.	48	17.15	0.50
Japan	9	16.82	0.30
Europe	19	17.05	0.57
Plates	22	17.19	0.36
Bars & Forgings	33	17.20	0.55
Tubes & Pipes	19	16.75	0.45

Figure 5 compares the minimum stress-to rupture as a function of temperature for BPV III-NH Table I-14.6 with the values calculated from the Larson-Miller Parameter for the full and 100-h censored databases. Except for the long-time value at 816°C (1500°F), the newly estimated values were close to or slightly higher than the Code values The differences were not sufficient to justify changes to the BPV III-NH values which appears to be conservative for most conditions.

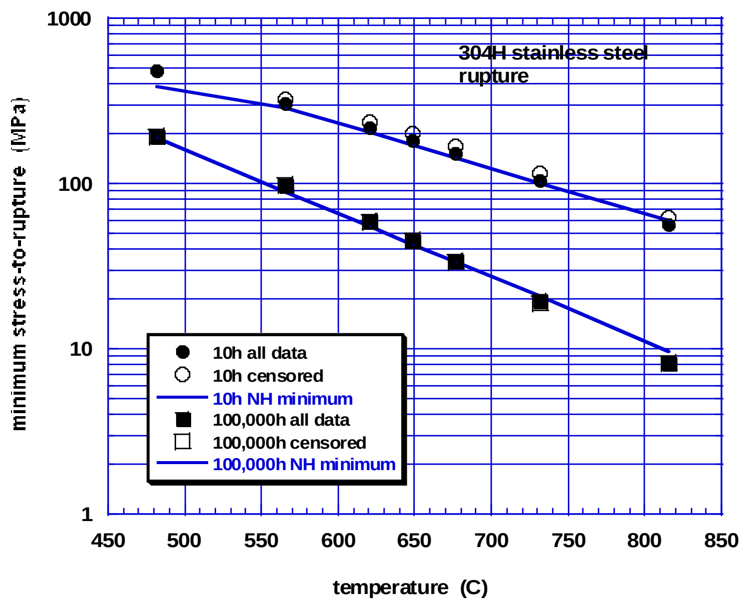

Figure 5. Comparison of BPV III-NH minimum stress-to-rupture values with the values estimated from the analysis of the expanded database for 304H stainless steel

Minimum time to tertiary creep for 304H stainless steel:

Tertiary creep as a criterion for setting stress allowables in the time-dependent temperature range is unique to BPV III-NH. The criterion was developed in the formative days of Code Case 1331-5. The advantages and disadvantages of introducing the tertiary creep criterion were vigorously discussed in Code meetings and the emphasis was on the impact of the early appearance of tertiary creep in alloy 800H and the limitation that such a criterion placed on the allowable time-dependent stresses. It appeared that justification for the criterion partly rested on the observation of Leyda and Rowe [5] that tertiary creep in stainless steels occurred fairly late in life at low temperatures [566°C (1050°F)] but early in life at high temperatures [816°C (1500°F)]. In their study, the time to tertiary was defined by Leyda and Rowe as a visual departure from "secondary creep" rather the 0.2% offset intercept from the line extended from the minimum creep rate that came into later usage. Either way, the database for tertiary creep is meager. For 304H stainless steel, data for only 18 lots (224 values) were found. With such a meager data base, the identification of a statistically defined minimum time to tertiary creep for a broad range of temperatures and times was difficult. Three possible approaches were considered: 1) develop a correlation between the time to tertiary creep and the rupture life and assume that the scatter and lot-to-lot variation would be similar; 2) proceed with a time-temperature parametric model similar to the Larson-Miller parameter for rupture; 3) develop a damage model or tertiary creep law and determine the stress, temperature, and lot-to-lot variation. The first two approaches were investigated.

Figure 6 provides a plot for the log time to tertiary, t_3, versus log time to rupture, t_r, for data at 593°C (1100°F). If the temperature dependence observed by Leyda and Rowe holds, the data should plot as a straight line with a slope representing the ratio t_3/t_r. The data scattered a bit but a least squares fit to a power law produced an exponent near unity. When data for other temperatures were examined, however, some data sets seemed to fit the Leyda-Rowe relation and other data sets were poor fits. Table 3 provides information on the average t_3/t_r for several temperatures.

Table 3. Ratio of time to tertiary to time to rupture for 304H stainless steel at several temperatures

Temperature (°C)	No. of data	Avg Ratio	Standard Deviation
538	25	0.794	0.192
593	58	0.713	0.174
649&650	50	0.510	0.161
700&704	29	0.445	0.186
760	8	0.550	0.074
816	9	0.591	0.117
871	15	0.407	0.107

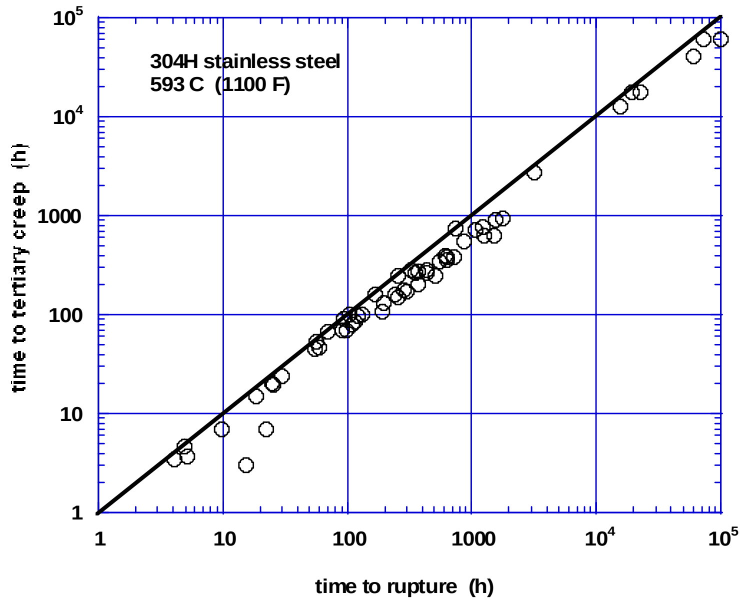

Figure 6. Time to tertiary creep versus time to rupture for 304H stainless steel at 593°C (1100°F)

The parametric analysis of the tertiary creep data was similar to that applied to the rupture data, except the no censoring was used. The average Lot Constant for the Larson- Miller parameter was a bit higher than the value found for the rupture data (18.07113 versus 17.1398) and the standard error of estimate (SEE) was about the same (0.50 versus 0.53). However, the fit of the polynomial stress function, f(S), to the Larson-Miller parameter left something to be desired. Figure 7 shows the stress versus LMP correlation. At low stresses the curve that represents f(S) seemed to fall below the data. A refit of the Larson-Miller data to second, third, and fourth order polynomial did not produce significant improvements. A linear stress function f(S) did capture the low-stress trend, as shown in Figure 8, but in view of the meager data at stress below 20 MPa (2.9 ksi), the f(S) indicated in Figure 7 was retained as a conservative estimate of the time to tertiary creep.

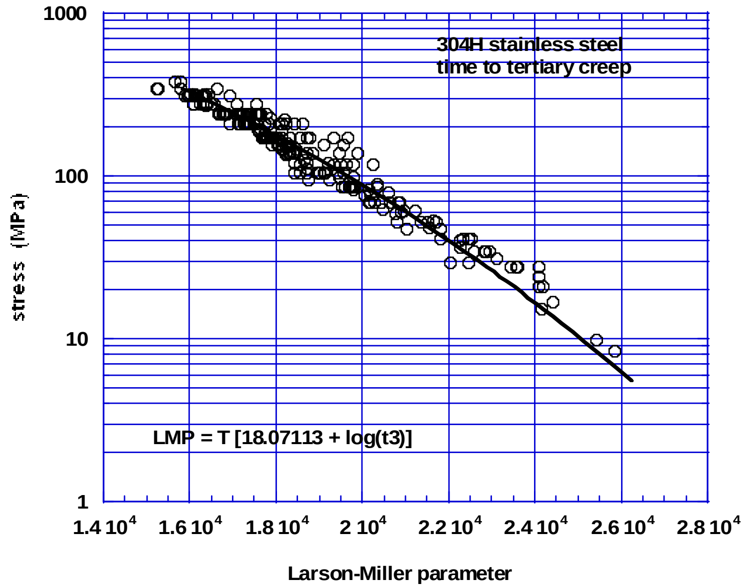

Figure 7. Stress versus the Larson-Miller parameter for the time to tertiary creep, t_3, of 304H stainless steel

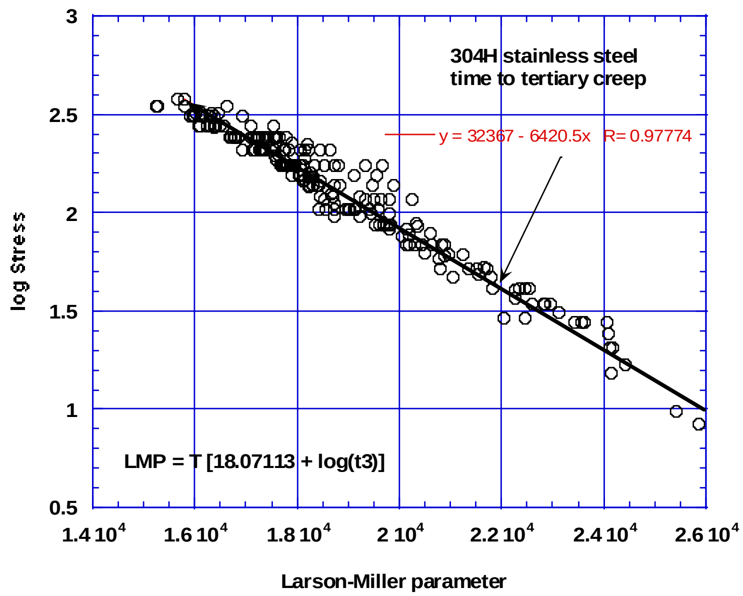

Figure 8. Fit of linear f(S) model to log stress versus the Larson-Miller parameter for the time to tertiary creep, t_3, of 304H stainless steel

The minutes of Code committees on CC 1331-9, CC N-47, and BPV III-NH revealed that S_t and the time-dependent values for S_{mt} were controlled by 80% of the minimum stress to produce tertiary creep for most times at 788°C (1450°F) and 816°C (1500°F). In Figure 9, the S_t values are compared to the estimates from the correlations shown in Figures 7 and 8. Values based on the 3rd order polynomial (Figure 7) fell below the S_t curves for longer times and higher temperatures while the values based on the 1st order polynomial (Figure 8) were above or equivalent to the BPV III-NH values.

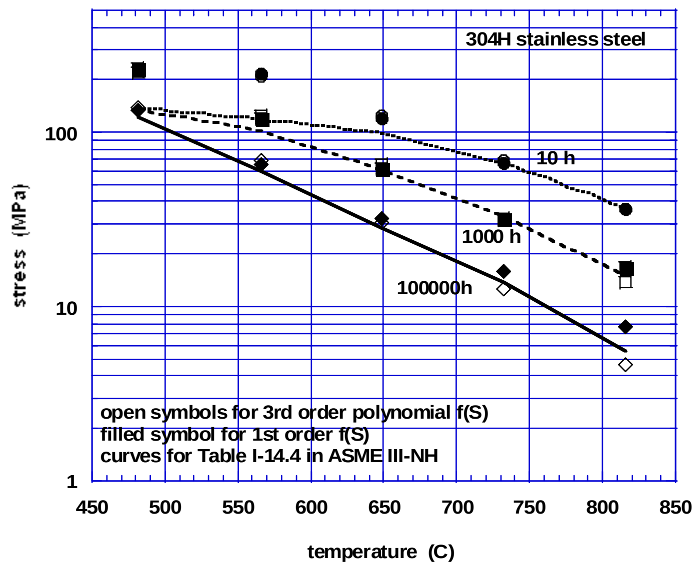

Figure 9. Comparison of the S_t values from BPV III-NH Table I-14.4 for 304H with estimations based on 80% of the minimum stress for tertiary creep

<u>Average time to 1% strain for 304H stainless steel.</u>

The third criterion for setting time-dependent allowable stresses was based on 100% of the average stress to produce 1% strain (elastic, plastic, primary creep and secondary creep) in the specified time. The minutes of the Code committee meetings indicated that the minimum rather than the average stress for 1% strain was considered at one time or another, but eventually the average stress was selected to be consistent with the use of the average stresses for the isochronous stress versus strain curves provided in Appendix T of BPV III-NH. The isochronous curves and the creep law that was used to calculate the time-dependent component of the isochronous curves were based on formulations by Blackburn in 1972 [6]. Considerably more creep data have become available since then, and several alternate creep laws have been developed. However, it was beyond the scope of this assessment to develop a replacement creep law. Rather, the assessment was limited to a demonstration that the time to 1% strain did not control the S_t and S_{mt} values in the time-dependent range. To this end, the original and newer data were reviewed. It was found that much of the creep data produced on 304 stainless steel involved materials that were in the "full-annealed" or laboratory-annealed condition. Often, the materials exhibited room temperature yield strengths that were near or below the minimum specified yield strength for 304H stainless steel, namely 205 MPa (30 ksi). At creep testing temperatures, the yield strength was often in the range of 60 to 80 MPa (9 to 12 ksi). The creep strength of such steels was high relative to the yield strength so most testing at lower temperatures began with fairly large plastic loading strains. These strains often exceeded 1%. Tests starting below the yield strength usually accumulated very long times (100,000 h) without reaching 1%. The isochronous curves, however, were constructed from a creep law that only considered the time-dependent deformation. Elastic and plastic components were added to the strains calculated from the creep law but these time-independent components were based on what was considered to be a material of average strength with a yield strength in the range of 100 to 140 MPa (15 to 20 ksi) in the creep temperature range. A second complicating factor was a product form effect. The tubing heats often exhibited small primary creep strains while some of the plate products exhibited large primary creep strains. These differences were not noticed in the early work on the creep laws which produced the "double exponential" primary creep formulation of Blackburn [6]. The result was an increase in the spread of the variation in the time to 1% creep for a specific temperature and time. Overall, however, it was concluded the stress corresponding to the time to 1% strain should not govern the time-dependent stress allowables in BPV III-NH Tables I-14.3 and I-14.4. A comparison of the stresses derived from the isochronous curves with the S_t values for three times and several temperatures is shown in Figure 10. A wide margin in stresses is apparent. A few data interpolated for isothermal stress versus time curves for 1% strain are included in Figure 10. These indicate the experimental data will scatter about the values from the isochronous curves by approximately ±20%.

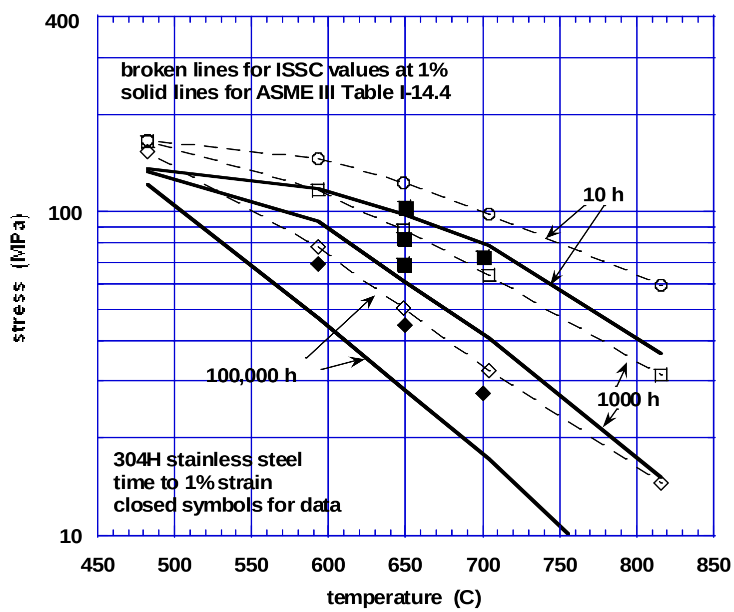

Figure 10. Comparison of the stress for 1% strain from the isochronous stress versus strain curves with the stresses from BPV III-NH Table I-14.4 for 304H stainless steel

Assessment of the database for 304H stainless steel:

Overall, the 304H stainless steel database is judged to be adequate to meet the needs for setting the allowable stress intensity values for BPV III-NH for temperatures to at least 649°C (1200°F). Additional test data covering very long times, especially above 649°C (1200°F) would help to eliminate some concerns regarding the extrapolation of data trends to times beyond 100,000 h. However, it seems unlikely that 304H stainless steel would be chosen for very long time service in nuclear components at such high temperatures. Nonetheless, there are some issues that could be addressed using the existing database:

> Although not covered in any detail in this assessment, there remains a need to re-assemble the creep curves and re-assess the creep laws. Such a study, with the additional data that has accumulated in the last thirty years, would improve the understanding of primary creep and tertiary creep. The information would be helpful in the development of continuum damage mechanics (CDM) models and creep-crack-growth models.

> There is a need for a detailed review of the work that has been undertaken by the National Institute of Materials Science (NIMS) in Japan to explain the lot-to-lot variability of the creep and rupture behavior [7]. To some extent this variability has been attributed to the effects of "unspecified elements" in the composition of the steels. The goal of the review would be to produce a restricted chemistry version of 304H stainless steel for the construction of critical nuclear components.

> There is a need to re-visit the methods and procedures of data analysis. Here, an assessment of procedures used in Europe, Japan, and elsewhere [8-12] should be reviewed with respect to the special requirements and criteria for setting stress allowables in BPV III-NH.

EVALUATION OF THE 316H STAINLESS STEEL DATABASE

The database for 316/316H stainless steel consisted of more than 1900 lines covering temperatures from 427 to 1093°C (800 to 2000°F) and times to 224,000 hours. As with the 304H stainless steel database, not all lines for 316H stainless steel included rupture points and relatively few lines provided the time to tertiary creep and the time to 1% creep strain. Most of the data for long times came from the collection at NIMS.

Expected minimum stress-to-rupture for 316H stainless steel:

In contrast to the previous evaluation of 304/304H stainless steel, only two sets of rupture data were analyzed. One set contained all data with times of one hour and more and the second set was based on censoring the rupture data less than 100 h. The average Lot Constant for the Larson-Miller parameter decreased from 16.4023 to 15.6111 for the second set. The fit to the LMP for the two sets was about the same, and a plot of the stress versus the parameter for the first set is shown in Figure 11. The large ganglion of data around the LMP value of 18,000 reflects a region around 649°C (1200°F) where the precipitation of fine carbides enhances the strength for a period of time. One could break the master curve plotted through the data into two straight lies with a break around the LMP value of 18,000. However, the master curve was considered to be a reasonable representation of the trend for stresses to as low as 20 MPa (2.9 ksi). The distribution of the residuals for the polynomial fit is shown in Figure 12 and was similar for both the full data fit and the 100-h censored data fit.

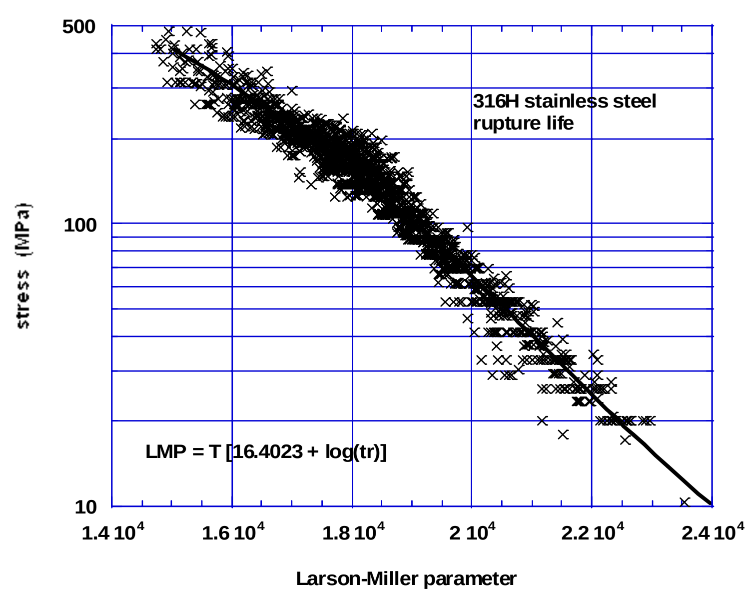

Figure 11. Stress versus the Larson-Miller parameter for rupture of 316H stainless steel

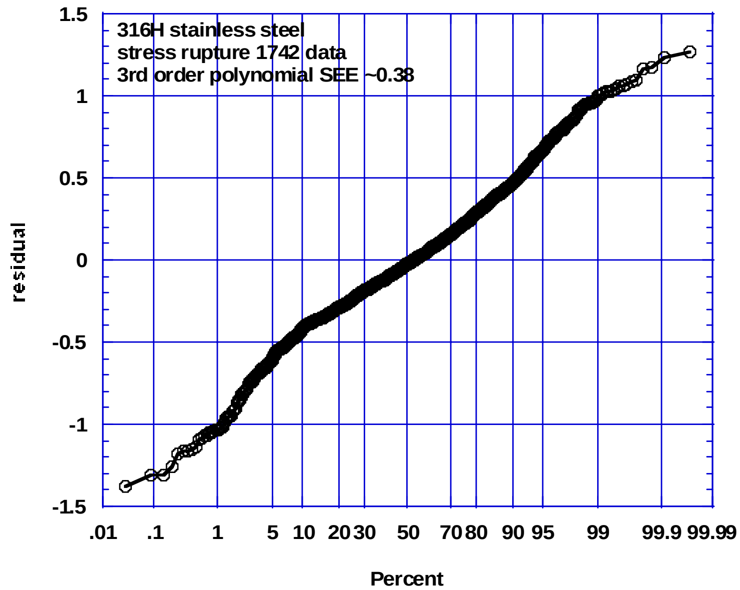

Figure 12. Distribution of residuals from the fit of the Larson-Miller parameter to rupture life data for 316H stainless steel

Figure 13 shows a histogram of the Lot Constants in which the data sources are identified, and Table 3 summarizes the information. Here, it may be seen that the largest number of lots was collected from U.S. and European sources. The standard deviation for the lots of data sources was the smallest for the Japanese lots.

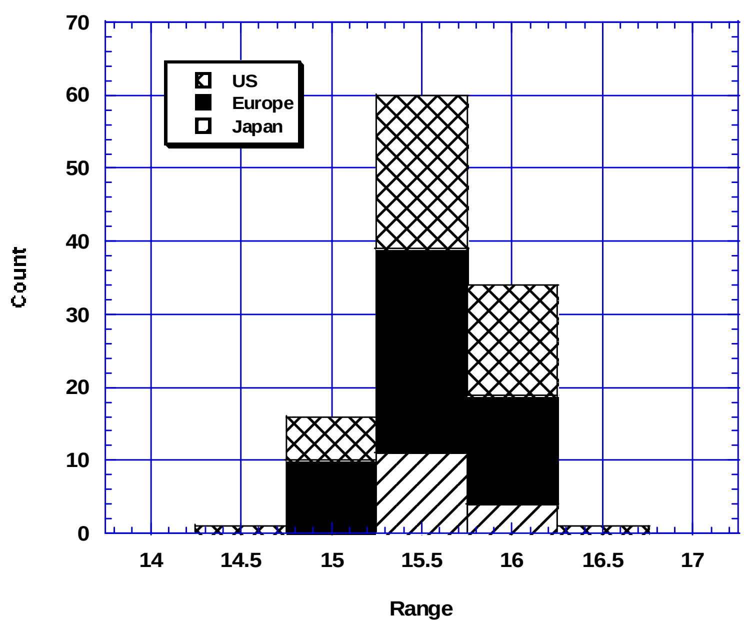

Figure 13. Distribution of the lot constants for the rupture life of 316H stainless steel according to the source of the rupture data

Table 4. Summary of the Larson-Miller Lot Constants for the rupture life of 316H stainless steel in terms of the data sources

Source or Product	No. of Lots	Avg of Lot Constants	Standard Deviation
U. S.	44	15.62	0.36
Japan	15	15.67	0.11
Europe	53	15.50	0.33

Figure 14 compares the minimum stress-to rupture, S_r, as a function of temperature for BPV III-NH Table I-14.6 with the values calculated from the Larson-Miller Parameter for the full and 100-h censored databases. For most temperatures, the newly estimated values were above the S_r values at short times (10 h). Above 700°C (1292°F) and intermediate times (1000 h), the newly estimated values fell below the S_r values at temperature about 650°C (1202°F). At long times, the differences were small and not sufficient to justify changes to the BPV III-NH values.

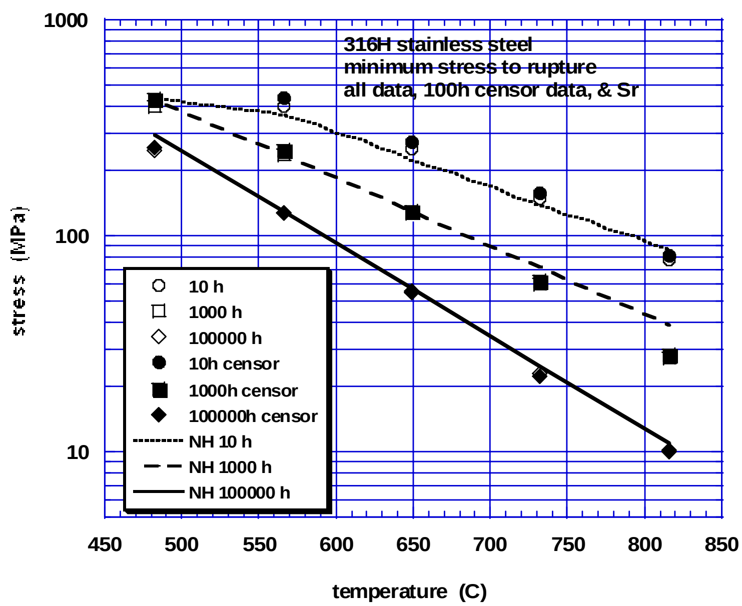

Figure 14. Comparison of BPV III-NH minimum stress-to-rupture values with the values estimated from the analysis of the expanded database for 316H stainless steel

Minimum time to tertiary creep for 316H stainless steel:

For 316H stainless steel, data for only 19 lots (305 values) were found for tertiary data. As for the case of 304H stainless steel, the meager data base made it difficult to identify a statistically defined minimum time to tertiary creep for a broad range of temperatures and times. Historically, two approaches were considered: 1) develop a correlation between the time to tertiary creep and the rupture life with the assumption that the scatter and lot-to-lot variation would be similar; and 2) proceed with a time-temperature parametric model similar to the Larson-Miller parameter for rupture. The correlation between t_3 and t_r was used by Booker [13] on a much smaller database but, as for the case of 304H stainless steel, the temperature and stress dependency of the ratio t_3/t_r introduced complications which made the direct parametric approach more suitable. A plot of the t_3 against t_r is shown in Figure 15. It may be seen that the trend of the data is away from the linear (constant ratio line) with increasing time. The width of the data scatter is significant, as well.

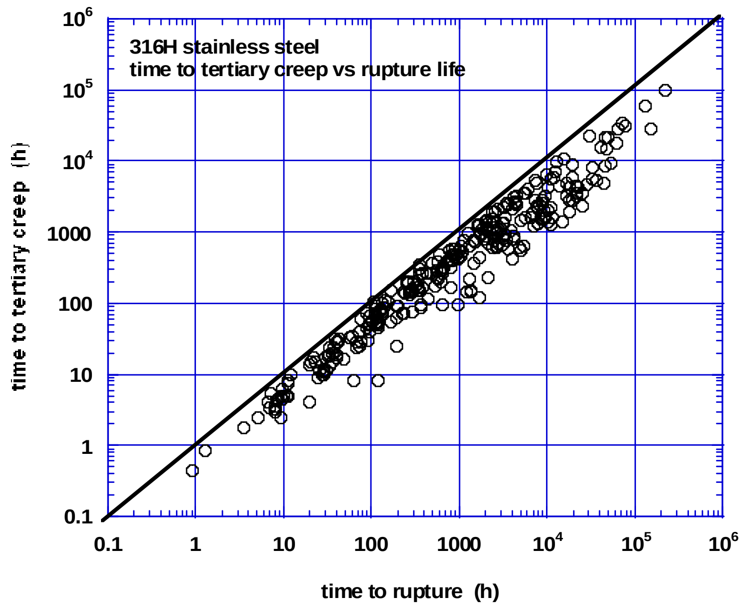

Figure 15. Time to tertiary creep versus time to rupture for 316H stainless steel

The parametric analysis of the tertiary creep data was similar to that applied to the rupture data. The average Lot Constant for the Larson-Miller parameter was similar to the value found for the rupture data (15.471 versus 16.402 and 15.511 for the full and censored rupture data sets, respectively) and the standard error of estimate (SEE) was similar, 0.39 in log time versus 0.39 and 0.35 for the rupture data sets. The fit of the polynomial stress function, f(S), to the Larson-Miller parameter curved downward, but the polynomial tended to show a bit more downward curvature than the data, as indicated in Figure 16. The database ended abruptly at 20 MPa (2.9 ksi), and this stress was judged to be the lower limit for the analysis and the estimation of the stress corresponding to the tertiary creep criterion. The distribution of the data, mostly produced by NIMS, appeared to be normal. No evaluation of the parametric lot constants on the basis of the data sources or product forms was undertaken.

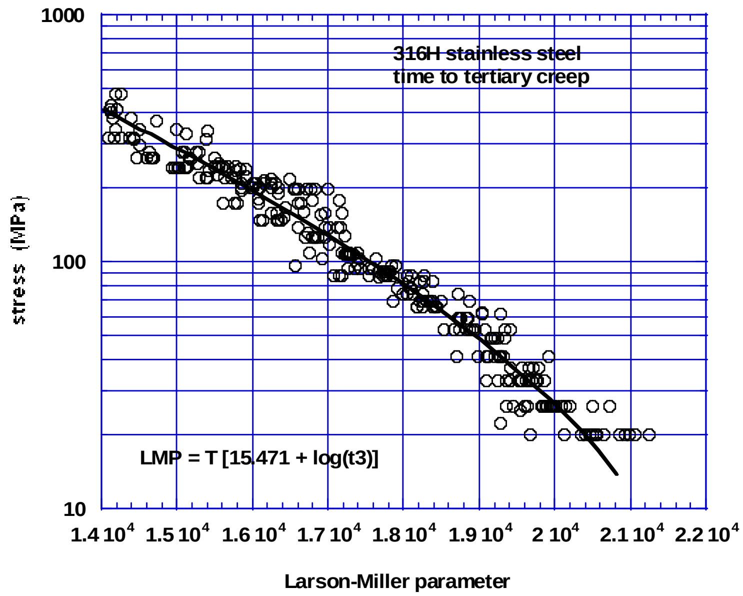

Figure 16. Stress versus the Larson-Miller parameter for the time to tertiary creep, t_3, of 316H stainless steel

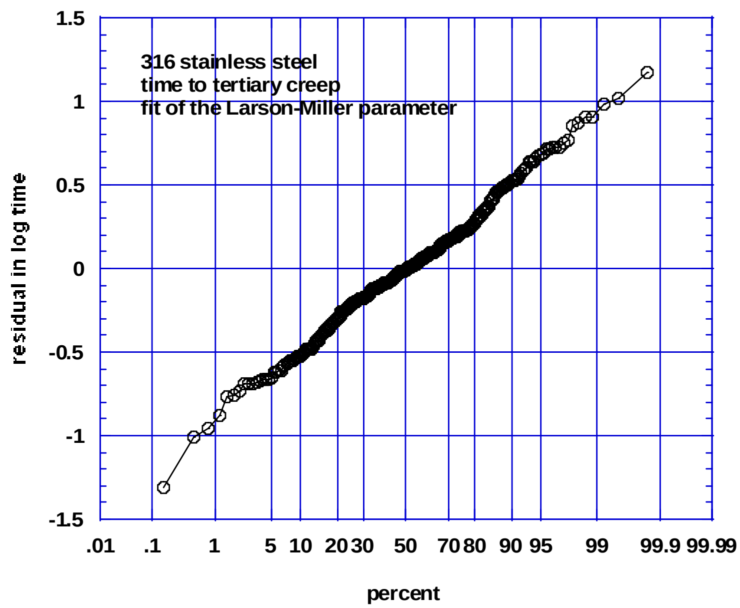

Figure 17. Distribution of residuals from the fit of the Larson-Miller parameter to the time to tertiary creep data for 316H stainless steel

The minutes of Code committees on CC 1331-9, CC N-47, and BPV III-NH revealed that, depending on the temperature and time, the S_t and the time-dependent values for S_{mt} for 316H stainless steel were controlled by 80% of the average stress to produce 1% strain or 67% of the minimum stress to produce rupture in a specific time. The criterion based on 80% of the stress to produce tertiary creep was examined but was never found to be the controlling criterion. In Figure 18, these S_t values are compared to the estimates based on 80% of the minimum stress for t_3 calculated from the correlation shown in Figure 16. Stress values calculated for below 20 MPa (2.9 ksi) were judged to be invalid and have not been plotted. There are two reasons for being invalid- the lack of tertiary creep data and the "severe" downward turn of the polynomial f(S) in the stress region where extrapolation would be required. It is clear that the values for tertiary creep criterion based on the expanded database could control S_t at long times and a closer look at the application of this criterion to 316H stainless steel will be needed.

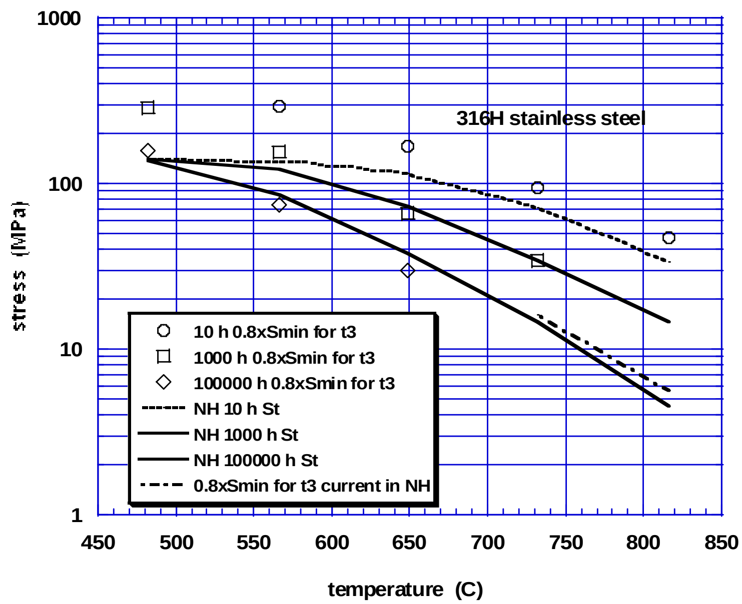

Figure 18. Comparison of BPV III-NH S_t values from Table I-14.4 (based on the lower of 67% of the minimum stress to rupture or 80% of the average stress to produce 1% strain) with the values estimated from the analysis of the tertiary creep criterion and the expanded tertiary creep database for 316H stainless steel

<u>Average time to 1% strain for 316H stainless steel.</u>

The minutes of the Code committee meetings indicated that 80% of stress to produce 1% strain in a specified time was invoked as the third criterion for setting S_t and the time dependent values for S_{mt}, and that the stress values so determined controlled the allowable time-dependent allowable stress intensities for most of the temperature and time range covered in Table I-14.4 for 316H stainless steel. The current rules stipulate 100% of the average stress for 1% strain in a specific time. An inspection of the isochronous stress versus strain curves provided in Appendix T of BPV III-NH revealed that the time-dependent values in the isochronous curves at 1% strain were identical to the average values which were used for satisfying the 1% strain criterion for S_t. It appeared as if the 80% factor was incorporated as a method to estimate the minimum stress for 1% creep. Similar to the case for 304H stainless steel, the isochronous curves and the creep law that were used to calculate the time-dependent component of the isochronous curves were based on formulations by Blackburn in 1972 [6]. Again, as with 304H stainless steel, considerably more creep data became available in the last 35 years, and several alternative creep laws were developed. However, it was beyond the scope of this assessment to introduce a replacement creep law. Rather, the assessment was limited to a demonstration that the time to 1% strain did not control the S_t and S_{mt} values in the time-dependent range. To this end, the original and newer data were reviewed. Considerations regarding the development of the 1% strain criterion for 316H stainless steel were much the same as those identified in the section on 304H stainless steel discussed above and will not be repeated here.

The database used for the assessment consisted of 14 lots and 159 points. The initial approach was to analyze the data on the basis of the Larson-Miller parameter using the lot-centered method and the 3rd order polynomial in log stress for f(S). The results of the regression analysis are shown in Figure 19. The average Lot Constant was found to be near 20.795 and the SEE was near 0.49 in log hours. The distribution of the residuals in log time is shown in Figure 20. A simple 1st order polynomial was also examined but offered no significant improvement.

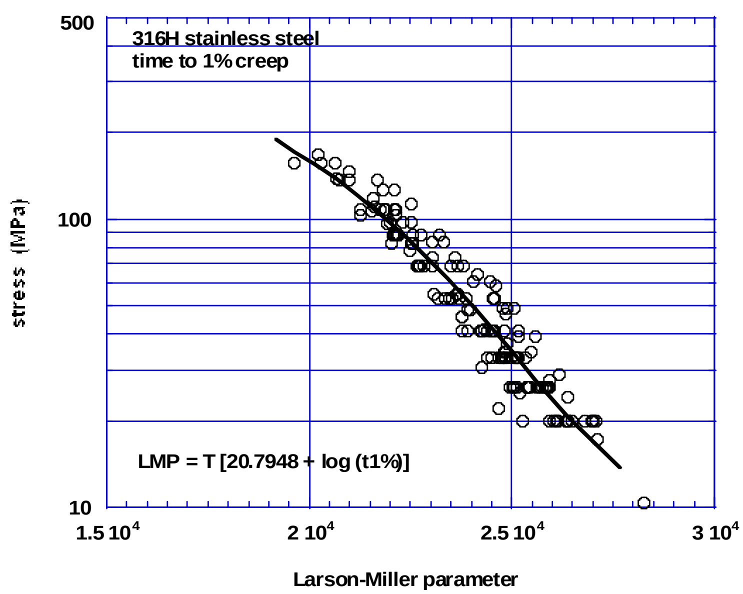

Figure 19. Stress versus the Larson-Miller parameter for the time to 1% creep for 316H stainless steel

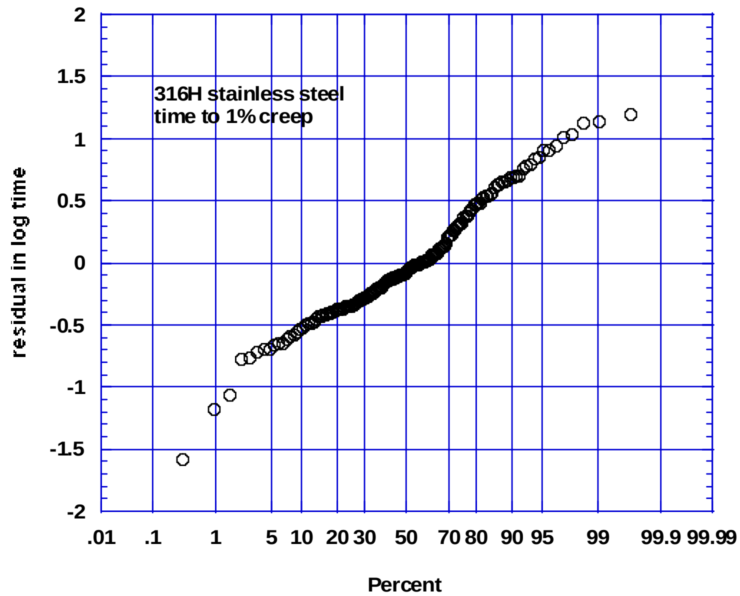

Figure 20. Distribution of residuals from the fit of the Larson-Miller parameter to the time to 1% strain for 316H stainless steel

A comparison of newly calculated strength values based on 1% strain with the average strength values for 1% creep, obtained from the isochronous stress-strain curves for three times and several temperatures, and the S_t values from BPV III-NH Table I-14.4 is shown in Figure 21. As mentioned above, the S_t values were based on 80% of the average creep strength values over much of the range of temperature and time. The newly estimated values tended to be greater than the values from the isochronous curves, but the database only extended to 20 MPa (2.9 ksi) and time-wise extrapolations of more than an order of magnitude were required to estimate strength values for 100,000 h at temperatures above 700°C (1292°F). In Figure 21, a new value for 732°C (1350°F) is shown which is at the lower limit of the data range [20 MPa (2.9)].

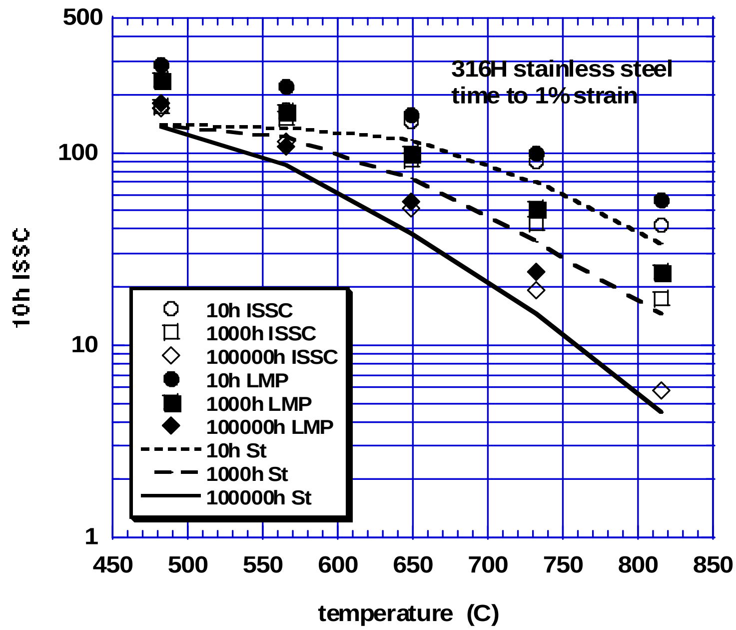

Figure 21. Comparison of BPV III-NH S_t values for 316H stainless steel from Table I-14.4 with the values from the isochronous stress-strain curves at 1% strain and new values estimated from the LMP analysis of the expanded 1% strain database

Assessment of the database for 316H stainless steel:

Overall, the 316H stainless steel database is judged to be adequate for setting the allowable stress intensity values for BPV III-NH for temperatures to at least 649°C (1200°F). Of course, additional test data covering very long times, especially above 649°C (1200°F) would help to eliminate some concerns regarding the extrapolation of data trends to times beyond 100,000 h. This is especially true for the estimation of values based on 1% strain and tertiary creep. The issues that could be addressed using the existing database are similar to those proposed for 304H stainless steel:

> The creep curves produced for 316H stainless steel should be re-assembled and used to re-assess the creep laws. Many such curves were produced since the original collection that was used to produce the isochronous stress-strain curves in BPV III-NH. Several new models for creep have been advanced in connection with the Nuclear Systems Materials Handbook (NSMH), for example, and further study would improve the understanding of primary creep and tertiary creep. The information would be helpful in the development of continuum damage mechanics (CDM) models and creep-crack-growth models.
>
> There is a need for a detailed review of the work that has been undertaken by NIMS to explain the lot-to-lot variability of the creep and rupture behavior. To some extent this variability has been attributed to the effects of "unspecified elements" in the composition of the steels. The goal of the review would be to

produce a restricted chemistry version of 304H stainless steel for the construction of critical nuclear components. The validity of the extrapolation of data to estimate the 500,000-h stress allowables needed for the Generation IV reactors and the explanations offered for the fall-off in strength of the steels must be carefully considered.

The methods and procedures of data analysis for setting the allowables for BPV III-NH must be revisited and well-documented. Also, an assessment of procedures used in Europe, Japan, and elsewhere should be reviewed with respect to the special requirements and criteria for setting stress allowables in ASME III-NH.

EVALUATION OF THE 2 ¼ Cr-1Mo STEEL DATABASE

The database for 2 ¼ Cr-1Mo steel consisting of more than 1460 lines extracted from U.S, European, and Japanese sources was examined and checked for conformance with the requirements for the Gr 22 Class 1 material. Products were identified as annealed, furnace cooled, or isothermally annealed. The yield/tensile values, when provided, met or exceeded 205/415 MPa (30/60 ksi) but were below the values specified for the Class 2 material [310/515 MPa (45/75 ksi)]. Rupture data lasting less than 100 hours were censored and many tests performed in helium were not included in the analysis (but retained in the database). Data from tests in excess of 415 MPa (60 ksi) were deleted. Temperatures ranged from 400 to 700°C (750 to 1290°F) and times from 100 to 213,000 hours. The final database included about 1180 lines. Most of the data for long times came from the collection at NIMS.

Expected minimum stress-to-rupture for 2 ¼ Cr-1Mo steel:

To assess the adequacy of the database, the rupture data were evaluated on the basis of the Larson-Miller parameter using the 3rd order polynomial described by eq. (1). The optimized value of the average Lot Constant was found to be 15.948153, with a standard error of estimate (SEE) near 0.465 in log hours. The stress versus the Larson-Miller parameter is shown in Figure 22. The 3rd order polynomial stress function, f(S), was not included in the figure because it found that a 2nd order provided a fit that was equally "good." A plot of the distribution of the residuals for the 2nd order polynomial fit is shown in Figure 23.

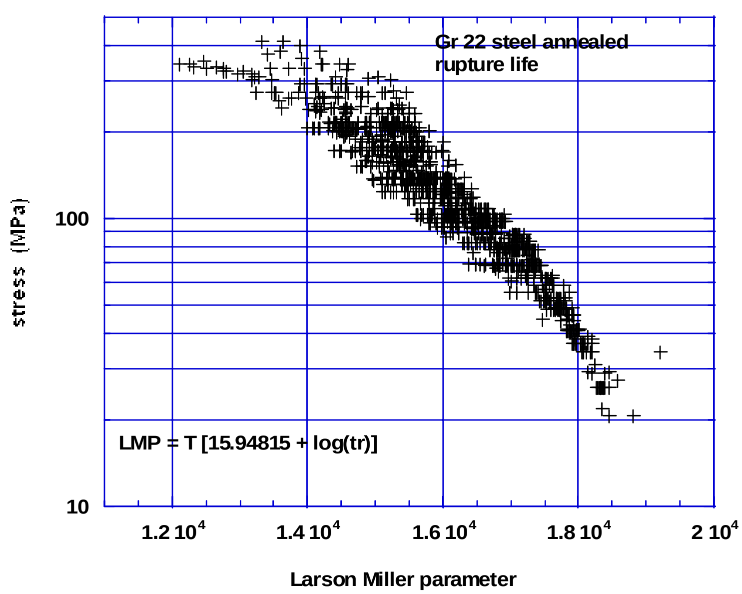

Figure 22. Stress versus the Larson-Miller parameter for rupture of 2 ¼ Cr-1Mo steel

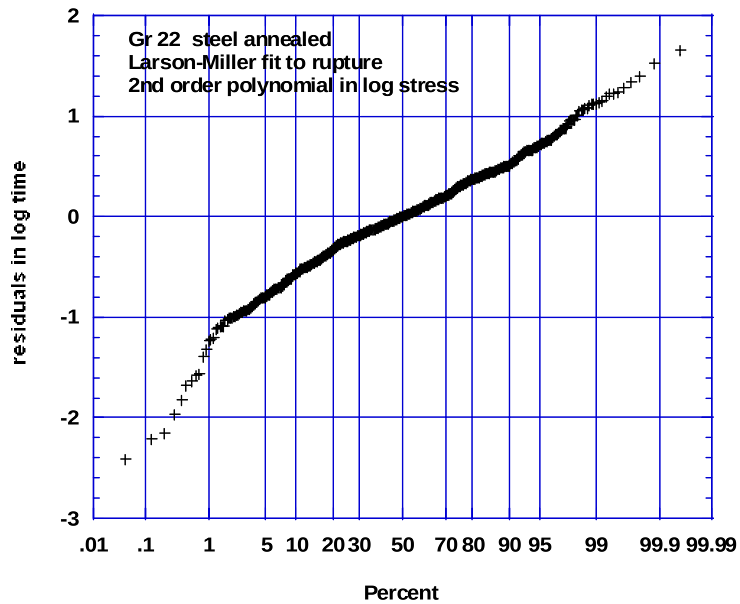

Figure 23. Distribution of residuals from the fit of the Larson-Miller parameter to the time to rupture data for 2 ¼ Cr- 1Mo steel annealed

Inspection of the data trend in Figure 22 revealed two features not seen in the austenitic steels. Firstly, data scattered widely at high stresses and narrowly at low stresses. Secondly, there was a rapid turndown in the data at low stresses. The turndown in data at low stresses could be attributed to oxidation effects at long times and low stresses. Also, fewer lots were tested to long times and low stresses. The wide scatter at high stresses could be attributed to a wide variation in strength associated with the various melting practices and heat treatments that were used to produce the materials. For ferritic steels, such effects tend to be mitigated with increasing temperature.

With respect to the establishment of a minimum stress to rupture, as required for BPV III-NH Table I-14.6, the required range of temperatures is from 375° to 650°C (700 to 1200°F) with times as short as 1 hour. This requirement resulted in values listed in the table that were far above the yield strength and close to the room temperature ultimate strength. Hence, consideration of the wide scatter at high stresses cannot be avoided by any convenient censoring method to eliminate scatter at high stresses. Also, it is clear that a single value for the SEE produced by the regression analysis was not realistic for this material, and basing the minimum stress-to-rupture on the stress corresponding to 1.65 SEE short of the average trend in time would grossly overestimate stresses at short times and high stresses and grossly underestimate stresses at long times and low stresses. Recognizing these limitations, the variation in the Lot Constants was examined for product forms and heat treatments. Figure 24 shows the histogram for the variation of Lot Constants with product form. Figure 25 shows the histogram for the variation of Lot

Constants with heat treatment. Table 5 provides some quantitative information. Based on the average of the Lot Constants for the products, the bars were slightly stronger than others, while the annealed condition was the strongest of the heat treatments.

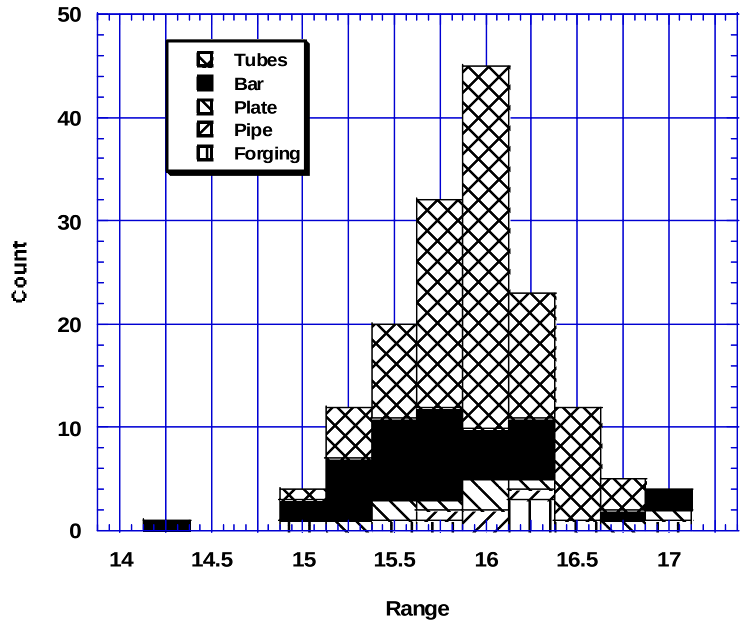

Figure 24. Histogram showing the distribution of Lot Constant with the product form for the Larson Miller analysis of the rupture life of 2 ¼ Cr- 1 Mo steel

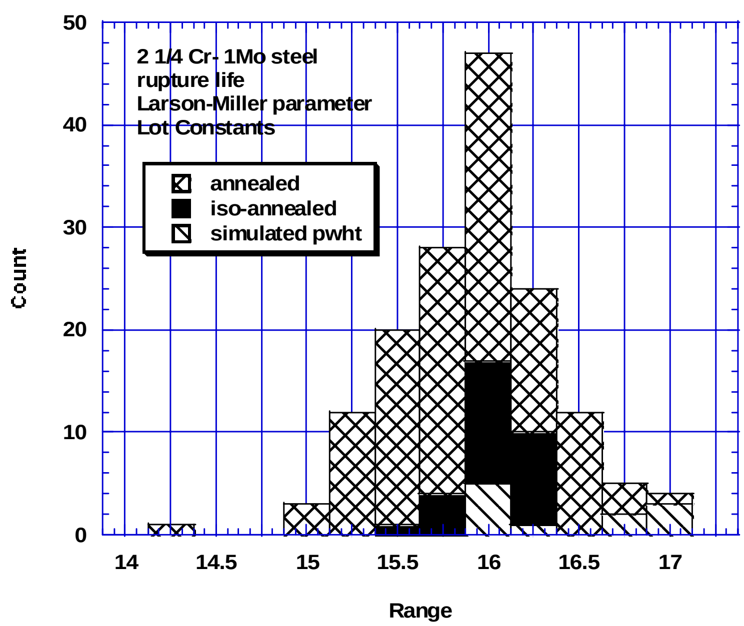

Figure 25. Histogram showing the distribution of Lot Constant with the heat treatment for the Larson Miller analysis of the rupture life of 2 ¼ Cr- 1 Mo steel

Table 5. Summary of the Larson-Miller Lot Constants for the rupture life of 2 ¼ Cr- 1Mo steel in terms of the products and heat treatments.

Source or Product	No. of Lots	Avg of Lot Constants	Standard Deviation
Tubes	96	16.00	0.36
Bar	40	15.74	0.53
Plate	10	16.05	0.55
Pipe	4	16.07	0.18
Forge	8	16.04	0.57
Annealed	119	15.86	0.44
Isothermal annealed	26	16.04	0.18
Simulated pwht	11	16.44	0.46

Figure 26 compares the minimum stress-to-rupture values, estimated from a 2nd order polynomial fit through the data shown in Figure 22, with the S_t values in BPV III-NH Table I-14.3. Data show the expected trend wherein the short-time low temperature estimates are above the S_t values and the long-time high-temperature estimates fall below the S_t values.

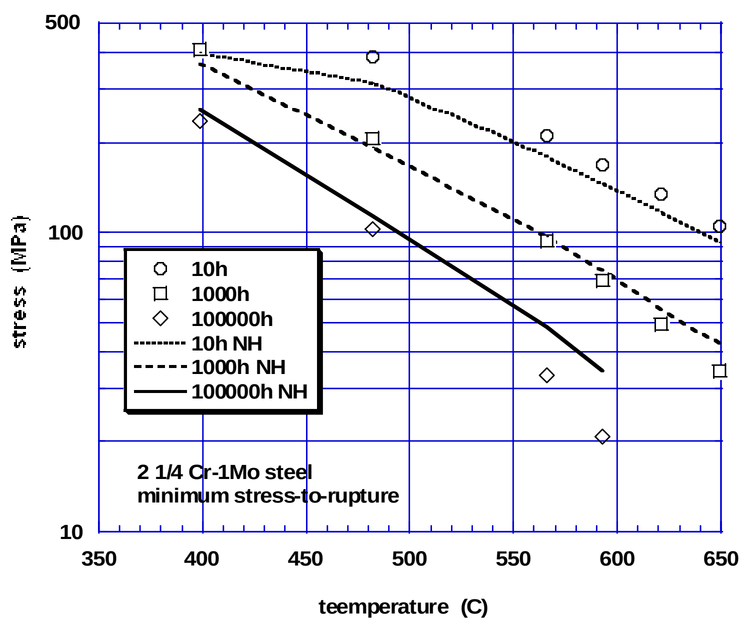

Figure 26. Comparison of BPV III-NH minimum stress-to-rupture values with the values estimated from the analysis of the expanded database for 2 ¼ Cr- 1Mo steel

Minimum time to tertiary creep for 2 ¼ Cr-1 Mo steel:

The time to tertiary creep for the Gr 22 Class 1 material presented problems to the experimentalist and to the compilation of data bearing on the criterion. These problems were discussed in some detail by Klueh and had to do with the "non-classical" behavior of the creep curves for some of the heat treated conditions [14]. Undulations in some creep curves made it difficult to define the "minimum" or "steady state" creep stage. In these instances two minimum creep rates were often reported, one at a low fraction of the rupture life and one at a higher fraction of the rupture life. Tertiary creep, defined as the departure from steady state creep in the Leyda-Rowe correlation, could have either of two values. For 2 ¼ Cr steel, 277 data for only 37 lots were found. As for the case of 304H stainless steel, two approaches were considered: 1) develop a correlation between the time to tertiary creep and the rupture life with the assumption that the scatter and lot-to-lot variation would be similar; and 2) proceed with a time-temperature parametric model similar to the Larson-Miller parameter for rupture. The correlation between t_3 and t_r was used by Booker [15] on a much smaller database but, as for the case of 304H stainless steel, the temperature and stress dependency of the ratio t_3/t_r introduced complications that made the direct parametric approach more suitable. A plot of the t_3 against t_r is shown in Figure 27. It may be seen that the trend of the data suggested a linear (constant ratio line) between t_3 and t_r with a ratio near 0.4. The width of the data scatter is significant, however, and data for long time indicated ratios approaching 0.9. Points to the "far right" of the line were generally for a few lots of a single vacuum-arc-remelt/electroslag remelt (VAR/ESR) heat.

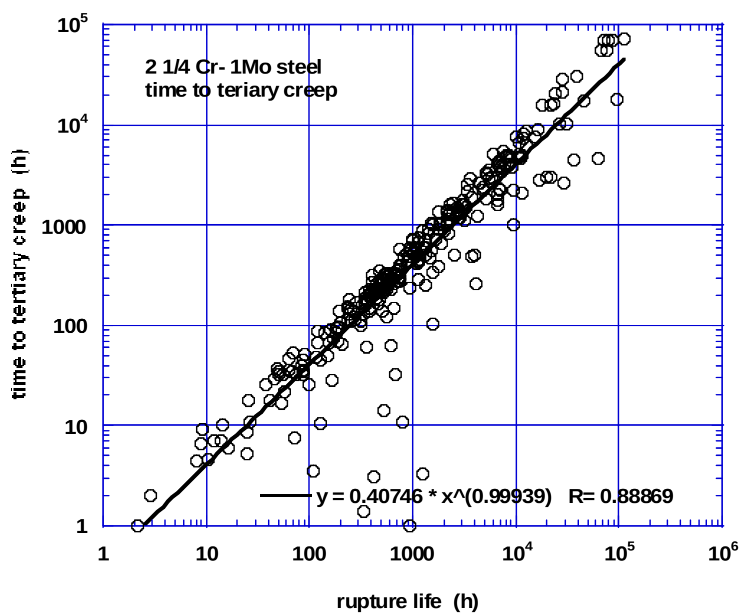

Figure 27. Time to tertiary creep versus time to rupture for 2 ¼ Cr- 1Mo steel

Data that departed significantly (a factor of 20) from the overall trend in Figure 27 were deleted and the remaining points were used to calculate the Larson-Miller parameter conforming to eq. (1). The results are plotted in Figure 28. The trend was similar to the rupture data in Figure 22, with a wide scatterband at high stresses and a narrowing band at lower stresses. The average Lot Constant was found to be near17.15057 with a standard error of estimate near 0.71 in log time. An evaluation of the BPV III-NH tertiary creep criterion for S_t indicated that the criterion would control, if based on the correlation shown in Figure 28. However, estimates as to what these values should be are not provided at this time because of the uncertainty in the meaning of the values reported for the time to tertiary creep. Further, as for the case of rupture, if one allowed the SEE to decrease with decreasing stress, the minimum stress for the time to tertiary creep would increase relative to estimates based on a constant SEE value for all stresses and temperatures.

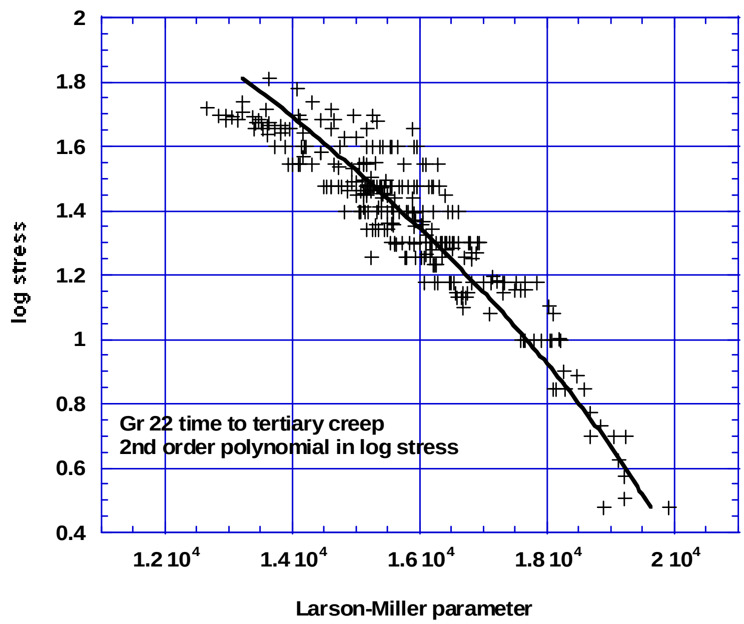

Figure 28. Larson-Miller correlation for tertiary creep of 2 ¼ Cr- 1Mo steel.

<u>Average time to 1% strain for 2 ¼ Cr- 1Mo steel.</u>

The average times to 1% strain for 2 ¼ Cr- 1Mo steel, provided in the isochronous curves of BPV III-NH Appendix T, were based on a creep model developed by Sterling in 1974 [16]. An alternate model was proposed by Booker in 1977 [15]. In both cases, the databases were somewhat limited. The expanded database assembled here consisted of 277 data for 37 lots of material. Similar to the tertiary creep issue, a plot of time to 1% against the rupture life was used to assess the consistency of the data and such a plot is shown in Figure 29. The features of the database were these: a wide variation in the time to 1% strain for the same rupture life; a tendency for the time to 1% strain to approach the time to rupture as testing times increased; and about the same variation for all times.

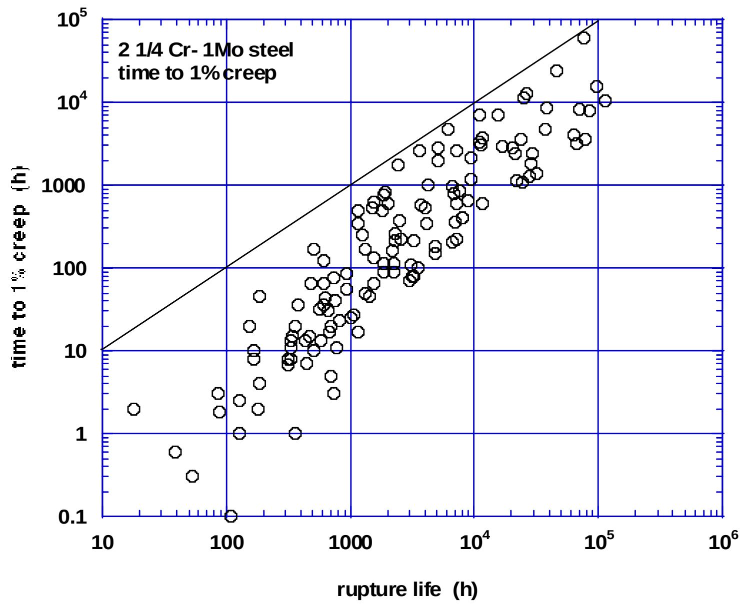

Figure 29. Time to 1% strain versus time to rupture for 2 ¼ Cr- 1Mo steel

As stated above, there was no compelling reason to expect that the time to 1% strain should conform to a simple temperature-stress-time parametric model, because the components of the strain that we called "1% strain" (labeled as creep in Figure 29) included elastic strain (linear with stress and time-independent), plastic strain for some loading conditions (nonlinear with stress and time-independent), and various fractions of time-dependent deformation (primary, secondary, and tertiary creep). Nevertheless, a parametric fit was undertaken to capture the general characteristics of the database and the results are provided in Figure 30. The characteristics of the stress versus Larson-Miller parameter were similar to the characteristics of the parametric fits for rupture life and time-to-tertiary creep; large scatter at high stresses, narrow scatter but fewer data at lower stresses, and a sharper decrease in stress as the parameter value increased. For a parametric value corresponding to 100,000 h at 593°C (1100°F) the data plotted in Figure 30 indicated a stress for 1% strain in the range 20 to 30 MPa (2.9 to 4.3 ksi). The value for S_t in BPV III-NH Table I-14.4 listed 22.8 MPa (3.3 ksi).

Assessment of the database for 2 ¼ Cr- 1Mo steel:

The database for 2 ¼ Cr- 1Mo steel is judged to be adequate to meet the needs for setting the allowable stress intensity values for BPV III-NH for temperatures to 649°C (1200°F). The actions that could be taken using the existing database are similar to those proposed for 304H and 316H stainless steels:

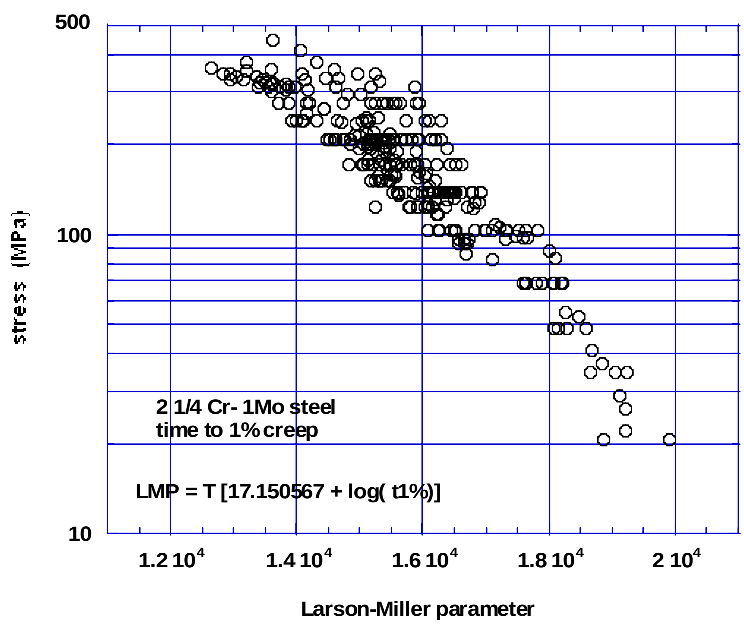

Figure 30. Stress versus the Larson-Miller parameter for 1% creep of 2 ¼ Cr- 1Mo steel.

The creep curves produced for 2 ¼ Cr-1Mo steel should be re-assembled and used to re-assess the creep laws. Many such curves were produced since the original collection that was used to produce the isochronous stress-strain curves in BPV III-NH. Such a study would improve the understanding of primary creep and tertiary creep. The information would be helpful in the development of continuum damage mechanics (CDM) models and creep-crack-growth models.

A detailed review could be undertaken of the research by NIMS aimed at an explanation of the lot-to-lot variability of the creep and rupture behavior in 2 ¼ Cr- 1Mo steel. In particular, the similarities and differences in the materials evaluated by NIMS and materials in the collection from U.S sources should be explored.

An effort should be made to examine the data that has been produced on the effect of chemistry, melting practice, and processing on the variability of the creep behavior. It is important to resolve the issue of how one factors tertiary creep into the criteria for setting time-dependent stresses.

The methods and procedures of data analysis should be re-visited. Here, an assessment of procedures used in Europe, Japan, and elsewhere should be reviewed with respect to the criteria for setting stress allowables in III-NH.

EVALUATION OF THE ALLOY 800H DATABASE

A database compiling the creep-rupture properties of alloy 800H and its variants was reviewed and referenced in the ASME Task 1, Part 1 report on *Verification of Allowable Stresses in ASME Section III Subsection NH for Alloy 800H* [17]. For the most part, the database was judged to be adequate to meet the needs for time-dependent properties in the extension of alloy 800H in BPV III-NH to 900°C (1650°F) and 500,000 h or perhaps 600,000 h. Procedures for analyzing creep and stress-rupture data for III-NH were reviewed and compared to the current procedure endorsed by the BPV II. The stress-rupture database for alloy 800H in the temperature range of 750 to 1000°C (1382 to 1832°F) was assembled and used to estimate the average and minimum strength for times to 600,000 hours at 900°C (1650°F).

An example of one of the correlations for alloy 800H is shown in Figure 31. Here, the log stress for rupture for alloy 800H data has been plotted against the Larson-Miller parameter for data covering temperatures from 750 to 1000°C (1382 to 982°F). Testing times extended to over 190,000 hours. A comparison of the stresses estimated from the rupture data with the BPV Section II-D Table 1B allowables is made in Figure 32. The comparison is judged to be good.

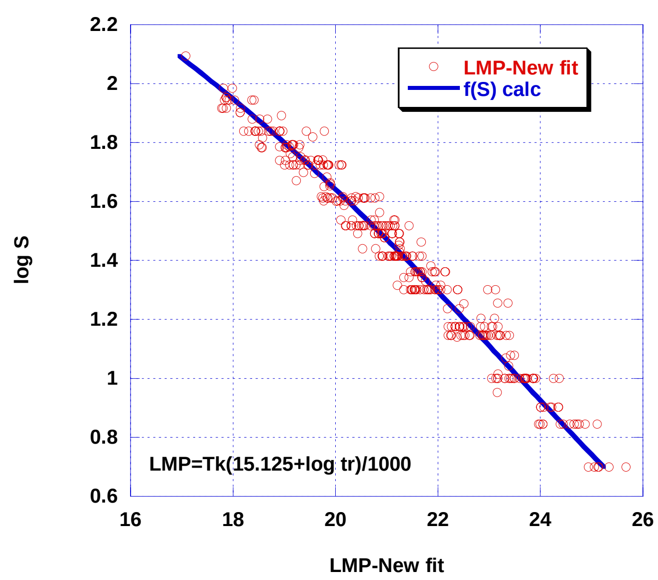

Figure 31. Log stress versus the Larson-Miller parameter for rupture of alloy 800H.

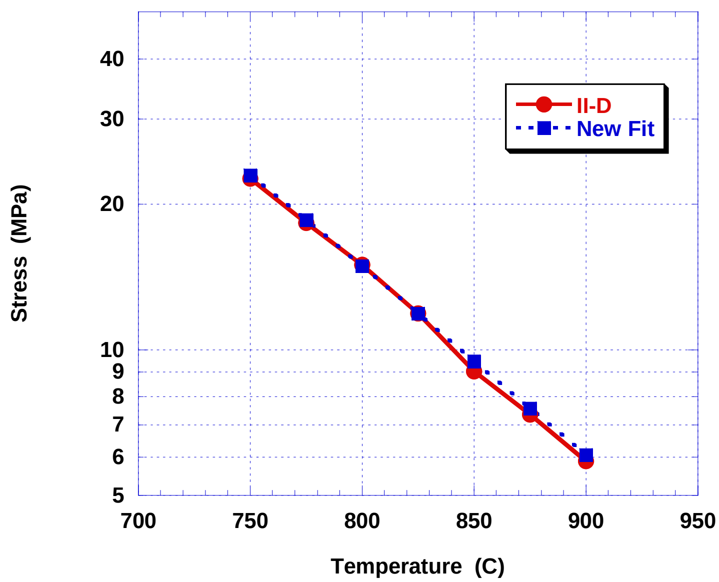

Figure 32. Comparison of BPV II-D Table 1B stresses with the new fit for the expanded database for alloy 800H.

In the ASME Task 1, Part 2 report, it was shown that the variability in the primary creep behavior complicated the development of a temperature-stress-time model needed for evaluation of the BPV III-NH 1% strain criterion for long-times at temperatures of 800°C (1472°F) and above [18]. A low value for the stress exponent caused the estimated stresses to fall rapidly at long times and at 850 and 900°C (1562 and 1650°F) the model reached its stress-based extrapolation limit before reaching the 600,000 hours life target. Similar difficulties were encountered in estimating the BPV III-NH tertiary creep criterion. An alternate correlation between the time to tertiary creep and the rupture life produced a favorable model for estimating 80% of the minimum strength for tertiary creep. The estimated strengths from this tertiary creep model, based on rupture life, were very close to those estimated from 67% of the minimum stress-to-rupture. Both the Larson-Miller parameter and the Orr-Sherby-Dorn parameter were used to estimate the stresses for 100% of the average time to 1% strain. The Orr-Sherby-Dorn parameter in combination with a well-behaved stress function was selected for the estimation of the long-time strength for 1% strain. Tables were developed in an appendix of the report that compared the strengths produced by the three BPV III-NH criteria for time-dependent allowables. It was reported that the minimum rupture strength criterion controlled S_t for most times at 750°C (1382°F), for the first 100,000 hours at 800°C (1472°F), and for shorter times at 850 and 900°C (1562 and 1650°F). The average stress to produce 1% strain controlled the long time stress limits at 850 and 900°C (1562 and 1650°F), as shown in Figure 33. It was concluded that additional data are needed to better assess the stress for 1% strain at long times and above 800°C (1472°F), since a possibility for diffusional creep existed.

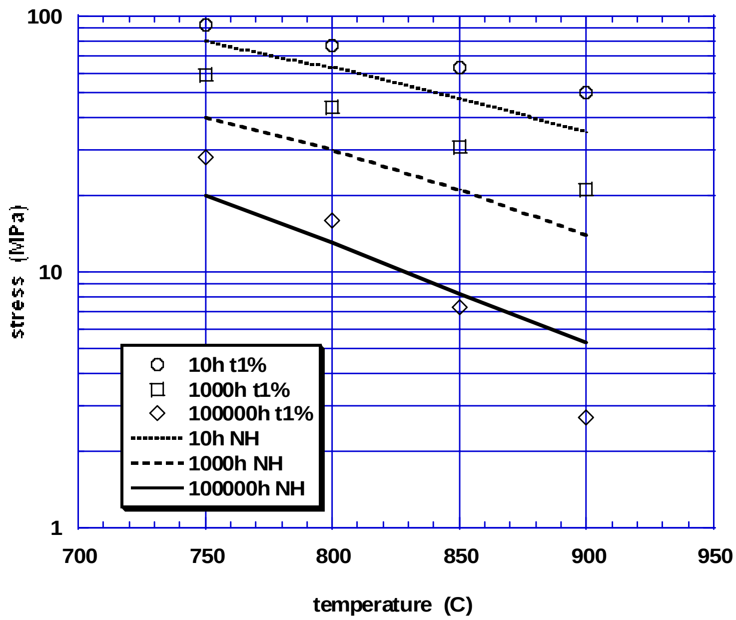

Figure 33. Comparison of the stress to produce 1% strain with estimates of the S_t values based on rupture for alloy 800H to 900°C (1650F)

Further studies were recommended to better understand the factors that contribute to variability in the creep behavior and justify the assembly of a database that would improve the precision and accuracy of the estimated strengths for the 1% strain and tertiary creep strength criteria.

EVALUATION OF THE 9Cr- 1Mo- V STEEL DATABASE

Databases compiling the creep-rupture properties of 9Cr-1Mo-V steel were reviewed and referenced in the ASME Task 1, Part 1 report on *Verification of Allowable Stresses in ASME Section III Subsection NH for Gr 91 Steel* [19]. The database for the creep-rupture of 9Cr-1Mo-V (Grade 91) steel was reviewed to determine if it met the needs for recommending time-dependent strength values, S_t, for coverage in BPV IIII-NH to 650°C (1200°F) and 500,000 or 600,000 hours. The accumulated database included over 300 tests for 1% strain, nearly 400 tests for tertiary creep, and nearly 1700 tests to rupture. Procedures for analyzing creep and rupture data for BPV III-NH were reviewed and compared to the procedures used to develop the current allowable stress values for Gr 91 for BPV II-D. The criteria in BPV III-NH for estimating S_t included the average strength for 1% strain for times up to 600,000 hours, 80% of the minimum strength for tertiary creep for times up to 600,000 hours, and 67% of the minimum stress-to-rupture values for times up to 600,000 hours. Time-temperature-stress parametric formulations were selected to correlate the data and make predictions of the long-time strength. Figure 34 below, taken from the Task 1 Part 1 report, is shown as an example. It was found that the stress corresponding to 1% strain and the initiation of tertiary creep were not the controlling criteria over the temperature-time range of concern. It was found that small adjustments to the current values in BPV III-NH could be introduced but that the existing values were conservative and could be retained. The existing database was found to be adequate to extend the coverage to at least 500,000 hours for temperatures below 600°C (1112°F) and perhaps continue coverage at 649°C (1200°F) to 100,000 hours.

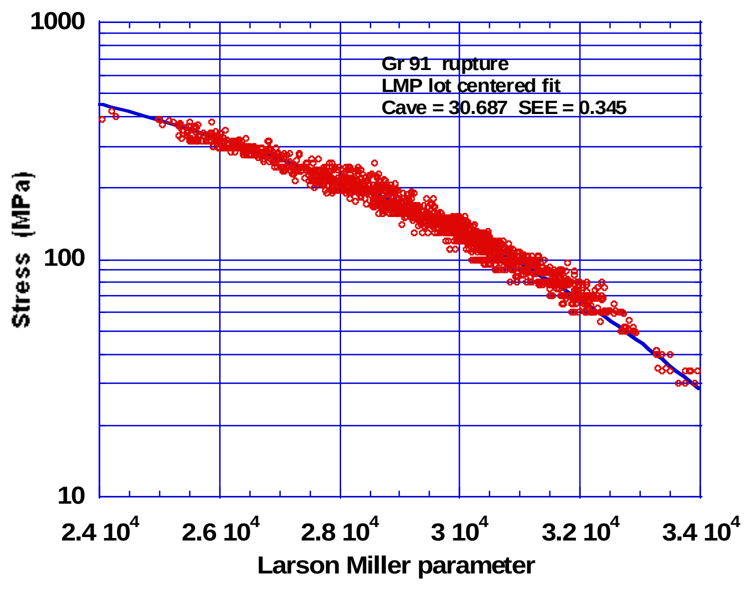

Figure 34. Stress versus the Larson-Miller parameter for rupture of 9Cr-1Mo-V steel

For example, Figure 35 plots the S_t values from BPV III-NH Table 14.4 against time for several temperatures where they may be compared to values calculated from the correlation of the expanded database for 9Cr-1Mo-V steel. Generally, the newly calculated values are greater than the values currently in BPV III-NH.

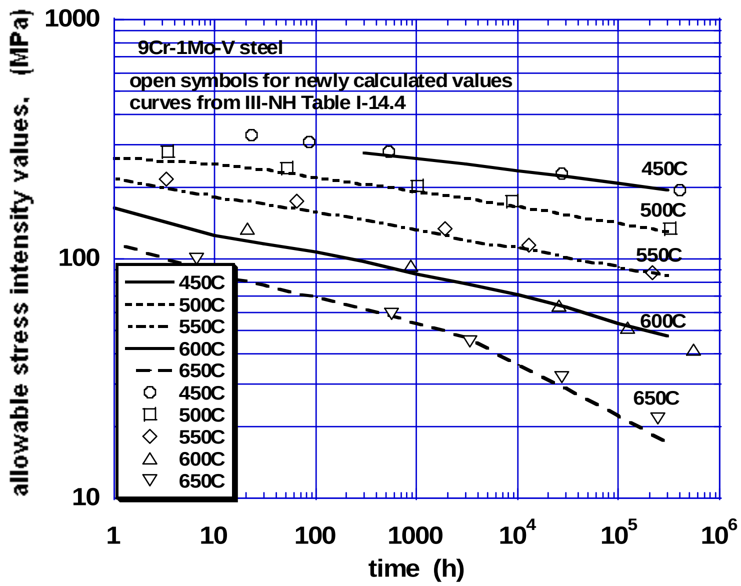

Figure 35. Comparison of BPV III-NH S_t values with 67% of the minimum stress-to-rupture calculated from the expanded database for 9Cr-1Mo-V steel.

RECOMMENDED ACTION FOR THE CORRECTION OF CURRENTLY LISTED VALUES FOR S_o, S_t, and S_r

The stresses listed in BPV III-NH Table I-14.6 for the minimum stress-to-rupture for 304H stainless steel and 316H stainless steel were derived from databases assembled in the 1970s and determined with the use of a factor on stress (approximately 80% of the average) rather than a minimum rupture curve based on a reduction of the average life in log time by a constant multiple (1.65) of the standard error of estimate (SEE) representing the "scatter" in the rupture data. The Task Force on Allowable Stress Criteria of the BPV Subgroup on Elevated Temperature Design (BPV-III) should examine the criterion for setting the minimum stress-to-rupture. This action is especially important for very long life where the "average" log-stress versus log-rupture-life curve exhibits a steeper slope. Based on the consensus of the Task Force, the expanded databases for type 304H and 316H stainless steels should be used to re-establish these stresses for 100,000 hours and to extend the applicable range of time for 316H stainless steel to 500,000 hours for the temperature range of interest to the Generation IV reactor concepts. These activities would not require testing.

Similar to the situation with the minimum stress-to-rupture, the time-dependent stresses listed in BPV III-NH Table I-14.3 and Table I-14.4 for 304H stainless steel and 316H stainless steel were derived from databases assembled in the 1970s. The criterion that controlled the stresses varied with the temperature and time. In addition, the criterion on creep was 80% of the minimum stress for 1% strain rather than the average stress provided in the isochronous curves. The time to 1% strain was based on a curve constructed from three components of strain: elastic, plastic, and creep. Likewise, the creep strain was constructed of three components: fast transient, slow transient, and "steady state." Revisions to the Blackburn equation have been proposed, and several alternative creep models have been proposed [6, 10, 13, 20, 21]. The Task Force on Allowable Stress Criteria of the BPV III Subgroup on Elevated Temperature Design should examine the methods for estimating the time to 1% strain and review the estimates for very long-time behavior. The creep data produced by NIMS would be of great assistance in this regard, if it could be accessed. Data from other sources such as India and Korea would be of value. This activity would not require testing.

With respect to strain limits, data from long-time testing at NIMS suggest that low creep ductility may be experienced in 304H and 316H stainless steels. Some sensitivity has been associated with chemistry but this issue is still being investigated in Japan [7]. It would not be practical to begin new testing to explore this issue, since testing times to around 100,000 h may be necessary. Nonetheless, heats of steels have been tested to these times in the US, and archival specimens could be chemically analyzed to determine the content of elements that are thought to contribute to low creep rupture ductility. This activity would not involve more testing, although some archival specimens could be placed back into test should justification be established.

The issue of tertiary creep is central to the extension of the allowable time-dependent stresses to 500,000 hours or more. Rather than basing the time to tertiary creep on the point of departure from secondary creep, or the time to 0.2% offset strain from the extension of the secondary creep stage, the tertiary creep process should be modeled just as primary and secondary creep are modeled to develop the isochronous curves. The impact of tertiary creep on the isochronous stress-strain curves should be considered. There are several tertiary creep and continuum damage mechanics (CDM) models currently available and some have been applied to 304H and 316H stainless steels with emphasis on 316H stainless steel. One of the task forces under the BPV III Subgroup on Elevated Temperature Design should undertake a review of work in this field. No need for experimental work is anticipated.

Several of the action items identified for 304H and 316H stainless steel apply to alloy 800H, as well. With respect to the near-term needs of the Generation IV reactor concepts, alloy 800H appears to have a higher priority than the stainless steels. Although no inconsistencies were found between S_o, S_t, and S_r for alloy 800H, there remain issues with respect to the isochronous stress-strain curves, the time to 1% strain, and the "minimum" stress for the initiation of tertiary creep.

Some Generation IV reactor concepts require allowable stresses for alloy 800H to 850 or 900°C (1562 or 1650°F). At such temperatures, the tensile behavior is very strain-rate sensitive and the "hot tensile" curve for the isochronous curves above 750°C (1380°F) must be linked to a specific strain rate. It was concluded that experimental work is needed to produce stress-strain curves over several orders of magnitude and at temperatures from 750 to 900°C (1382 to 1650°F). Such work is being undertaken at the National Laboratories.

The evaluation of alloy 800H undertaken in Task 1, Part 2 found that the average stress to produce 1% strain could not be estimated at long times at 900°C (1650°F) because it required extrapolation to stresses at which no testing had been performed [18]. In addition, there have been claims that diffusional creep for such conditions is possible. Experimental work on the subject is being planned and supported by the Department of Energy. It is known that the German high-temperature design code KTA 3221 supplies information to temperatures as high as 1000°C (1830°F). Some of the data supporting this code are available at the Petten database facility and should be examined.

The resolution of the issue of the significance of tertiary creep in alloy 800H is critical to its usage in components operating to 850 or 900°C (1562 or 1650°F) and the BPV III Subgroup on Elevated Temperature Design should undertake consideration with respect to the significance of the "minimum" stress for the initiation of tertiary creep. As with the stainless steels, there are several tertiary creep and continuum damage mechanics (CDM) models currently available and some have applicability to alloy 800H. Again, data have been produced by NIMS and the German HTGR program that could supplement the existing U.S database to resolve this issue. No experimental testing effort is suggested.

As mentioned in the Task 6 Part 1 report, the allowable stresses for 2 1/4Cr-1Mo steel were reviewed and revised in 1990 for BPV II-D Table 1A. The revisions were relatively minor, and a decision was made to retain the stress allowables in BPV III-NH without change. However, the stresses in BPV II-D are based on values at 100,000 h, and, as was seen above, the stresses drop rapidly after long times. The following more-or-less repeats the recommendations made above on the section addressing the evaluation of the 2 1/4Cr-1Mo database and suggests actions for the Task Force on Allowable Stress Criteria of the BPV III Subgroup on Elevated Temperature Design. No experimental work is needed.

> The creep curves produced for 2 ¼ Cr-1Mo steel should be re-assembled and used to re-assess the creep laws. Many such curves were produced since the original collection that was used to construct the isochronous stress-strain curves in BPV III-NH. Such a re-assessment would improve the understanding of primary creep and tertiary creep. The information would be helpful in the development of continuing damage mechanics (CDM) models and creep-crack-growth models.
>
> A detailed review for 2 ¼ Cr-1Mo steel should be undertaken of the research by NIMS aimed at an explanation of the lot-to-lot variability of the creep and rupture behavior in 2 ¼ Cr- 1Mo steel. In particular, the similarities and differences in the materials evaluated by NIMS and materials in the collection from U.S sources should be explored.
>
> An effort should be made to examine the data for 2 ¼ Cr-1Mo steel that has been produced on the effect of chemistry, melting practice, and processing on the variability of the creep behavior. It is important to resolve the issue of how one factors tertiary creep into the criteria for setting time-dependent stresses.

Experimental work on 9Cr-1Mo-V steel is an ongoing worldwide activity. The specific needs for the Generation IV reactors have been addressed in the testing plans that have been developed by the National Laboratories. The role of the task forces in the BPV III Subgroup on Elevated Temperature Design is to keep abreast of research work on the 9Cr-1Mo-V steel regardless of it usage (nuclear, fossil, petroleum, petrochemical, etc.).

One action that needs to be undertaken is a review and revision of the isochronous stress-strain curves in BPV III-NH Appendix T for 9Cr-1Mo-V steel. Long-time creep data have been released by NIMS that will be of value in supplementing the existing data for a re-analysis. No experimental testing will be needed for this activity.

The Task Force on Negligible Creep Criteria of the BPV III Subgroup on Elevated Temperature Design has a need for creep data on 9Cr-1Mo-V steel at "low temperatures and stresses." These test conditions have been identified in the testing plans of the National Laboratories and await funding, so no further definition is needed here.

Finally, it is clear that methods and procedures of data analysis should be re-visited by the Task Force on Allowable Stress Criteria of the BPV III Subgroup on Elevated Temperature Design. Here, an assessment of procedures used in Europe, Japan, and elsewhere should be reviewed with respect to the criteria for setting stress allowables in BPV III-NH.

Table 6 provides an outline for action on the stress allowables for the five alloys listed in BPV III-NH. The first item for action in each case is to produce consistency between Tables I-14.2 and Tables I-14.6. This may lead to inconsistencies between the S values in BPV II-D and the S_o values but the S_o values will be conservative. Several of the action items in Table 6 are directed toward limiting the temperature or times covered for the allowables until such time as re-evaluation of the database can justify the restoration or adjustment of the existing values. The extension of coverage for alloy 800H is needed and data are sufficient to justify the extensions to 500,000 hours which corresponds to 60 years at 95% availability. Further extension to 600,000 h for alloy 800H may be possible. Extension of coverage for 316H stainless steel and 2¼ Cr-1 Mo steel to longer times is not identified in the table but should be taken into consideration for lower temperatures applications. All action on the 9Cr-1Mo-V steel has been assigned to medium priority. This steel has potential usage in several reactor concepts but its usage as a thick-wall pressure vessel material is linked to a better understanding of the performance of weldments and research on this topic is continuing.

TABLE 6. A SUMMARY OF SUGGESTED ACTION REGARDING CHANGES TO THE BPV III-NH STRESS ALLOWABLES TO ACCOMMODATE THE NEEDS FOR THE GENERATION IV REACTOR CONCEPTS

ALLOY	ITEM	ACTION	PRIORITY
304H SS	S_o	Base S_o values on the current 0.80 S_{Rmin} values	Medium
	S_t	Limit long-time S_t values ≥ 750°C to 10^5 h (Tertiary creep data above 750°C are too limited)	Low
	S_{Rmin}	Reduce S_{Rmin} values at Temperatures above 750°C	Low
		Limit long time values at ≥800°C to 10^5 h	Low
316H SS	S_o	Base S_o values on the current 0.80 S_{Rmin} values	High
		Re-examine S_{Rmin} values at 10^3 h for ≥700°C	High
	S_t	Reduce S_t values if new tertiary creep data show a need for reduced values	Medium
	S_{Rmin}	Re-examine S_{Rmin} values at 10^3 h for ≥700°C	High
Gr 22	S_o	Base S_o values on the current 0.80 S_{Rmin} values	High
	S_t	Limit long-time S_t values ≥ 525°C to 10^4 h	Medium
		Develop a creep model for estimating 1% strain and tertiary creep	Medium
	S_{Rmin}	Re-examine S_{Rmin} values for >10^4 h for ≥525°C	Medium
	(all)	Restrict thermo-mechanical processing to reduce the variability in strength	
800H	S_o	Extend S_o values to 850°C	High
	S_t	Extend S_t values to 850°C and 500,000 h	High
		Develop a creep model for estimating 1% strain and tertiary creep	High
	S_{Rmin}	Extend S_{Rmin} values to 850°C and 500,000 h	High
Gr 91	S_o	Base S_o values on the current 0.80 S_{Rmin} values for ≥625°C	Medium
	S_t	Extend S_t values for ≤575°C to 500,000 h	Medium
		Limit long-time S_t values >575°C to 10^5 h	Low
		Develop a creep model for estimating 1% strain, tertiary creep, and negligible creep	Medium
	S_{Rmin}	Re-examine long-time S_{Rmin} values at >575°C	Low

Note: See Reference 1 for comparison of values produced by 0.80 S_{Rmin} with S from ASME Section II-D and S_o. In Reference 1, S_r in BPV III-NH is identical to S_{Rmin} in BPV II-D.

ACKNOWLEDGEMENTS

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APPENDIX 1. CRITERIA FOR SETTING THE STRESS ALLOWABLES IN ASME SECTION 2D TABLE 1A AND 1B AND ASME SECTION III, SUBSECTION NH

In ASME Section II Part D, the criteria for setting S of wrought products above room temperature are provided in Appendix 1 Table 1-100 and include:

(i) $S_T/3.5$, where S_T is the "specified minimum tensile strength at room temperature,"

(ii) $1.1S_TR_T/3.5$, where "R_T is the ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength,"

(iii) $2S_Y/3$, where S_Y is the "specified minimum yield strength at room temperature,"

(iv) $2S_YR_Y/3$ or $0.9\ S_YR_Y$ where R_Y is the "ratio of the average temperature dependent trend curve value of yield strength to the room temperature yield strength,"

(v) $F_{\text{avg}}S_{R\text{avg}}$, where $S_{R\text{avg}}$ is the "average stress to cause rupture at the end of 100,000 hr" and F_{avg} is a "multiplier applied to $S_{R\text{avg}}$" that has a value of 0.67 for temperatures of 1500°F and below,

(vi) $0.80S_{R\text{min}}$, where $S_{R\text{min}}$ is the "minimum stress to cause rupture at the end of 100,000 hr," and

(vii) $1.0S_c$, where S_c is the "average stress to produce a creep rate of 0.01%/1,000 hr."

In ASME III-NH, the criteria for setting S_m, "the lowest stress intensity value at a given temperature among the time-independent strength properties" for wrought metal are provided in ASME Section II Part D Appendix 2 and Table 2-100(a). These include:

(i) $S_T/3$, where S_T is the "specified minimum tensile strength at room temperature,"

(ii) $1.1S_TR_T/3$, where "R_T is the ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength,"

(iii) $2S_Y/3$, where S_Y is the "specified minimum yield strength at room temperature," and

(iv) $2S_YR_Y/3$ or $0.9\ S_YR_Y$ where R_Y is the "ratio of the average temperature dependent trend curve value of yield strength to room temperature yield strength,"

The criteria for setting S_o, the "maximum allowable value of general primary membrane stress intensity to be used as a reference for stress calculation under Design Loadings" above room temperature, are identical to the criteria of Section II-D Appendix 1 for wrought products and S_o is intended to be equivalent to S, "except for a few cases at lower temperatures" as defined in NH-3221. This exception sometimes appears as a lower value than S_m or greater value than S_t at the temperature where S_o transitions from the time-independent criteria to time-dependent criteria.

The criteria in ASME III-NH for setting S_t, "the temperature and time-dependent stress intensity limit," include:

(i) "100% of the average stress required to obtain a total strain (elastic, plastic, and creep) of 1%,"
(ii) "80% of the minimum stress to cause initiation of tertiary creep," and
(iii) "67% of the minimum stress to cause rupture."

The criteria for S_t, therefore, differ from the criteria for setting S and S_o in the sense that they need to cover a range of times from 1 to 300,000 hr, whereas S and S_o only pertain to 100,000 hr.

The value of S_{mt} is defined as "the lower of two stress intensity values, S_m (time-independent) and S_t (time-dependent)."

Finally, the stress S_r is defined as the "expected minimum stress-to-rupture strength" and pertains to base metal, although the definition is provided in the paragraphs of NH-3221 dealing with criteria for weldments. At 100,000 hr, $S_{R\min}$ and S_r should be equivalent.