INL-EXT-21-63802

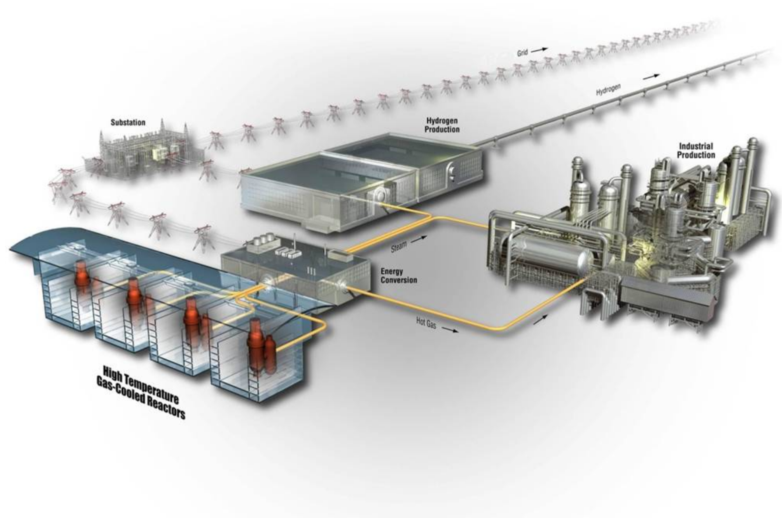
Recommendation for Limiting Conditions for ASME BPVC Section III Division 5 Allowable Stress Criteria

August 2021

Changing the World's Energy Future

Michael McMurtrey
Idaho National Laboratory

Richard Wright
Idaho National Laboratory



Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL-EXT-21-63802

Recommendation for Limiting Conditions for ASME BPVC Section III Division 5 Allowable Stress Criteria

Michael McMurtrey
Idaho National Laboratory

Richard Wright
Idaho National Laboratory

August 2021

Idaho National Laboratory
Advanced Reactor Technologies
Idaho Falls, Idaho 83415

http://www.ART.INL.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

INL ART Program

Recommendation for Limiting Conditions for ASME BPVC Section III Division 5 Allowable Stress Criteria

INL-EXT-21-63802

July 2021

Technical Reviewer: (Confirmation of mathematical accuracy, correctness of data, and appropriateness of assumptions.)

TING-LEUNG SHAM (Affiliate) Digitally signed by TING-LEUNG SHAM (Affiliate) Date: 2021.08.03 11:57:35 -05'00'

Ting Leung Sham INL NS&T Directorate Fellow	Date

Approved by:

M. Davenport	8/3/21
Michael E. Davenport INL ART Project Manager	Date
	08/03/21
Travis R. Mitchell INL ART Program Manager	Date
Michelle Sharp	8/2/21
Michelle T. Sharp INL Quality Assurance	Date

SUMMARY

Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) specifies rules for elevated-temperature nuclear reactors. Time-dependent allowable stresses are an important aspect of the high-temperature-design models and are related to the time to 1% strain, time to rupture, and time to onset of tertiary creep. The time to onset of tertiary creep criterion has an overly strong negative influence on the allowable stresses for some structural materials, likely due to very limited datasets and misidentification of microstructural changes, not the onset of significant creep damage, which tertiary creep is meant to represent. It is recommended that onset of tertiary creep be determined through an alloy-specific ratio between onset of tertiary creep and creep rupture time, enabling access to the significantly larger creep rupture time datasets.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
SEE	Standard Estimate of Error

Page intentionally left blank

Recommendation for Limiting Conditions for ASME BPVC Section III, Division 5 Allowable Stress Criteria

1. INTRODUCTION

Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) provides rules for elevated-temperature nuclear reactors. Originally existing as code cases, these rules were first brought into Section III, Division 1 under Subsection NH in 1995, before ASME consolidated all high-temperature construction rules for nuclear reactors under Division 5 in 2011. In 2018, after being requested to endorse Section III, Division 5, the Nuclear Regulatory Commission agreed to begin reviewing the 2017 edition of the ASME BPVC Section III, Division 5 [1].

Division 5 considers not only a time-independent allowable stress (S_m), but also a temperature- and a time-dependent allowable stress (S_t). The time-dependent allowable stress is defined as the lesser of the following three criteria:

- 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1% ($S_{1\%}$)
- 80% of the minimum stress to cause onset of tertiary creep (S_3)
- 67% of the minimum stress to rupture (S_r).

Tertiary creep is defined as the point at which the creep strain rate begins to increase from the typically linear region that represents the minimum creep rate (secondary creep). Similar to yield stress after the linear elastic region, tertiary creep may be defined using a 0.2% strain offset to determine the actual onset point. The historical basis for the tertiary creep criterion is explained in a recent report by Dabrow and Nestell [2]. Leyda and Rowe suggested that onset of tertiary creep ties in with onset of significant creep damage [3]. At the time, there was no consensus on this theory, and some (e.g., Marriott) believed that significant creep damage accumulated only very late in the creep life [4]. However, the tertiary creep criterion was included in the design criteria, due to concerns over potential coolant leakage from damage accumulation in tubes experiencing bi-axial stress [5,6], as well as concerns that excessive strain in localized sections of a structure may result from the rapid strain rate increase at constant stress in the tertiary regime [7]. Thus, as pointed out by Sham [8], while the rupture stress criterion reflects actual structural failure, onset of tertiary creep is instead primarily included to guard against coolant leakage in tubes. While Section III, Division 5 includes the onset of tertiary creep criterion, Sections I and VIII do not.

The tertiary creep criterion was originally found to be non-limiting to the allowable stresses for Division 5 materials, which were controlled by the time to 1% strain and the rupture life criteria, so there was originally little impact from including it. This was partly because the available dataset for onset of tertiary creep was very limited at that time. However, work conducted by Sengupta and Nestell [9] on type 304 and 316 stainless steels, and by Swindeman [10] on alloy 800H, to extend allowable stresses to 500,000 hours reveals that, when newer datasets are included, tertiary creep controls most of the allowable-stress table entries. For example, the values calculated by Sengupta and Nestell for the stainless steels are shown in Tables 1 and 2, along with the governing criteria.

Table 1. Type 304 stainless steel time-dependent allowable stresses (S_t)calculated by Sengupta and Nestell.

	Time in hours	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
Temperature in C													
425		179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83
450		177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	163.64	149.22
475		175.67	175.67	175.67	175.67	175.67	175.67	175.67	175.67	175.67	153.63	125.12	113.73
500		173.66	173.66	173.66	173.66	173.66	173.66	173.66	173.66	149.24	118.28	95.66	86.68
525		171.66	171.66	171.66	171.66	171.66	171.66	171.66	144.11	115.77	91.06	73.14	66.06
550		169.67	169.67	169.67	169.67	169.67	169.67	144.18	112.55	89.79	70.10	55.93	50.35
575		167.67	167.67	167.67	167.67	167.67	143.19	113.46	87.90	69.65	53.97	42.76	38.38
600		165.62	165.62	165.62	165.62	147.53	113.46	89.28	68.66	54.02	41.55	32.70	29.25
625		163.59	163.59	163.59	147.77	117.77	89.89	70.26	53.62	41.90	31.98	25.00	22.29
650		161.66	161.66	143.49	121.13	94.02	71.22	55.28	41.88	32.50	24.62	19.11	16.99
675		159.72	138.66	122.05	97.36	75.06	56.43	43.50	32.71	25.22	18.96	14.62	12.95
700		155.36	118.25	103.43	78.26	59.92	44.71	34.23	25.54	19.56	14.59	11.18	9.87
725		133.75	100.48	84.94	62.90	47.83	35.42	26.94	19.95	15.17	11.24	8.54	7.52
750		114.79	85.06	68.78	50.57	38.18	28.07	21.20	15.58	11.77	8.65	6.54	5.74
775		98.20	71.71	55.71	40.65	30.49	22.24	16.68	12.17	9.13	6.66	4.99	4.37
800		83.71	60.19	45.12	32.67	24.34	17.62	13.13	9.50	7.08	5.13	3.82	3.33

S1%   S3

Sr

Table 2. Type 316 stainless steel time-dependent allowable stresses (S_t) calculated by Sengupta and Nestell.

	Time in hours	1	3	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
Temperature in C														
425		179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	169.11	159.92
450		175.88	175.88	175.88	175.88	175.88	175.88	175.88	175.88	175.88	175.88	157.56	134.89	124.88
475		172.57	172.57	172.57	172.57	172.57	172.57	172.57	172.57	170.52	149.85	124.64	104.99	96.94
500		169.24	169.24	169.24	169.24	169.24	169.24	169.24	164.50	141.48	118.49	97.57	81.72	75.25
525		166.00	166.00	166.00	166.00	166.00	166.00	158.07	136.99	112.09	93.34	76.38	63.60	58.41
550		162.76	162.76	162.76	162.76	162.76	155.30	131.91	109.22	88.81	73.53	59.79	49.50	45.34
575		159.54	159.54	159.54	159.54	151.88	130.89	105.77	87.08	70.36	57.92	46.80	38.53	35.20
600		156.32	156.32	156.32	152.01	128.51	105.63	84.81	69.42	55.74	45.63	36.64	29.99	27.32
625		153.11	153.11	151.32	129.26	104.73	85.23	68.01	55.35	44.16	35.94	28.68	23.34	21.21
650		150.00	150.00	129.23	107.18	84.99	68.77	54.53	44.13	34.99	28.31	22.45	18.17	16.46
675		146.70	132.46	108.80	87.53	68.97	55.49	43.73	35.18	27.72	22.30	17.57	14.14	12.78
700		134.85	113.39	89.36	71.48	55.97	44.78	35.06	28.05	21.96	17.57	13.76	11.00	9.92
725		115.99	94.32	73.40	58.38	45.43	36.13	28.11	22.36	17.40	13.84	10.77	8.57	7.70
750		98.58	77.96	60.28	47.68	36.86	29.15	22.54	17.83	13.79	10.90	8.43	6.67	5.98
775		81.95	64.44	49.51	38.93	29.92	23.52	18.08	14.21	10.92	8.59	6.60	5.19	4.64
800		68.12	53.26	40.67	31.80	24.28	18.98	14.49	11.33	8.65	6.76	5.17	4.03	3.45

S1%   S3

Sr

It can be seen from the tables that the time to onset of tertiary creep criterion (highlighted in yellow) controls many of the allowable stresses, particularly for higher temperatures and longer operating times. The yellow S_t values are up to 40% less than current code values. Since the onset of tertiary creep criterion was thought to be a refinement of the code rules for nuclear service, it was not expected to control most of the stress table. The following were proposed as potential reasons why it does so in cases such as type 304H and 316H stainless steels:

- Tertiary creep data are sensitive to the shape of the creep curve, and identifying the point of onset of tertiary creep is sometimes difficult.
- Carbide precipitation during creep testing can markedly affect the shape of the creep curve.
- The actual number of tertiary creep data is very small compared to that of the rupture data available. This causes statistical uncertainties and poor extrapolation of the test data to operating times and temperatures.

Figure 1 shows example type-316L stainless steel creep curves that exhibit the “classic” behavior for onset of tertiary creep after a period of steady-state creep rate. Here, onset of tertiary creep is clearly visible and easily defined (such as via the 0.2% strain offset method).

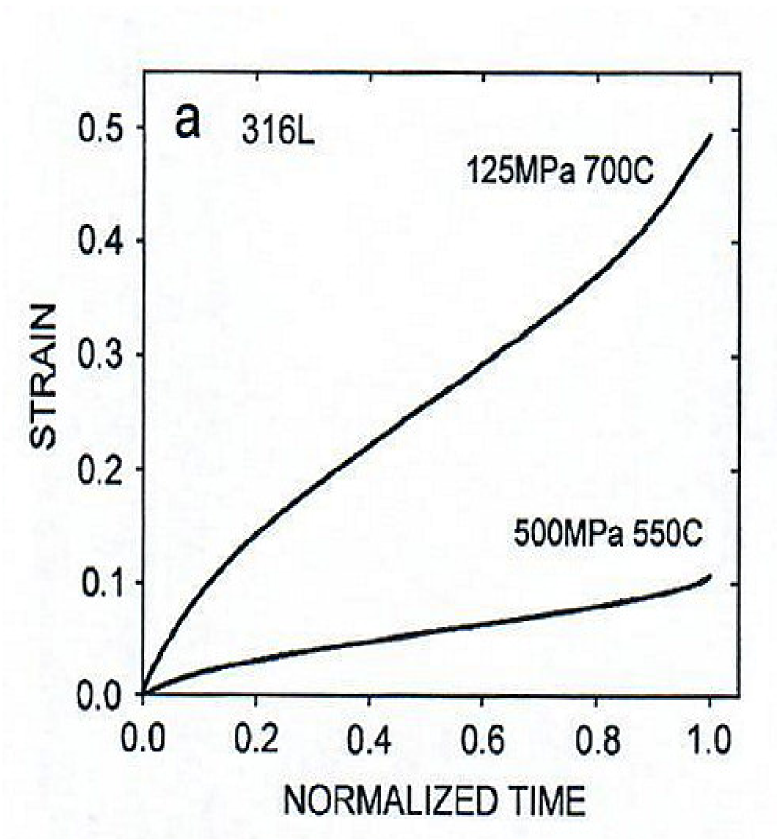


Figure 1. Type 316L stainless steel creep curves demonstrating “classic” behavior.

Figure 2, however, shows a common creep curve for type 316 stainless steel, with a low applied stress leading to the long creep life. In this curve, at least two different precipitates occur sequentially in time. The result is that the first increase in creep rate is not the onset of tertiary creep in the sense that it indicates incipient failure, but rather a change in the dominant strengthening mechanism. Attempts to apply methods such as the 0.2% strain offset to identify onset of tertiary creep would identify a point very early on in the specimen life—a point not indicative of onset of severe creep damage and imminent failure.

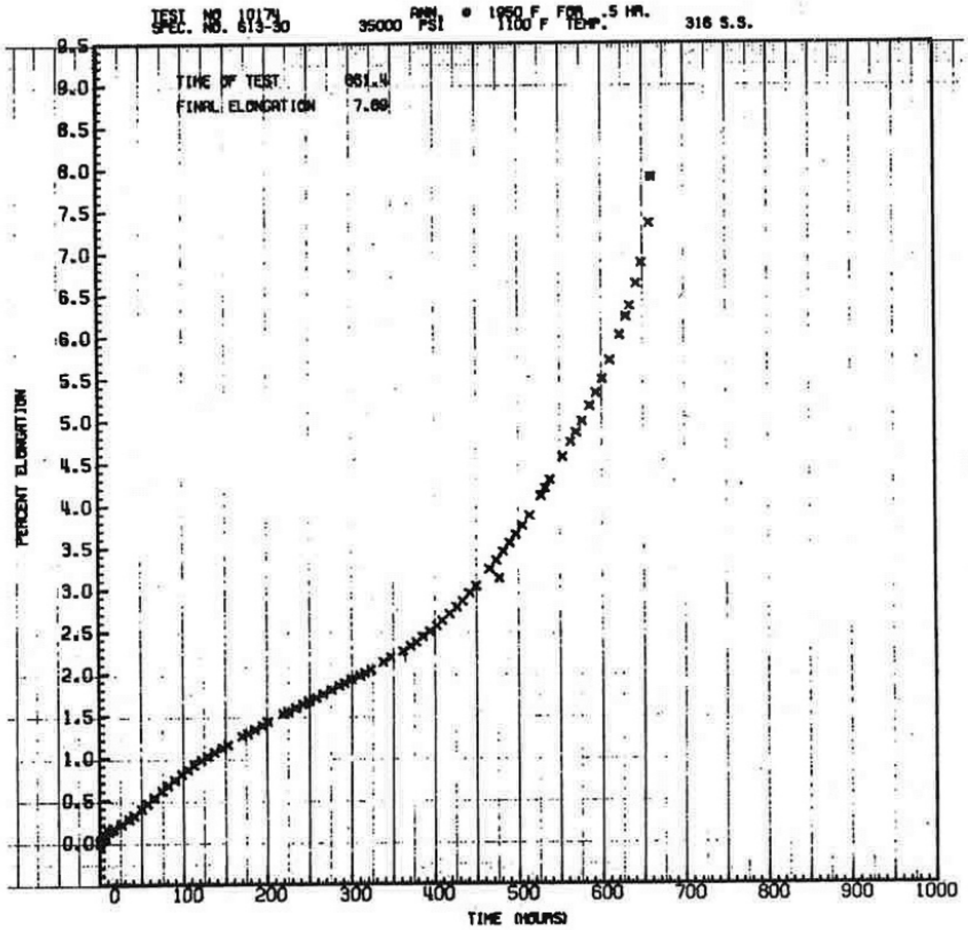


Figure 2. Type 316 stainless steel creep curve showing two different apparent minimum creep rates, corresponding to a change in the dominant strengthening mechanism.

The impact of tertiary creep on the stainless steel's allowable stresses is too large to simply incorporate the results into the code without further examining other options. This has raised concerns over using the onset of tertiary creep criterion as a Section III, Division 5 allowable stress criterion.

2. RECOMMENDATIONS

There are two potential paths forward: (1) determine a way to avoid the known tertiary creep data shortcomings that appear to reduce the resultant allowable stresses to unnecessarily low values, and (2) re-evaluate the need for a tertiary creep criterion for stainless steels, based on the current understanding of stainless steel creep behavior in the tertiary range.

For the first path, start by considering the massive amount of creep rupture data available, along with the observation made by others that onset of tertiary creep often occurs at a fixed ratio of the rupture life.

For austenitic steels, numerous empirical studies have revealed a consistent relationship between onset of tertiary creep and time to rupture. In 1969, Leyda and Rowe [3] determined that the ratio between the onset of tertiary creep time to rupture life for many creep-resistant materials was constant over specific temperature bands. They speculated that this ratio could be used to simulate tertiary creep data from rupture data over the selected temperature ranges. In 1976, Booker and Sikka [11] at Oak Ridge

National Laboratory found that the ratios for type 304 and 316 stainless steels were constant over a wide band of temperatures. In 1982, Sikka [12] determined that the ratio for some heats of type 316 stainless steel was impacted by carbide precipitation, causing a misidentification of the time to onset of tertiary creep in the creep curves. Type 304 was not affected by carbide precipitation. Figure 3 shows Booker and Sikka's plot of Log(t_3) vs. Log(t_r) for Type 304 stainless steel [11], whereas Figure 4 shows a similar plot for type 316 stainless steel.

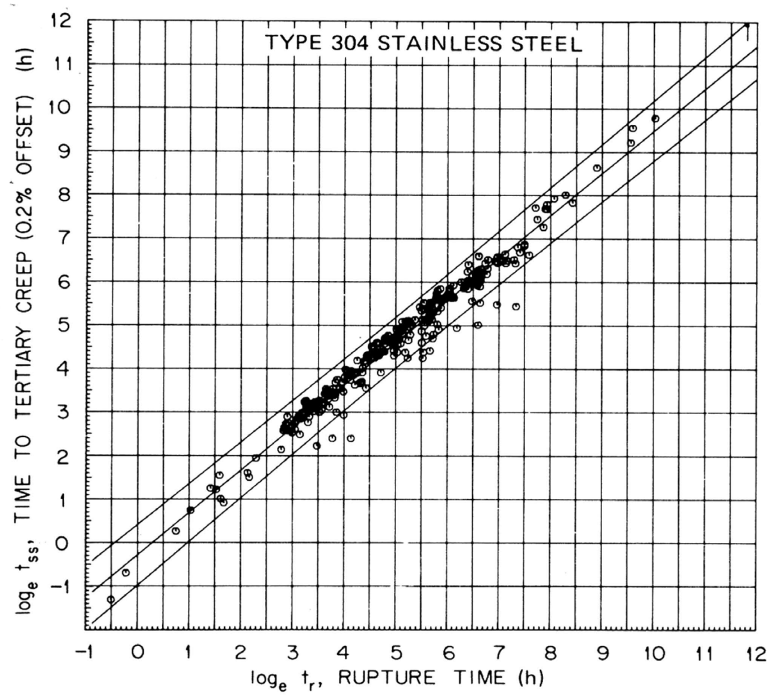


Figure 3. Log(t_3) vs. Log(t_r) for type 304 stainless steel (taken from Booker and Sikka [11]).

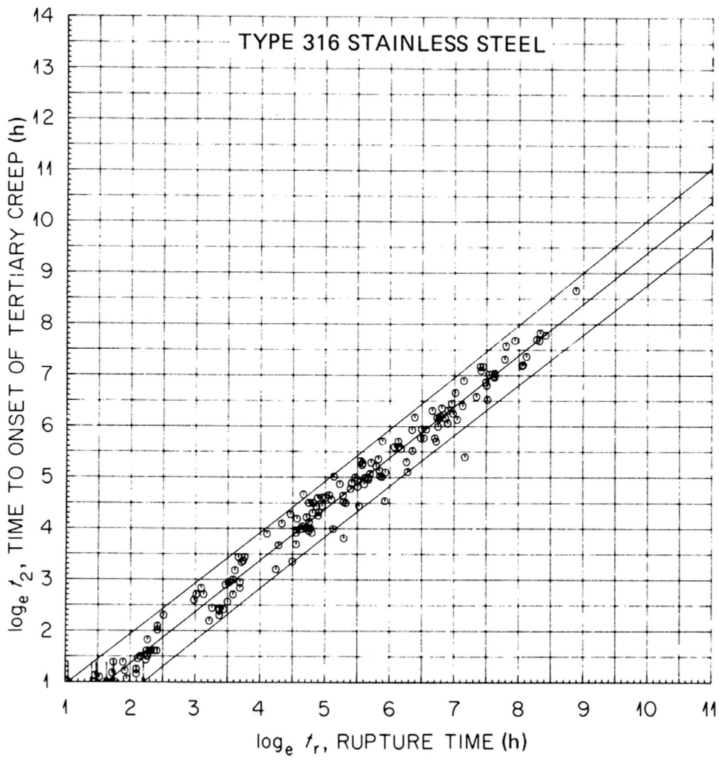


Figure 4. Log(t_3) vs. Log(t_r) for type 316 stainless steel (taken from Booker and Sikka [11]).

In current efforts to extend the allowable stresses of 316H/304H to longer lifetimes, the search for a relationship between time to rupture and onset of tertiary creep resulted in the decision to compute the t_3-to-t_r ratio for type 304H and 316H stainless steels using the National Institute for Materials Science tertiary creep database. The ratio thus obtained for each alloy was combined with the creep rupture data regression already done from ASME ST LLC Task 14a to compute the allowable stresses, based on the tertiary creep stress criterion.

This advantage of this method is that it only relies on the limited tertiary creep data for calculating a single number: the t_3-to-t_r ratio for each alloy. Issues of tertiary creep data contamination due to carbide precipitation or other issues in the tertiary data could be handled by culling the data in some controlled fashion prior to computing the ratios. The very robust rupture database and regression could then be used in computing allowable stresses based on tertiary creep.

As an example, in the current work on 304H/316H, it was concluded that the data for type 316H stainless steel showed a significant break in the curve associated with early behavioral changes stemming from carbide precipitation. For this reason, all data representing onset of tertiary creep earlier than 30% of rupture life were removed. All the data on type 304H stainless steel were used to find the average log(ratio), since carbide precipitation is not an issue for this material. Results of this work for type 316H stainless steel are log(ratio) = -0.27, ratio = 0.53. For type 304H, the values are log(ratio) = -0.24, ratio = 0.57. Booker and Sikka [11] found the ratios to be 0.526 and 0.685, respectively.

Larson-Miller regressions of rupture life data were completed in 2014 as part of ASME ST LLC Task 14a. Such regressions treat log stress (S) as an activation energy for Norton creep in the form of a log(S) polynomial. The regression varies the log(S) coefficients, a, and the constant, C, to minimize the error in log(t_r [rupture time]):

$$log(t_r) = \frac{a_0 + a_1 Log(S) + a_2 [Log(S)]^2}{T} - C \qquad (1)$$

The regression reduces the 1,000+ data points to five numbers: the three a's, the C, and an estimate of the fitted error (i.e., the Standard Estimate of Error [SEE]). The SEE is measured in units of log(time).

The lower bound stress based on creep rupture can be computed from Equation (1)—with some slight rearrangement—once the a's, C, and SEE are determined:

$$a_0 + a_1 log(S) + a_2[log(S)]^2 = T * (C + log(t_r) + 1.65 * SEE) \quad (2)$$

$S_r = 2/3*S$

Note that the 1.65*SEE term was added to produce a lower bound stress.

Using the following relation:

$t_3 = A* t_r$

where A is 0.53 and 0.57 for type 316H and 304H stainless steel, respectively, then substitute t_3 for t_r in Equation (2):

$$a_0 + a_1 log(S) + a_2[log(S)]^2 = T * (C + log(t_3/A) + 1.65 * SEE)$$
$$= T * (C + log(t_3) - \log(A) + 1.65 * SEE)$$

where the log(A) term effectively modifies the C constant. The a's, C, and the SEE remain untouched from the rupture regression. This equation can be used to compute tertiary creep lower bound stresses.

In applying this approach to type 304H and 316H stainless steel datasets, the tertiary creep criterion no longer appears to control the time-dependent stresses. A few cells are affected at the highest temperatures and longest times in the 316H stress intensity values, but those values would not be populated in the final table, since the stresses are low enough for diffusion creep rather than power law or Larson-Miller rules to apply. These findings from Dabrow and Nestell [2] highlight the importance of how tertiary creep is handled in the case of type 304H and 316H stainless steels. This report finds their approach to be an appropriate method of handling the concerns about the onset of tertiary creep criterion.

3. CONCLUSIONS

There are concerns that the onset of tertiary creep criterion is overly restrictive, particularly for alloys that, during creep testing, undergo phase transitions that would likely result in the misidentification of onset of tertiary creep at that point, as opposed to the intended point at which creep damage becomes significant. The more robust method of using the Leyda-Rowe ratio to analyze onset of tertiary creep data is recommended. This overcomes the issue of the limited dataset available for onset of tertiary creep, by enabling access to the much larger creep rupture database.

Additional research and development are required before a recommendation can be made as to whether prevention of coolant leakage should be covered through the onset of tertiary creep criterion in the definition of the allowable stresses, or through a separate new design provision that uses onset of tertiary creep but takes the onset of tertiary creep criterion out of the allowable stress definition for primary load.

4. REFERENCES

[1] B.E. Thomas, "NRC Response to ASME Letter of Request for NRC Endorsement of ASME Boiler and Pressure Vessel Code, Section III, Division 5," *U.S. Nuclear Regulatory Commission*, Accession No. ML18211A571, 2018.

[2] T. Dabrow and J.E. Nestell, "Impact of Tertiary Creep on Time Dependent Allowable Stresses for Type 304H and 316H Stainless Steels," *MPR Associates*, Alexandria, VA, 0300-0003-RPT-001, Accession No. ML21048A084, U.S. Nuclear Regulatory Commission, 2020.

[3] W.E. Leyda and J.P. Rowe, "A Study of the Time for Departure from Secondary Creep of Eighteen Steels," *American Society for Metals*, Technical Report P 9-6.1, Metals Park, Ohio, 1969.

[4] Douglas Marriott, email massage to Robert Swinderman, "RE: Task Squad of the Tertiary Creep Criterion," December 3, 2014.

[5] R.I. Jetter, "Effect of Multiaxial Stress State on Code Allowable Stresses," CA, 1977.

[6] G. Rowe, J. Stewart, K. Burgess, "Capped End, Thin-Wall Tube Creep-Rupture Behavior for Type 316 Stainless Steel," *Journal of Basic Engineering*, 1963, http://dx.doi.org/10.1115/1.3656543.

[7] W. O'Donnell. Letter to Paul Langford. "Tertiary Creep Criterion in Elevated Temperature Structural Design," 1976.

[8] T.-L. Sham. "Historical Context and Perspective on Allowable Stresses and Design Parameters in ASME Section III, Division 5, Subsection HB, Subpart B," *Argonne National Laboratory*, ANL/AMD-21/1, 2021. https://www.nrc.gov/docs/ML2109/ML21090A033.pdf

[9] M. Sengupta and J.E. Nestell, "Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel," STP-NU-063, ASME Standards Technology, LLC, American Society of Mechanical Engineers, New York, NY (2013).

[10] R.W. Swindeman, D.L. Marriott, J.R. Foulds, "Extend Allowable Stress Values for Alloy 800H," STP-NU-035, ASME Standards Technology, LLC, American Society of Mechanical Engineers, New York, NY (2012).

[11] M.K. Booker and V.K. Sikka, "Interrelationships between Creep Life Criteria for Four Nuclear Structural Materials," *Nuclear Technology*, 30 no. 1, (1976): 52-64. https://doi.org/10.13182/NT76-A31623

[12] V. Sikka, "Effects of Thermal Aging on the Mechanical Properties of Type 316 Stainless Steel-Elevated Temperature Properties," *Oak Ridge National Laboratory*, ORNL/TM-8371, 1982. https://doi.org/10.2172/708800