INL/EXT-14-32811
Revision 0

Creep of A508/533 Pressure Vessel Steel

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ABSTRACT

Evaluation of potential Reactor Pressure Vessel (RPV) steels has been carried out as part of the pre-conceptual Very High Temperature Reactor (VHTR) design studies. These design studies have generally focused on American Society of Mechanical Engineers (ASME) Code status of the steels, temperature limits, and allowable stresses. Initially, three candidate materials were identified by this process: conventional light water reactor (LWR) RPV steels A508 and A533, 2¼Cr-1Mo in the annealed condition, and Grade 91 steel. The low strength of 2¼Cr-1Mo at elevated temperature has eliminated this steel from serious consideration as the VHTR RPV candidate material.

Discussions with the very few vendors that can potentially produce large forgings for nuclear pressure vessels indicate a strong preference for conventional LWR steels. This preference is based in part on extensive experience with forging these steels for nuclear components. It is also based on the inability to cast large ingots of the Grade 91 steel due to segregation during ingot solidification, thus restricting the possible mass of forging components and increasing the amount of welding required for completion of the RPV. Grade 91 steel is also prone to weld cracking and must be post-weld heat treated to ensure adequate high-temperature strength. There are also questions about the ability to produce, and very importantly, verify the through thickness properties of thick sections of Grade 91 material.

The availability of large components, ease of fabrication, and nuclear service experience with the A508 and A533 steels strongly favor their use in the RPV for the VHTR. Lowering the gas outlet temperature for the VHTR to 750°C from 950 to 1000°C, proposed in early concept studies, further strengthens the justification for this material selection. This steel is allowed in the ASME Boiler and Pressure Vessel Code for nuclear service up to 371°C (700°F); certain excursions above that temperature are allowed by Code Case N-499-2 (now incorporated as an appendix to Section III Division 5 of the Code).

This Code Case was developed with a rather sparse data set and focused primarily on rolled plate material (A533 specification). Confirmatory tests of creep behavior of both A508 and A533 are described here that are designed to extend the database in order to build higher confidence in ensuring the structural integrity of the VHTR RPV during off-normal conditions. A number of creep-rupture tests were carried out at temperatures above the 371°C (700°F) Code limit; longer term tests designed to evaluate minimum creep behavior are ongoing. A limited amount of rupture testing was also carried out on welded material. All of the rupture data from the current experiments is compared to historical values from the testing carried out to develop Code Case N-499-2. It is shown that the A508/533 basemetal tested here fits well with the rupture behavior reported from the historical testing. The presence of weldments significantly reduces the time to rupture. The primary purpose of this report is to summarize and record the experimental results in a single document.

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ACRONYMS

AOO	Anticipated Operational Occurrence
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AVR	Albeitsgemeinschaft Versuchsreaktor (German reactor)
BDBE	Beyond Design Basis Events
BPVC	Boiler and Pressure Vessel Code
CPD	Conceptual and Preliminary Design
DBE	Design Basis Events
DOE	Department of Energy
FSV	Fort St. Vrain
GA	General Atomics
GT-MHR	Gas Turbine-Modular Helium Reactor
HAZ	Heat Affected Zone
HPCC	High pressure conduction cooldown
HTGR	High-Temperature Gas Reactor
HTR	High-Temperature Reactor
HTR-10	High-Temperature Reactor (China)
INL	Idaho National Laboratory
LPCC	Low pressure conduction cool down
LWR	Light-Water Reactor
VHTR	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Helium Reactor
PBR	Pebble Bed Reactor
PBMR	Pebble Bed Modular Reactor (South Africa)
PCS	Primary Cooling System
PCU	Power Conversion Unit
PMR	Prismatic Modular Reactor
PWR	Pressurized Water Reactor
PWHT	Post Weld Heat Treatment
QA	Quality Assurance
R&D	Research and Development

RPV	Reactor Pressure Vessel
SAW	Submerged Arc Weld
SG	steam generator
SSR	Simulated Stress Relief
THTR	Thorium Hochtemperatur Reaktor (German reactor)
TRISO	Tri-isotopic (fuel)
VHTR	Very High-Temperature Reactor

Creep of A508/533 Pressure Vessel Steel

1. INTRODUCTION AND BACKGROUND

The U.S. Department of Energy (DOE) has supported a number of studies related to a Very High-Temperature Gas-cooled Reactor (VHTR) design.[1-15] The concept for this VHTR is to demonstrate the use of nuclear power for electricity, process heat, and hydrogen production. The reactor design under consideration is a graphite moderated, helium-cooled, prismatic or pebble bed, thermal neutron spectrum reactor. The VHTR would use very high burn-up, low-enriched uranium, Tri-Isotopic (TRISO)-coated fuel, and have a projected plant design service life of 60 years. This concept is considered to be the nearest-term reactor design that has the capability to efficiently produce hydrogen. The plant size, reactor thermal power, and core configuration will ensure passive decay heat removal without fuel damage or radioactive material releases during accidents. As discussed below these design considerations place a number of specific requirements on the properties of the steel used for the reactor vessel.

The basic technology for the VHTR was established in previous demonstration plants such as DRAGON, Peach Bottom, Albeitsgemeinschaft Versuchsreaktor (AVR), Thorium Hochtemperatur Reaktor (THTR), and Fort St. Vrain (FSV). These reactor designs represent two design categories: the Pebble Bed Reactor (PBR) and the Prismatic Modular Reactor (PMR). Commercial examples of potential VHTR candidates are the Gas Turbine-Modular Helium Reactor (GT-MHR) from General Atomics (GA), the high-temperature reactor concept (ANTARES) from AREVA, and the Pebble Bed Modular Reactor (PBMR) from the PBMR consortium. The Chinese High-Temperature Reactor (HTR-10) is currently in operation demonstrating the feasibility of some reactor components and materials needed for a VHTR.

The operating conditions for VHTR represent a major departure from existing water-cooled reactor technologies. Few choices exist for metallic alloys for use at VHTR conditions and the design lifetime considerations for the metallic components impact the maximum operating temperature. Qualification of materials for successful application at the high-temperature conditions and 60-year-design life planned for the VHTR is a large portion of the effort in the VHTR Materials Research and Development (R&D) Program. As it was initially envisioned the R&D plan had components that addressed materials issues for both the pressure vessel and heat exchanger, described in detail in the research and development plans PLN-2803 and PLN-2804, respectively.[16,17] The experiments described here were part of an extensive program detailed in PLN-2803. The focus of the VHTR Materials R&D Program has shifted primarily to the high temperature heat exchanger material Alloy 617 and activity on the pressure vessel materials issues has terminated. It is desirable, however, to capture the primary results of creep testing of RPV steels that has been completed in a single document.

Beyond the general assumptions listed above, PLN-2803 primarily addressed a baseline design case for the first US VHTR that incorporates the following most likely design features and conditions:

- An outlet gas temperature of 750°C
- The “cold” vessel option, meaning a cooled pressure vessel fabricated from conventional pressure vessel steels A508 Grade 3 Class 1 for forgings and A533 Grade B Class 1 for rolled plate (referred to as “A508/533” in this report)
- A steam generator
- Possibly a heat exchanger with He as both the primary and secondary coolant.

An acquisition plan, INL/EXT 08-13951, was developed for the RPV that considers, in detail, issues that have significant bearing on RPV technology development planning.[18] Principal among these issues are the large size and restricted availability of forgings for VHTR. The very large size of VHTR RPV components dictates that onsite fabrication will likely be necessary. It is also clear that the worldwide capability to produce very large forgings is limited. Direct experience with forgings of the size required for VHTR is restricted to conventional pressure vessel steels. Furthermore, limitations on forging capacity, even with these conventional steels, suggest that welded structures from rolled heavy plate must be considered. Availability and relatively mature fabrication technology dictated the choice of the A508/533 steel, rather than one of the possible higher alloy steel options. Table 1 lists detailed design parameters for three pre-conceptual designs considered by the US VHTR program along with values from the Fort St. Vrain demonstration plant for comparison.

Table 1. Key operating parameters for the VHTR designs and the Fort St. Vrain HTGR.

Condition or Feature	Fort St. Vrain HTGR	General Atomics GT-MHR	AREVA ANTARES	Westinghouse PBMR
Power Output [MW(t)]	842	550–600	565	500
Average power density (w/cm^3)	6.3	6.5	–	4.8
Moderator	Graphite	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular	Annular
Reactor type	Prismatic	Prismatic	Prismatic	Pebble Bed
Safety Design Philosophy	Active	Passive	Passive	Passive
Plant Design Life (Years)	30	60	60	60
Core outlet temperature (°C)	785	750	750	750
Core inlet temperature (°C)	406	322	325	280
Coolant Pressure (MPa)	4.8	7	5	9
Coolant Flow Rate (kg/s)	428	–	282	204
Secondary outlet temperature (°C)	538	540	550	700/541
Secondary inlet temperature (°C)	NA	200	–	267/217
Secondary Fluid	Steam	Steam	Steam	He, Steam
Secondary Coolant Flow Rate (kg/s)	–	–	141	204
RPV Material	Prestressed concrete	A 508/A 533	A 508/A 533	A 508/A 533
RPV Outside Diameter (m)		8.2*	7.5*	6.8
RPV Height (m)		31*	25*	30
RPV Thickness (mm)		281*	150*	>200
*Value based on preconceptual designs for 950°C gas outlet temperature.				

There is extensive use of A508/533 materials in LWR RPVs for application at about 290°C. As a result these pressure vessel steels provide the following specific benefits:

- The A508 Grade 3 Class 1 and A533 Class B Grade 1 materials are in the nuclear pressure vessel section of the ASME Code for temperatures less than 371°C.
- ASME design rules in the form of a nuclear code case for limited use of these materials are available in the temperature range of 371 to 538°C.

- There is manufacturing experience in forging large-diameter, thick-ring sections, thus ensuring predictable through-thickness material properties.
- There is welding experience with these materials.
- There is an extensive irradiation response database at the normal operating temperatures incorporated in the NRC licensing guidelines (NRC Regulatory Guide 1.99) and other international standards (American Society for Testing and Materials E 900).
- Although the VHTR RPV dimensions vary somewhat with the particular design, it is on the order of 20 m or more in height, 8 to 9 m in diameter and 200 to 300 mm thick. Vessels with this diameter present challenges for both fabrication and transportation to the reactor site. The likelihood of assembling the pressure vessel on site introduces potential technical difficulties. These issues are discussed in greater detail in the VHTR RPV Acquisition Strategy.[18]

1.1 Plant Transients

During normal operation it is anticipated that the VHTR RPV will stay below the 371°C (700°F) limit set by the ASME Code, however, there are circumstances where the vessel may experience short excursions above this temperature as discussed in the section. The plant transient definitions below are borrowed from the PBMR white paper on Licensing Basis Event (LBE) selection for the purposes of discussing various scenarios.[19] These definitions have not yet been endorsed by the NRC and formal definitions for a HTGR have not been determined, however, they are relevant for planning purposes. The frequencies of LBEs are expressed in units of events per plant-year where a plant is defined as a collection of up to eight reactor modules having certain shared systems.

An anticipated operational occurrence (AOO) encompasses planned and anticipated events. AOOs are used to set operating limits for normal operation modes and states. AOOs are event sequences with a mean frequency greater than 10^{-2} per plant-year. Startup/shutdown is an example of a relatively frequent AOO.

PBMR gives an AOO example as the loss of the power conversion system (PCS) where one of the active core heat removal systems works as specified. Since the heat is successfully removed from the core, this occurrence would have little impact on the RPV.

Design basis events (DBEs) encompass unplanned, off-normal events not expected in the plant's lifetime, but which might occur in the lifetimes of a fleet of plants. DBEs are the basis for the design, construction, and operation of the safety significant components (SSCs) during accidents. Separate from the design certification, DBEs are also evaluated in developing emergency planning measures. DBEs have event sequences with mean frequencies less than 10^{-2} per plant-year and greater than 10^{-4} per plant-year. Any of a number of small break scenarios in the helium pressure boundary are examples of DBEs given by PBMR.

It is likely that a loss of flow leading to a high pressure conduction cooldown (HPCC) and loss of coolant leading to a low pressure conduction cooldown (LPCC) will be defined as DBEs. The HPCC results in decay heat that is more uniformly distributed within the core and vessel than during an LPCC because the system remains at high pressure. The LPCC is typically initiated by a small leak of the primary coolant, resulting in depressurization and initiating a reactor trip. In both events, the shut-down cooling system fails to start and decay heat is removed passively by thermal radiation and natural convection from the reactor vessel. Peak temperatures for these events have been reported for the fuel, the control rods, and the RPV.[4] The calculated vessel temperature for this case is well above the 371°C normal operating condition. Higher vessel temperatures resulting from an LPCC may affect the properties of A508/A533.

1.2 ASME Code Considerations

The general requirements for Divisions 1 and 2 rules for construction of nuclear facility components are given in Section III, Subsection NCA of the ASME Boiler and Pressure Vessel Code (BPVC). Section III, Division 1 of the BPVC contains specific rules for the construction of different nuclear facility components. The VHTR RPV is a Class 1 component and the relevant rules of construction are covered under Subsections NB for operating temperatures below 371°C. The rules of construction in Subsection NB are based on the design-by-analysis approach in which detailed stress analysis is required to demonstrate that stress intensities through sections in the component do not exceed the allowable limits.

The design-by-Analysis approach requires categorizing stresses into primary (load controlled), secondary (displacement controlled), and peak (local stress elevation) stresses with different stress limits. Different stress limits are used for design conditions; operating conditions grouped into Service Level A (normal), B (upset), C (emergency), and D (faulted) events; and test conditions. The various stress limits are developed to guard against the structural failure modes of ductile rupture from short-term loading, gross distortion due to incremental collapse and ratcheting, loss of function due to excessive deformation, and buckling due to short-term loadings. Additional considerations in setting the stress limits are the consequence of failure and the probability of occurrence.

The design conditions include design pressure, design temperature, and design mechanical loads. Sizing of component dimensions is established by using the design conditions. The design temperature is the expected maximum mean metal temperature through the thickness of the part considered for which Level A (normal) service limits are specified. The maximum temperature limit permitted by Subsection NB for Class 1 components is 371°C (700°F) for ferritic steels. The values for the stress limit, S_m, for Subsection NB code materials are tabulated in Section II, Part D, Table 2A. The Subsection NB rules shall not be used for materials at metal and design temperatures that exceed the maximum temperature limits listed in the applicability columns of these tables. These maximum temperature limits are adopted to ensure that creep deformation is negligible and does not negatively impact the fatigue performance of a component.

Rules that govern the deterioration of material caused by service (e.g., corrosion) are not covered by Subsection NB. The owner is responsible to account for such effects. Procedures for calculating the effects of neutron irradiation embrittlement of the low-alloy steels in LWRs are provided in NRC Regulatory Guide 1.99.

The criteria for design-by-analysis for Class 1 components covered by Subsection NB is given in a separate document.[20] A detailed summary of the Subsection NB rules is given in the Companion Guide to the BPVC.[21] A recent overview of the Subsection NB rules is given in an NRC NUREG.[22] The significance of these rules to the VHTR reactor vendor is the need to limit the RPV design temperature, which bounds the maximum through-wall average metal temperature for Service Level A (normal) conditions, to a maximum of 371°C (700°F) in order to apply the Subsection NB rules to the RPV design.

If off-normal conditions occur Code Case N-499-2-2 was developed to provide rules of construction for two specific low-alloy steels: A533 (UNS K12539) and A508 forgings (UNS K12042) and their weldments for short-term temperature excursions above the temperature limit of 371°C (700°F). Only Level B (upset), C (emergency), and D (faulted) service events are allowed. Metal temperatures are limited to 427°C (800°F) during Level B events, and 538°C (1000°F) during Level C and D events. The total duration of such temperature excursions is limited to 3,000 hours in the temperature range of 371°C (700°F) to 427°C (800°F) and 1,000 hours in the range of 427°C (800°F) to 538°C (1000°F). The number of Level C and D events above 427°C (800°F) is limited to three. Even for these few cycles, hold time effects reduce design margin. The use of A533 plates and/or A508 forgings and their weldments as the RPV materials permits short-term off-normal temperature excursions above 371°C (700°F). This provides design flexibility in the RPV; material behavior described in Code Case N-499-2 governs design considerations during these excursions.

With the recent interest in HTGRs and Liquid Metal Reactors (LMRs), a new division, the Division 5, was formed within Section III to address the Code rule needs of these high-temperature reactors. Division 5 is responsible for the development of rules for the VHTR and the LMR. The rules of Division 5 constitute the requirements for materials, design, fabrication, examination, testing, inspection, overpressure protection, certification and stamping. Code Case N-499-2 has been officially superseded by a mandatory (Appendix HBB-I) to Division 5. Acknowledging that this is the case, it is convenient to continue to refer to Code Case N-499-2 in this report since the contents of Division 5 are still relatively little known in the design community and much of the historical data to which the current experiments are compared are described in the context of developing Code Case N-499-2.

1.3 Analysis of Existing Creep Data

The creep data that supported Code Case N-499-2 were mainly based on data from A533 rolled plates. Confirmatory tests are described here that are designed to extend the database in order to build higher confidence in ensuring the structural integrity of the VHTR RPV.

Current consideration of the "cold" vessel option by reactor vendors appears to be based on the logical assumption that if the temperature is within the bounds of Subsection NB (< 371°C for RPV materials) then creep effects do not need to be considered. While this is undoubtedly true for typical LWR operating temperatures, it may not be true for the higher VHTR operating temperature and a 60-year design life, and in particular, with the consideration of localized high stress areas. The reason is that creep deformation depends on stress, time, and temperature and does not have a distinct temperature cut-off that separates creep from non-creep regimes. This could potentially affect the primary stress limits and impact RPV sizing. The potential impact could also likely show up at structural or metallurgical discontinuities. If there is a real problem in the RPV due to creep effects, it is not likely to show up until the component is well into its operating life.

Such a concern was prompted by a recent statistical re-analysis of the A533 database reported in the data package that was used to support the development of Code Case N-499-2.[23,24] This database consists of 51 creep experiments from four heats of A533 plates, with temperatures ranging from 371°C to 593°C and applied stresses from 7 MPa to 517 MPa. Both rupture data and run-out data (where tests were stopped before rupture occurred) are contained in the database. The rupture data were less than 3,500 hours while one run-out datum at 482°C and 207 MPa reached ~11,500 hours and another at 593°C and 28 MPa reached ~26,000 hours. Only the rupture data were used in establishing the rupture stress and time-dependent primary stress limits for Code Case N-499-2 as the objective of the code case was to develop code rules for limited, short-term temperature excursions beyond the Subsection NB temperature limit of 371ºC.

The Code Case N-499-2 database is the only currently available data that could provide (limited) information in framing the issue of whether or not the consideration of creep is needed for the RPV in the VHTR design. A statistical methodology similar to that employed in analyzing the Alloy 617 and Alloy 230 creep data was used to re-analyze the Code Case N-499-2 creep data.[25] This method allows the inclusion of run-out data in the statistical analysis, and hence makes full use of the information from the database. Best estimate and 95% confidence limit lower bounds were developed for stress to one-percent strain, stress to onset of tertiary creep, and stress to rupture. Extrapolations to 100,000 hours, 300,000 hours, and 600,000 hours in the temperature range of 340°C to 390°C were made. The Subsection NH procedure for establishing the time-dependent primary stress limit S_t was used and the results are shown in Figure 1 and Figure 2. The Subsection NB time-independent primary stress limit S_m is also included in these two figures for reference.

It should be noted that sizing methods in Subsections NB and NH are somewhat different. In Subsection NB, the wall thickness is based on the design condition while Subsection NH uses both design condition (based on 100,000-hour allowables as in Section VIII) and operating conditions. Further, in Subsection NB the limit on P_m is S_m and on $P_L + P_b$ is 1.5 S_m, while in Subsection NH the limit on P_m is

S_{mt}, and on $P_L + P_b$ is 1.5 S_m, and in addition, the limit on $P_L + (P_b/1.25)$ is S_t. Since the Subsection NH limit of S_{mt} is the lesser of S_m and S_t, the limits on the general membrane stress intensity P_m from Subsections NB and NH can be compared by considering the relative magnitudes of S_m and S_t.

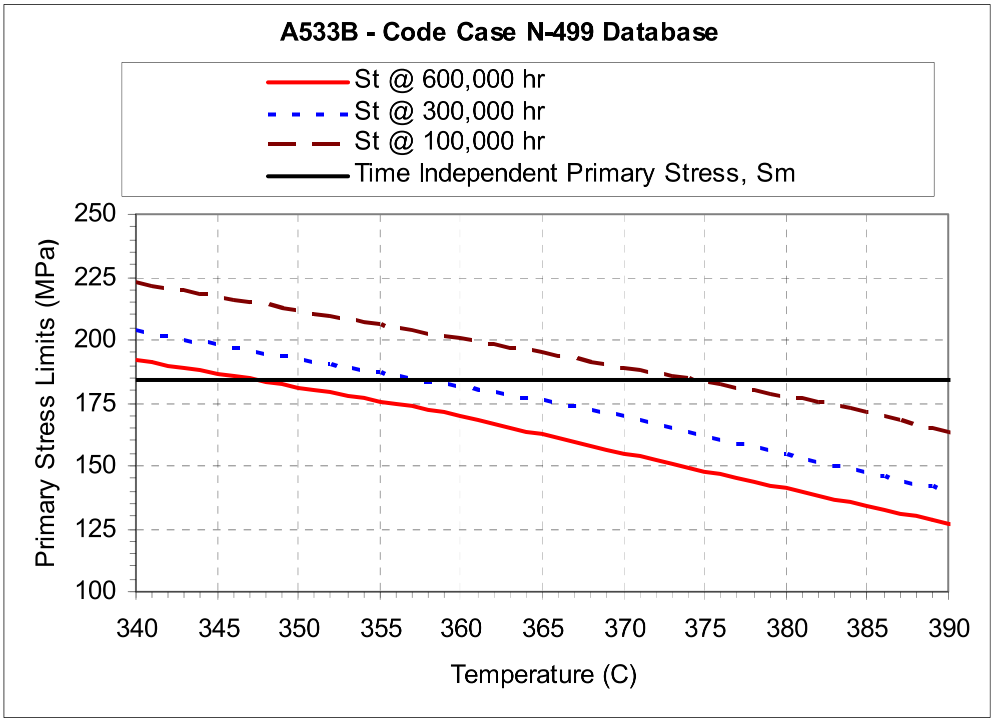

Figure 1. Extrapolated time-dependent primary stress limits for A533B rolled plate.

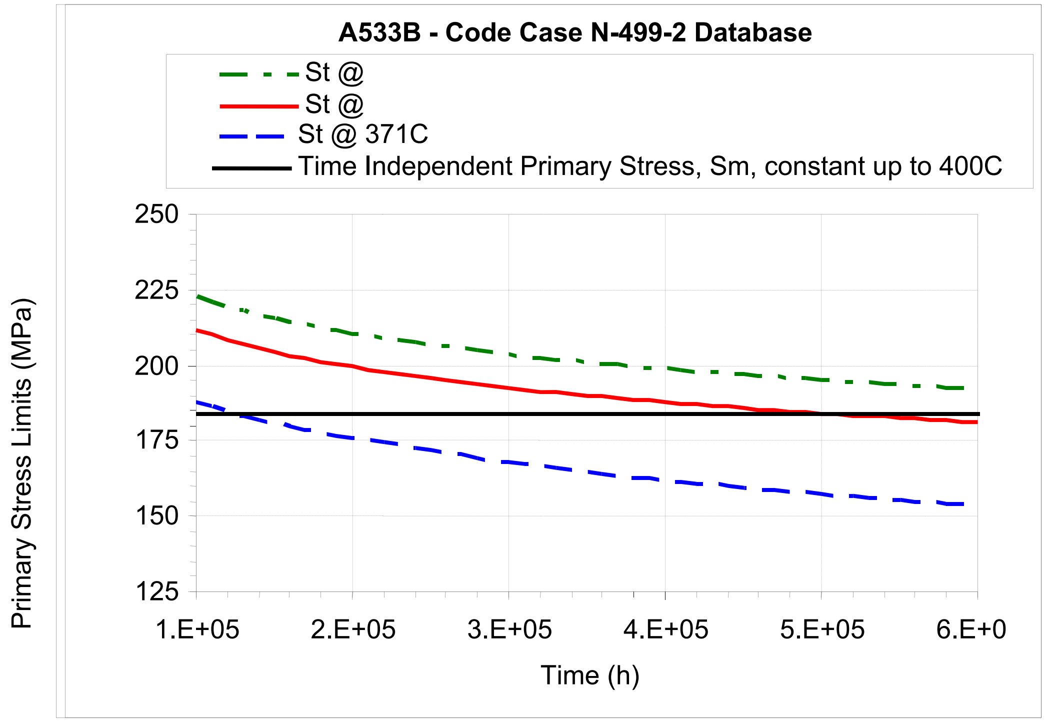

Figure 2. Extrapolated time-dependent primary stress limits for A533B at 340°C, 350°C, and 371°C.

The extrapolated results in the plots show that the time-independent primary stress limit S_m is lower, and hence more conservative, than the time-dependent primary stress limit S_t for times below 500,000 hours at 350°C, and slightly non-conservative relative to S_t for times between 500,000 and 600,000 hours. For a temperature of 340°C, the extrapolated values of S_t are higher than those for S_m in the range of time considered; hence, the use of S_m is conservative for at least up to 600,000 hours. At the Subsection NB cut-off temperature of 371°C, S_m is non-conservative for lifetimes beyond ~125,000 hours.

Figure 3 shows the extrapolated lower bound creep rupture stress at 340°C, 350°C, and 371°C as a function of time. One of the negligible creep criteria in Subsection NH, Article T-1324 is:

$$\sum_i \frac{t_i}{t_{id}} \le 0.1$$

where t_i is total duration of time during the service lifetime that the metal is at temperature T_i and t_{id} is the rupture time given by the lower bound rupture stress that is equal to $\left.S_y\right)_{T_i}$, the minimum yield strength at temperature T_i, multiplied by a factor s which is equal to 1.5. The factor s is based on a factor of 1.25 to bring the minimum yield strength at temperature to the average value and a factor of 1.2 to account for cyclic hardening of austenitic stainless steel in order to approximate the achievable stress state at geometric discontinuities.

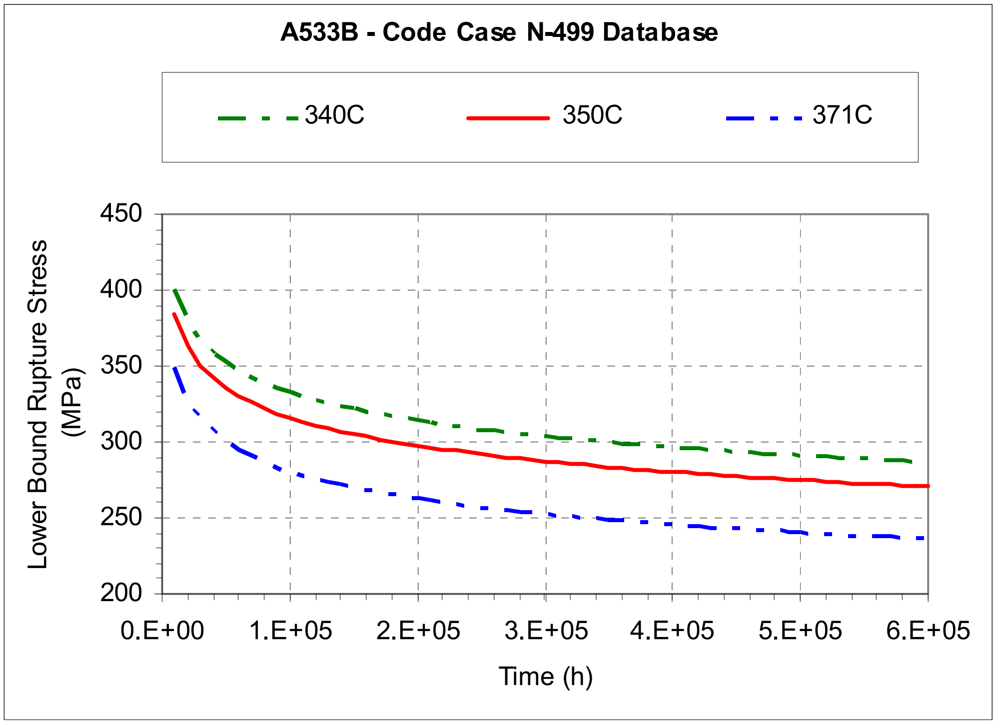

Figure 3. Extrapolated lower bound creep rupture stress for A 533B at 340°C, 350°C, and 371°C.

The lower bound rupture stress that is required to evaluate the rupture time t_{id} in the negligible creep criterion as a function of the factor s is tabulated in Table 2. It is seen from Table 2 and the curves in Figure 3 that the rupture time t_{id} obtained from the rupture stresses given in Table 2 would not satisfy the negligible creep criterion of Subsection NH for t_i equal to 60 years.

Table 2. Lower bound rupture stress given by factor s multiplied by $\left.S_y\right)_{T_i}$.

Factor s	Lower Bound Rupture Stress to Determine t_{id} (MPa)		
	340°C	350°C	371°C
1	287	285	281
1.25	358	356	351
1.5	430	428	421

It is noted that the current re-analysis of the Code Case N-499-2 database gives values of lower bound creep rupture stress at 371°C that are much lower than those given in Code Case N-499-2-2 for the expected minimum rupture stress. The comparison is shown in Table 3. An inspection of the Code Case N-499-2 database showed two experimental rupture stresses for approximately 1,000 hour rupture life (shown in Table 4), both of which are below the rupture stress prediction currently in Code Case N-499-2.

Table 3. Comparison of rupture stress predictions from Code Case N-499-2-2 and statistical re-analysis.

Time to Rupture (h)	Code Case N-499-2-2 (Table 4)		Statistical Re-analysis	
	Rupture Stress at 371°C (ksi)	Rupture Stress at 371°C (MPa)	Rupture Stress at 371°C (ksi)	Rupture Stress at 371°C (MPa)
1,000	77	531	62	425
10,000	70	483	51	349

Table 4. Rupture data at 371ºC from Code Case N-499-2 database.

Heat No.	Measured Creep Rupture Time (h)	Applied Stress at 371°C	
		ksi	MPa
5795	956	65	448
9583A	1004	75	517

It is concluded from the results shown in these two tables that the values of the creep rupture stress given in Code Case N-499-2-2 are non-conservative relative to the rupture data at 371°C, and the results from the statistical re-analysis give adequately conservative lower bounds to the rupture data. This provides a level of confidence in the results presented in Figure 1 to Figure 3 from the statistical re-analysis. As the emphasis of Code Case N-499-2 was on creep-fatigue rules at higher temperatures, it could very well be that the discrepancy at the lower temperatures was over looked.

To put the results presented in Figure 1 to Figure 3 into perspective, it is well to recognize that the extrapolations are based on a small database with relatively short-term creep data as compared with the extrapolated times of 500,000 to 600,000 hours. Thus definitive conclusions could not be drawn based on these results. However, the results shown in these figures do underscore the need to develop additional and longer-term confirmatory creep-rupture data, and to follow-up on the creep-fatigue issue to ensure that creep effects are properly accounted for in design for very long operating lives.

2. CURRENT TESTING PROGRAM

In light of the above discussion on uncertainty of the Code treatment of creep properties, the areas that need particular attention for A508/533 steels and their weldments for VHTR RPV application are creep-rupture and creep-fatigue damage, which is closely related to the definition of when creep effects become significant. The test plan for creep and creep-rupture testing of A508/533 RPV steel is presented in this section.

Approximately 1400 kg of A508/533 178-mm-thick steel plate was procured for material testing from the Industeel France Division of Arcelor Mittal, manufactured at the Chateauneuf Plant. The material has been both forged and rolled during its processing, resulting in dual certification as ASTM A508 Grade 3 Class 1 and ASME SA533 Grade B Class 1. The chemistry of this heat and the compositions called for by the specifications is shown in Table 5.

Table 5. Composition of the heat of steel obtained from Industeel and the values in specifications A508 and A533.

Spec.	C	Si	Cr	Cu	S	V	Ti	Ca	Mn	Ni	Mo	Al	P	Nb	B
A508 Req.	≤0.25	≤0.40	≤0.25	≤0.20	<0.025	≤0.05	≤0.015	≤0.015	1.2-1.5	0.4-1.0	0.45-0.60	≥0.025	≤0.025	<0.01	≤0.003
A533B Req.	≤0.25	0.15-0.40	≤0.30	≤0.40	≤0.035	≤0.03	≤0.03	-	1.15-1.5	0.4-0.70	0.45-0.60	≥0.02	≤0.035	≤0.02	-
Actual	0.18	0.22	0.18	0.11	0.001	0.002	0.002	0.0001	1.43	0.62	0.51	0.025	0.006	0.001	0.0002

During construction of a RPV, stress relief heat treatments are typically applied after welding the conventional pressure vessel steels to produce a stress relieved state before operation. In order to develop property data, the practice called for in the specifications is to select a time that would bound the total stress relief time, and subject the as-received RPV material to a “simulated” stress relief (SSR) heat treatment. Any degradation such as thermal aging or irradiation embrittlement occur subsequent to this stress relief treatment; therefore, SSR will be applied to all A508/533 material before specimens are machined. This will ensure that the properties measured are appropriate for RPV applications.

In order to determine the specific SSR ASME rules on welding were considered. In accordance with the ASME III NB requirements (Table NB-4622.1-1) summarized in Table 6, all RPV welds are to receive a post-weld heat treatment with a holding time commensurate with the thickness. Assuming the RPV plate will be 178 mm (7.128 in) thick, a post-weld heat treat time of 3.28 hours is required based on this table. Allowing for 6 cycles of post-weld heat treatment, the SSR has been set at 607 ± 13°C (~1125°F) for a total of 19 hours, 40 minutes. The ASME Code also limits the rate of heating and cooling above 425°C to no more than 220÷plate thickness °C/hr., but not less than 56°C/hr. The SSR treatment used here maintained an average of 66°C /hour during heating and 77°C/hour during cooling.

Table 6. Mandatory post-weld heat treatment according to ASME Table NB-4622.1-1.

	Minimal holding time for nominal section thickness (t, inches)		
Temperature Range (°F)	≤½	½ < t ≤ 2	2 < t ≤ 5
1100–1250	30 minutes	1 hour/inch	2 hours + 15 minutes/inch over 2 inches

As discussed in Section 1.3 the Code Case N-499-2 database does not provide adequate creep rupture data to address the issue of whether or not creep effects for the RPV need to be considered under a normal operating temperature of 350ºC. Longer-term creep rupture data are needed and testing was carried out to address this issue. In addition to plate and forgings, the issue of adequate creep rupture data is particularly problematic for weldments. As a result, ASME qualified submerged-arc welds were produced by a vendor for creep testing in parallel with the basemetal characterization. Details of the welding procedure are given in Appendix A as carried out by Precision Custom Components.

Testing was carried out at test temperatures of 350, 371, and 390°C, to cover the normal operating temperature of 350°C, and to provide some acceleration of the creep process. All testing was done in laboratory air. The single heat of basemetal was tested; the welds to be tested are cross-welds and creep test specimens were machined from thick section welds. The longest average creep rupture time in the test plan was estimated to be about two years. This estimation was based on the best estimate statistical correlation (i.e., without accounting for data scatter) developed from the Code Case N-499-2 database, as discussed above.

Longer-term creep rupture tests in air were also carried out; 5-year data are targeted for these tests at 350°C. The temperature and applied stress combinations were selected based on the best estimate of the statistical model developed from the Code Case N-499-2 database. The five-year data will be used to check the adequacy of the extrapolation based on the statistical analysis of the shorter-term data. This is to support final design/licensing.

As described in Section 1.3 data that supported Code Case N-499-2 were from A533 rolled steel. However, the intersection point of the creep-fatigue damage interaction diagram was not determined using A508/533 and associated weldment creep-fatigue data. Thus, in order to address these database issues, short-term creep rupture tests that cover the applicable durations of the code case for A508 base metal and weldment were called for. Test temperatures are 350, 371, 427, 482, 538, and 593°C, selected to match the Code Case N-499-2 database.

Finally, limited cyclic temperature excursions above the subsection NB cut-off temperature of 371°C but within the time-and-temperature restrictions of Code Case N-499-2 could occur. Creep specimens in the SSR condition were given a “damage” treatment by subjecting the specimen to strain-controlled cycling, with a tensile strain hold of up to 30 minutes, for 180 cycles at 427°C. Since the stress relaxes during the strain hold, this form of cycling is called fatigue-stress relaxation. Creep rupture tests were then performed on the “damaged” specimens. This is considered to be a very aggressive accelerated test protocol.

3. RESULTS AND DISCUSSION

A simulated stress relief heat treatment was performed on the A508/533 plate prior to mechanical testing. Two sections of material approximately 25 mm in thickness were taken from the as-received plate centered on a location of ¼ thickness from each surface as specified by the ASME Code. The heat treatment was 607 ± 13°C (~1125°F) for a total of 19 hours and 40 minutes. The ASME code also limits the rate of heating and cooling above 425°C to no more than 220÷plate thickness °C/hour, but not less than 56°C/hour. The SSR treatment average selected 66°C /hour during heating and 77°C/hour during cooling. The microstructure of the plate following SSR is shown in Figures 4 and 5. It consisted of a fine Bainitic structure; there were some regions of locally higher carbide density within the Bainitic microstructure that appear to be associated with banding within the plate resulting from the initial ingot solidification.

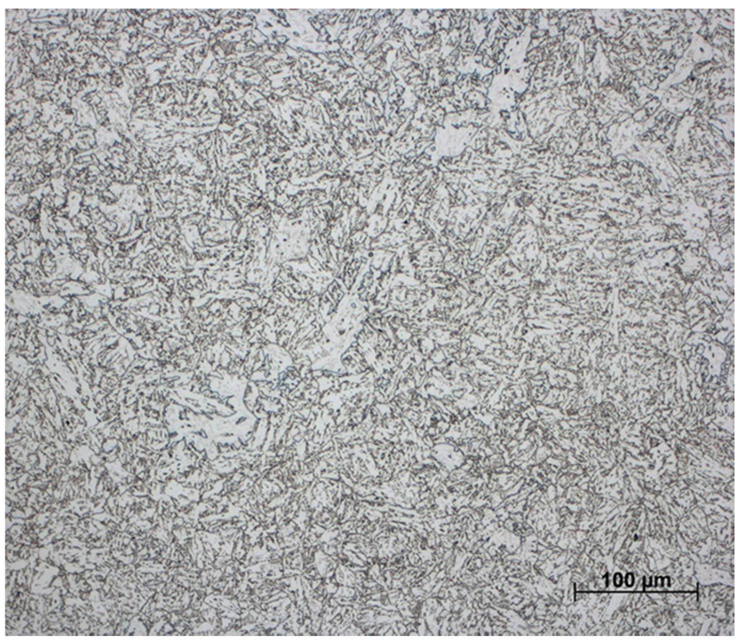

Figure 4. Bainitic microstructure after simulated post-weld heat treatment.

The tensile properties of the steel were characterized as a function of temperature after SSR to aid in establishing the creep rupture stresses. The yield and tensile strength are shown in Figure 6 for tests temperatures from ambient to 550°C for two tests at each temperature and the corresponding ductility is shown in Figure 7. Note that comparison values were not available in this temperature range from the literature since the majority of application of this steel for LWR applications is for A533 steel up to about 320°C. In Figure 6 a comparison is presented between the experimental values from the current testing and the ASME Code allowables up to 371°C; the allowable values are designed to show conservative lower bound values for the yield strength and average tensile strength values.

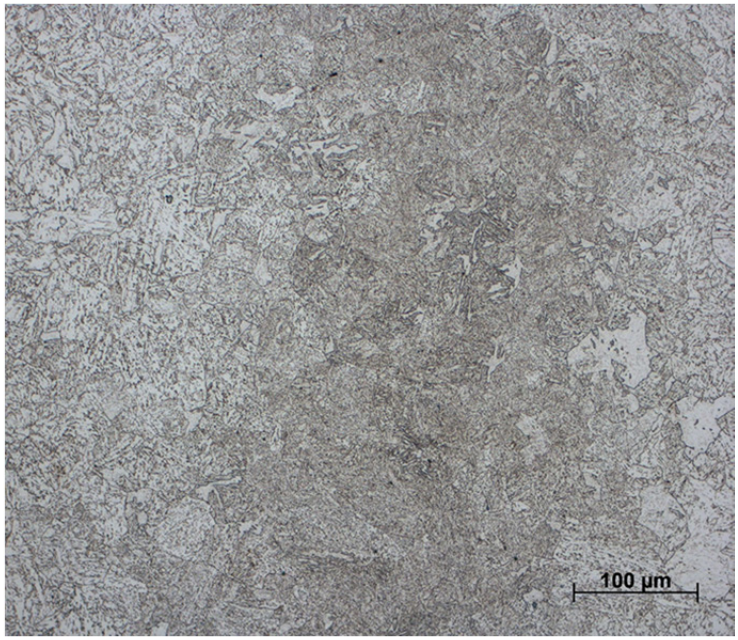

Figure 5. Region of locally higher carbide density in the Bainitic microstructure after simulated post-weld heat treatment.

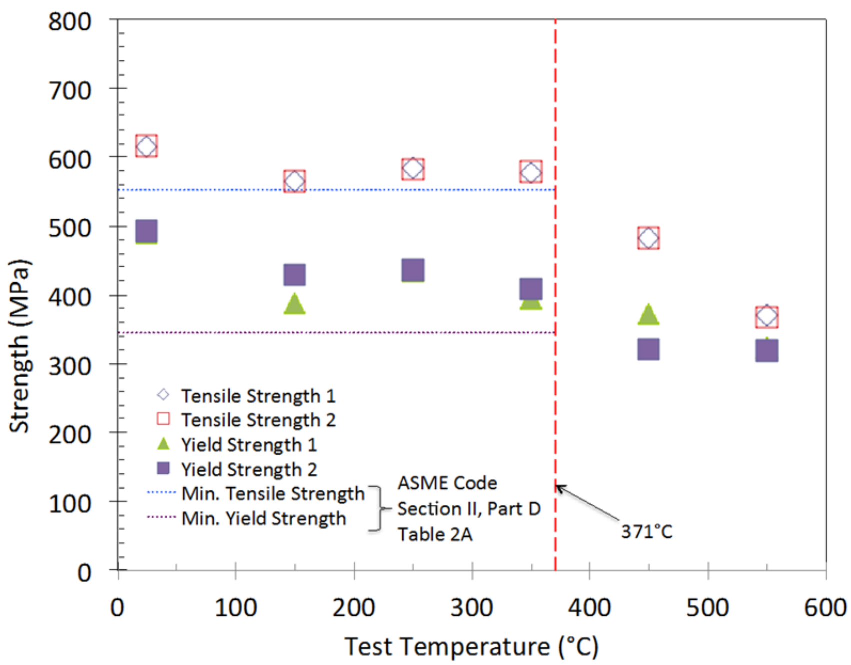

Figure 6. Yield and tensile strength of A508/533 steel after SSR as a function of test temperature; a comparison is shown between the experimental values and the ASME Code allowable values up to 371°C.

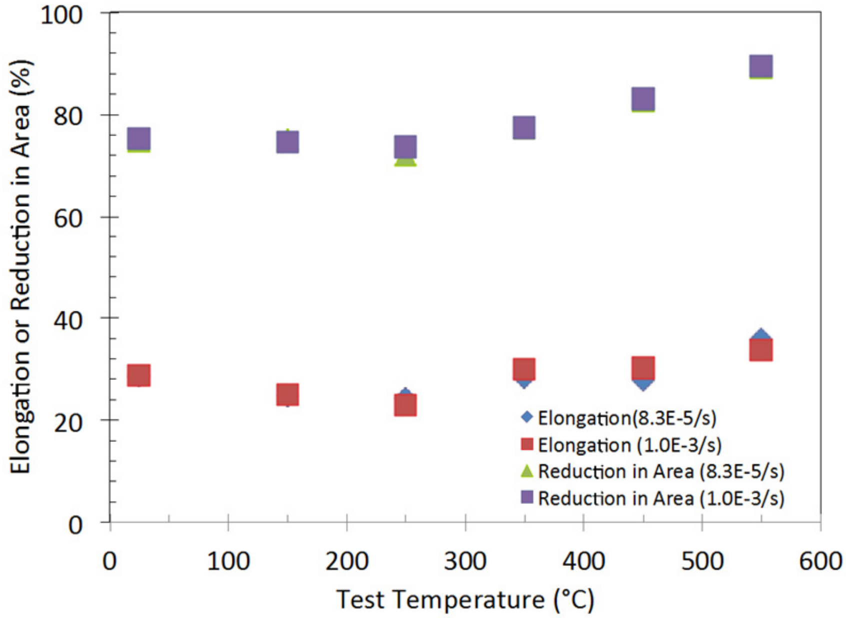

Figure 7. Elongation and reduction in area from tensile tests of A508/533 steel after SSR.

3.1 Creep-Rupture Characterization

Short term creep-rupture testing was carried out at two vendor laboratories, Wesmoreland and Dirats. Both vendors were qualified by INL to perform ASME NQA 1 testing. Exemplary curves are shown in Figure 8 for steel tested in the SSR condition at 371°C and two different stresses. It can be seen from the figure that for these test conditions there is little or no secondary or steady state creep observed. Reasonable reproducibility between replicate tests is also evident. A complete set of stress-rupture curves for all of the testing that was carried out in the current experiments is provided in Appendix B.

Creep-rupture data are frequently normalized for time, temperature and stress using the Larson-Miller equation. The rupture data generated in the current testing program (and contained in Appendix B) are shown in Figure 10 along with the data from four heats of A533 steel that were measured at ORNL and used to develop Code Case N-499-2. Data from the current testing program for the dual certified A508/533 steel are very similar to those from the historical A 533 testing. The Larson-Miller coefficient is frequently assumed to be 20, as is done for the data shown in Figure 10. This value was used to develop the plot because that value was used in the original analysis.[24] As discussed below, this coefficient can be different from 20 if a regression fit is applied to the experimental values.

The standard method of analyzing creep-rupture data for ASME Code applications is to use a calculation package developed by Swindeman. This analysis used the data from individual lots of material and applies a polynomial equation to determine a best fit Larson-Miller equation. Analysis of the two sets of test data for the A508/533 plate determined in this program along with data from the historical ORNL testing program have been analyzed using the Swindeman fitting program and the results are shown in Figure 11. The best fit to the rupture data was obtained with a third order polynomial equation and a coefficient of 19.1 rather than the value of 20 that is frequently assumed and used for Code Case N-499-2.

Figure 11 also shows the creep-rupture behavior of weldments tested in the current program. It can be seen from the limited amount of testing in this program that in general the rupture behavior of weldments is inferior to basemetal tested over a similar range of temperature and stress. Note that the Larson-Miller parameter determined using the third order polynomial fit was 19.1 for the A508/533 steel was the same regardless of whether the rupture data for weldments were included along with the basemetal data.

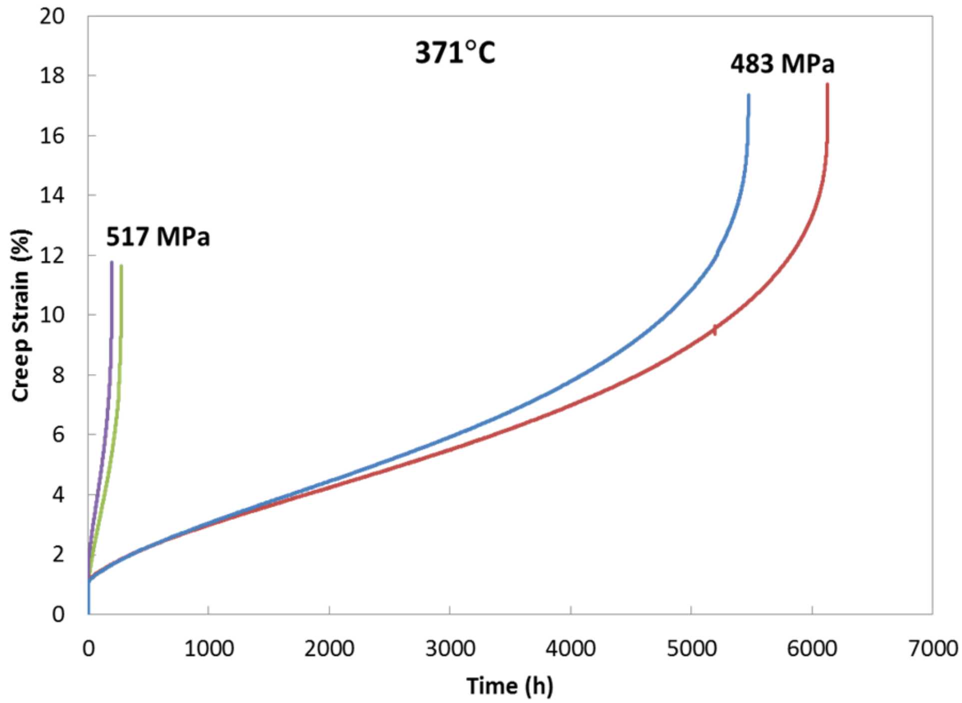

Figure 8. Creep-rupture curves for A508/533 steel in the SSR condition for two stresses at 371°C.

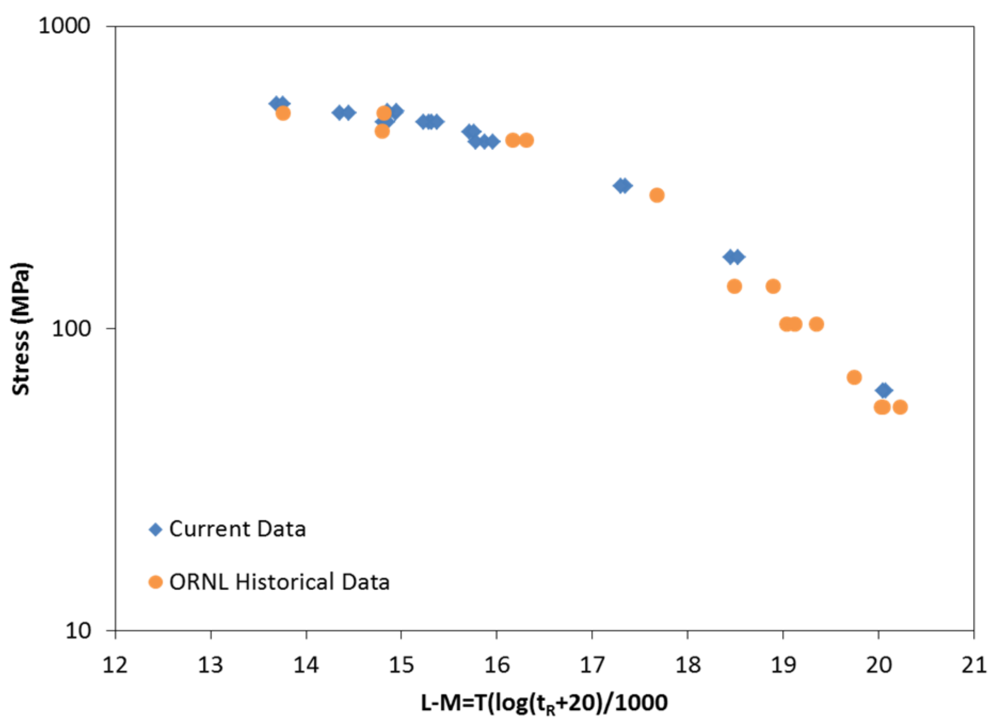

Figure 9. Larson-Miller plot of creep-rupture data from the current test program and from the historical data base that were used in the development of ASME Code Case N-499-2.

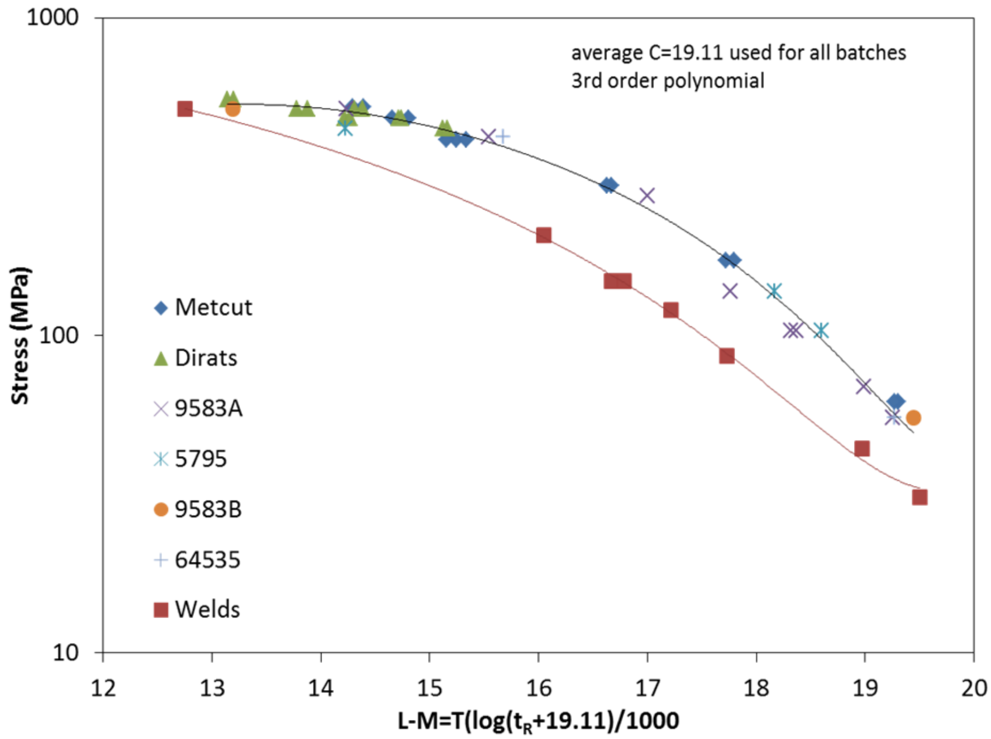

Figure 10. Larson-Miller plot for RPV steel plate and weldments developed using the ASME analysis method.

3.2 Long Term Confirmatory Testing

In addition to the creep-rupture tests, there are several long term creep tests running to aid in evaluating the negligible creep analysis in Subsection NH of the Code. These tests are planned to run for a minimum of five years and are being carried out at INL. Testing has been underway on these samples for approximately three years. The creep curves for the testing to date are shown in Figure 9; all of these tests are continuing. The total creep strain accumulated to date is only approximately 4%, while the strain to rupture is a minimum of 20% and so it is likely that these tests will continue well past the desired five year time frame.

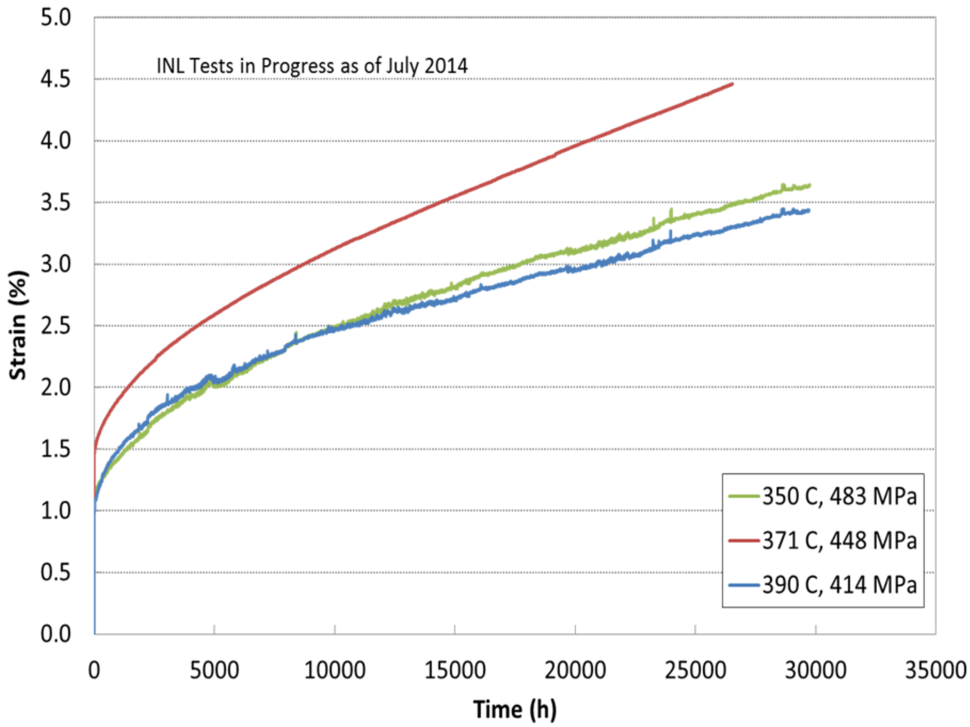

Figure 11. Creep curves for long term confirmatory minimum creep rate tests. Data in the figure represent creep strain to date; all of the tests are continuing.

3.3 Creep-Rupture of Cyclic Damaged Specimens

To simulate potential for damage to the RPV from cycling to above normal operating conditions in addition to time-at-temperature creep specimens in the SSR condition were given a "damage" treatment by subjecting the specimen to strain-controlled fatigue cycling, with a tensile strain hold of 1000 minutes, for 180 cycles at 427°C. This will accumulate creep-fatigue damage for about 3000 hours. Since the stress relaxes during the strain hold, this form of cycling is called fatigue-stress relaxation. Creep rupture tests were then performed on the "damaged" specimens. The time to rupture results subsequent to this damage treatment are shown as a function of hold time at 427°C in Figure 12 for three creep test temperatures. Note that several of the rupture tests for the longest tensile hold time during cyclic treatment failed on loading.

Cyclic damage without a hold time was found to reduce the creep-rupture life for tests at the lower test temperatures compared to specimens tested to rupture in the SSR condition. It was found that increasing the hold time during the tensile hold period of cyclic testing dramatically reduced the resulting creep-rupture life. The standard ASME method of creep-fatigue analysis is a time fraction approach, where the time spent during the tensile hold can be referred to a fraction of the creep-rupture life. Since the stress relaxation of A508/533 steel is limited at the 427°C creep-fatigue pre-treatment temperature there can be a substantial amount of the potential rupture life that is exhausted during the cyclic pre-damage phase. Thus the reduced rupture life following long hold time creep-fatigue is consistent in a qualitative way with the time fraction methodology.

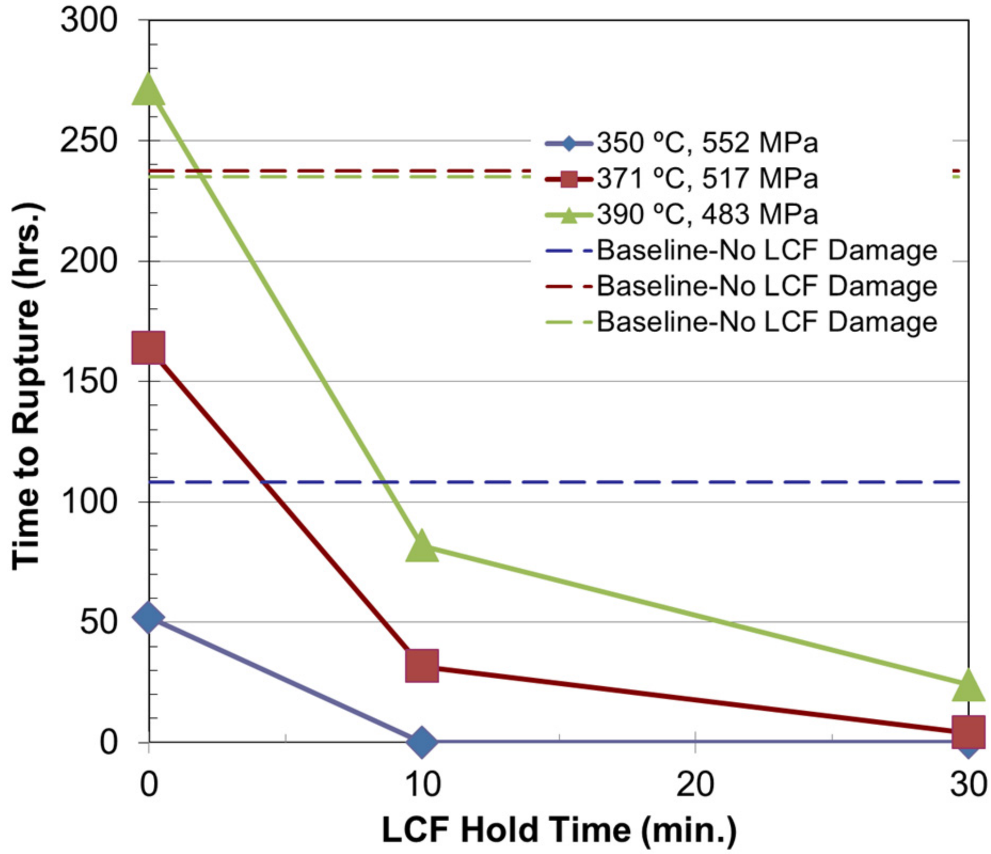

Figure 12. Time to rupture for A508/533 steel tested after prior damage accumulation from cyclic loading or cyclic loading with a tensile hold time.

4. CONCLUSIONS

For the creep conditions examined in this study there is little or no secondary or steady state creep observed for A508/533 steel in the SSR condition. Reasonable reproducibility between replicate tests is also evident. Analysis of the two sets of test data for the A508/533 plate determined in this program along with data from the historical ORNL testing program have been analyzed using the Swindeman fitting program. Contemporary data and the ORNL results used to develop Code Case N-499-2 align along the same curve. The best fit to the rupture data was obtained with a third order polynomial equation and a coefficient of 19.1 rather than the value of 20 that is frequently assumed and used for Code Case N-499-2. The presence of a weldment in the creep-rupture specimen significantly reduces the rupture life.

In addition to the creep-rupture tests, several long term creep tests are underway to aid in evaluating the negligible creep analysis in Subsection NH of the Code. These tests are planned to run for a minimum of five years and are being carried out at INL. Testing has been underway on these samples for approximately three years; all of these tests are continuing. The total creep strain accumulated to date is only approximately 4%, while the strain to rupture is a minimum of 20% and so it is likely that these tests will continue well past the desired five year time frame.

Cyclic damage without a hold time was found to reduce the creep-rupture life for tests at the lower test temperatures compared to specimens tested to rupture in the SSR condition. It was found that increasing the hold time during the tensile hold period of cyclic testing dramatically reduced the resulting creep-rupture life. The standard ASME method of creep-fatigue analysis is a time fraction approach, where the time spent during the tensile hold can be referred to a fraction of the creep-rupture life. Since the stress relaxation of A508/533 steel is limited at the 427°C creep-fatigue pre-treatment temperature a substantial amount of the potential rupture life can be exhausted during the cyclic pre-damage phase. Thus the reduced rupture life following long hold time creep-fatigue is consistent in a qualitative way with the time fraction methodology.

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Appendix A

ASME Section IX Weld Procedure

PRECISION CUSTOM COMPONENTS, LLC
WELDING PROCEDURE SPECIFICATION
ASME SECTION IX

TITLE : SAW & FCAW Welding of P3 to P3 / Stress Relieved Applications

WPS NUMBER : SW-63-004 **DATE :** 10/7/06 **SUPPORTING PQRs** 935-635

REVISION : --- **DATE :** 10/7/06

BY : Michael Bunnell

PROCESS (ES) : SAW, FCAW **TYPE (S) :** Machine, Semi-Auto

JOINTS (QW-402)

JOINT DESIGN : Grooves, Fillets, and Repairs as specified by manufacturing documents.

BACKING : Required, Compatible carbon steel base material or weld metal

OTHER :

BASE METALS (QW-403)

P- NO. 3 **GROUP-NO.** All **TO** **P-NO.** 3 **GROUP-NO.** All

-OR-

SPECIFICATION N/A

to SPECIFICATION N/A

THICKNESS RANGE

BASE METAL : **GROOVE:** 3/16" - 10.64" **FILLET:** Unlimited

PIPE DIA. RANGE : **GROOVE:** Unlimited **FILLET:** Unlimited

OTHER: N/A

FILLER METALS (QW-404)

SPECIFICATION NO. (SFA)	5.29		5.17	
CLASSIFICATION	E81T1-Ni1		EM14K	
F NUMBER	6		6	
A NUMBER	None		None	
SIZE (s)	1/16"		5/32"	
WELD METAL (Thickness)				
GROOVE	8" Maximum		8" Maximum	
FILLET	Unlimited		Unlimited	
ELECTRODE - FLUX (CLASS.)	N/A		N/A	
FLUX TRADE NAME	N/A		ESAB OK 10.71	
OTHER	Flux Cored wire only, No supplemental filler or powder additions.		Solid wire only, No supplemental fillers, No re-crushed slag	

Page 1 of 2

PRECISION CUSTOM COMPONENTS, LLC
WELDING PROCEDURE SPECIFICATION
ASME SECTION IX

TITLE : SAW & FCAW Welding of P3 to P3 / Stress Relieved Applications

WPS NUMBER : SW-63-004 **DATE :** 10/7/06 **REV.:** ---

POSITIONS (QW-405)

POSITION (s) OF GROOVE FCAW 1&2, SAW 1G
POSITION (s) OF FILLET FCAW 1&2, SAW 1F
PROGRESSION Up for vertical welding

POSTWELD HEAT TREATMENT (QW-407)

TEMPERATURE RANGE 1150°F. +/- 50°F
TIME RANGE 8 Hours Maximum

PREHEAT (QW-406)

PREHEAT TEMP. MIN. 100°F. Minimum
INTERPASS TEMP. MAX. 500°F. Maximum
PREHEAT MAINTENANCE N/A

GAS (QW-408)

	PERCENT COMPOSITION		
SHIELDING	**GASES**	**MIXTURE**	**FLOW RATE**
FCAW	Ar - CO2	75%-25%	35 CFH Minimum
GTAW	N/A		
BACKING	N/A		
OTHER	N/A		
OTHER	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

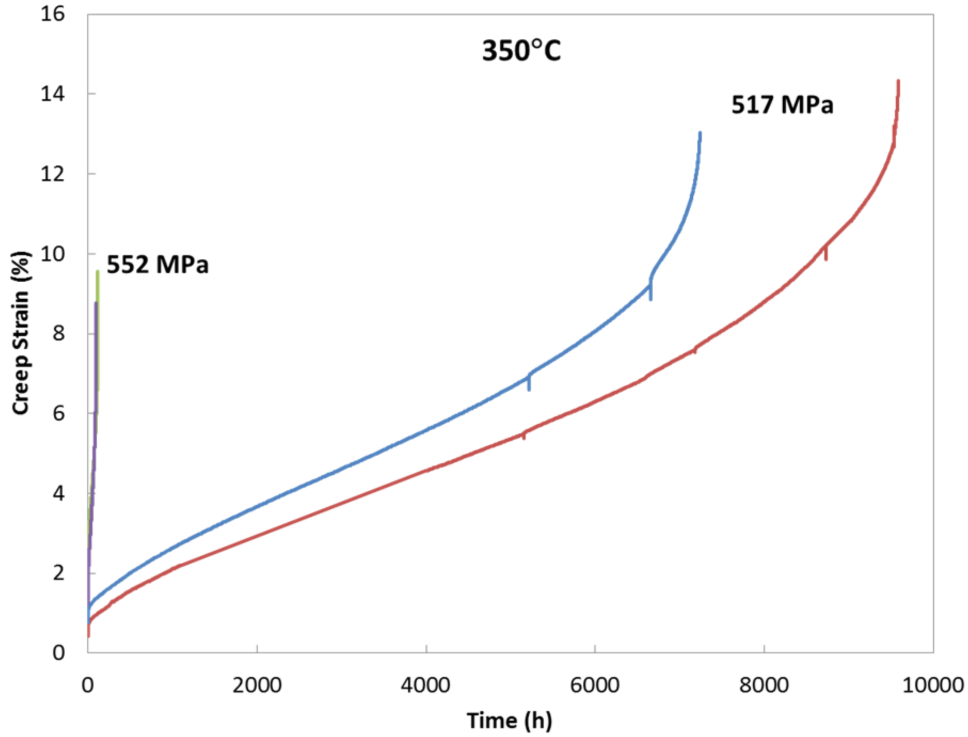
CURRENT (AC OR DC) DC **POLARITY** Reverse
AMPERAGE RANGE See Below **VOLTAGE RANGE** See below
TUNGSTEN TYPE (GTAW) N/A **DIAMETER :** N/A
MODE of TRANSFER (GMAW/FCAW) Globular to Spray
ELECTRODE WIRE FEED SPEED RANGE Wire feed speed controlled by amperage setting

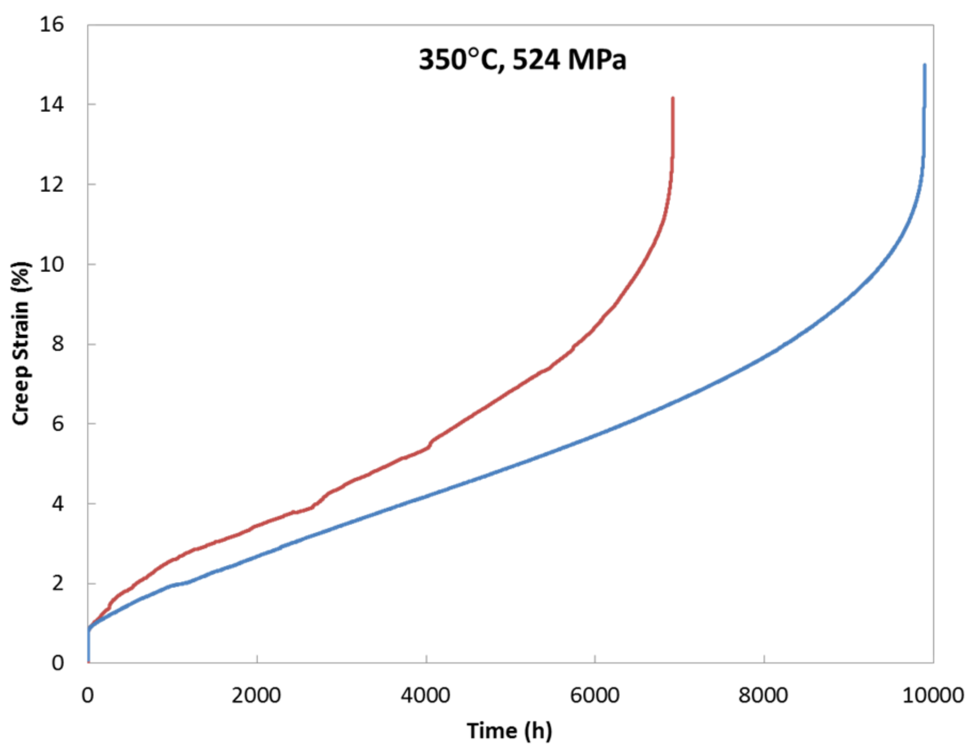
TECHNIQUE (QW-410)

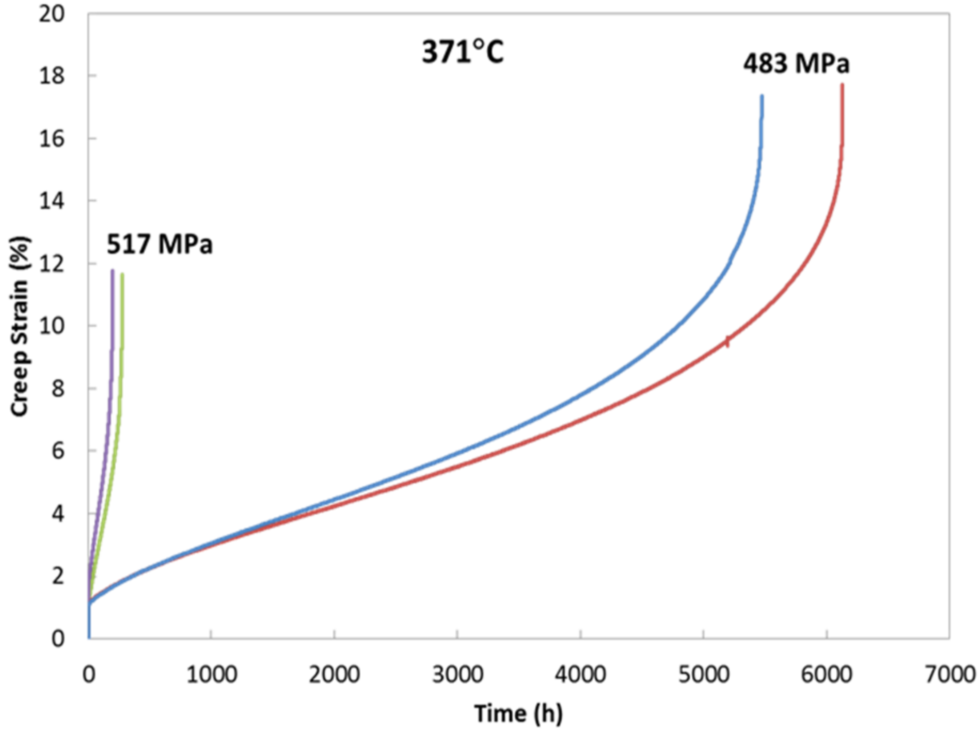
STRINGER OR WEAVE BEAD	FCAW = Stringer or weave, SAW = Stringer only
ORIFICE OR GAS CUP SIZE	FCAW = 1/2" ID Minimum
INITIAL & INTERPASS CLEANING	Grind and or wire brush. Acetone or Alcohol / Water wipe as necessary
METHOD OF BACKGOUGING	Arc gouge, grind, and or machine. Grind to bright metal following air arcing
OSCILLATION	None
CONTACT TUBE TO WORK DISTANCE	FCAW = 1/2" - 1", SAW = 3/4" - 1 1/2", Flux Depth 3/4" - 1 1/2"
MULTIPLE or SINGLE PASS (per side)	Single or multiple, No single pass to exceed 1/2" in thickness
MULTIPLE or SINGLE ELECTRODES	Single
TRAVEL SPEED RANGE	See Below
PEENING	None
OTHER	N/A

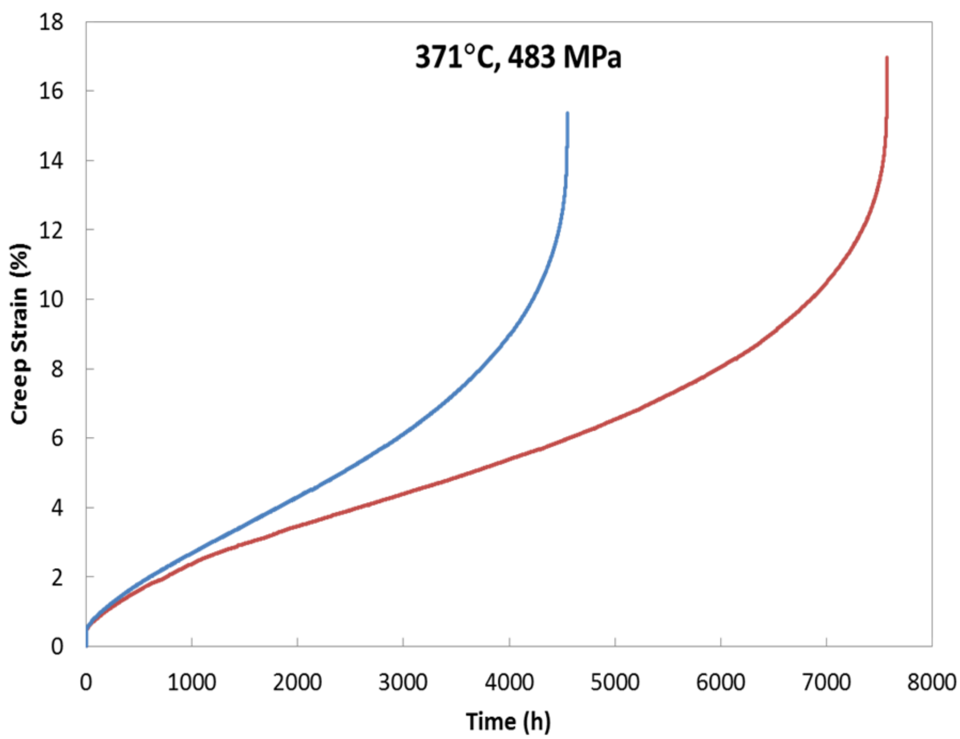
WELD LAYERS	WELD PROCESS (s)	CLASSIFICATION	DIAMETER	TYPE POLARITY	AMP RANGE	VOLTAGE RANGE	TRAVEL SPEED IPM	OTHER
All	FCAW	E81T1-Ni1	1/16"	DC - RP	150 - 290	20 - 29	14 min.	36,960 J/in Max.
All	SAW	EM14K / ESAB OK 10.71	5/32"	DC - RP	400 - 625	26 - 33	18 min.	70,400 J/in Max.

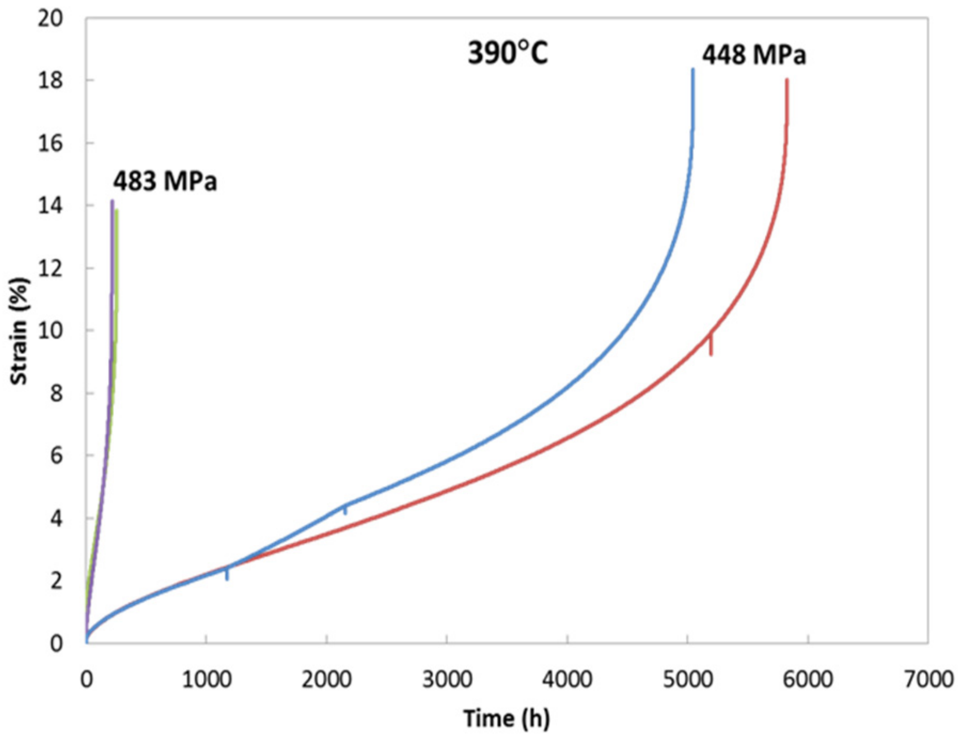
Appendix B Creep Curves for A508/533 Pressure Vessel Steel

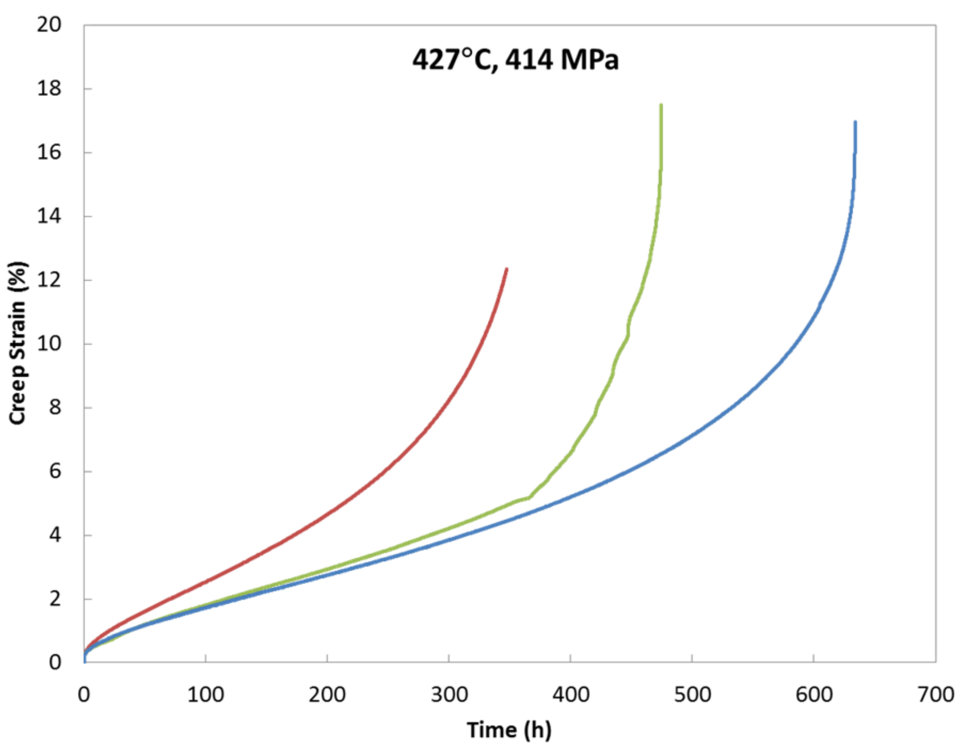


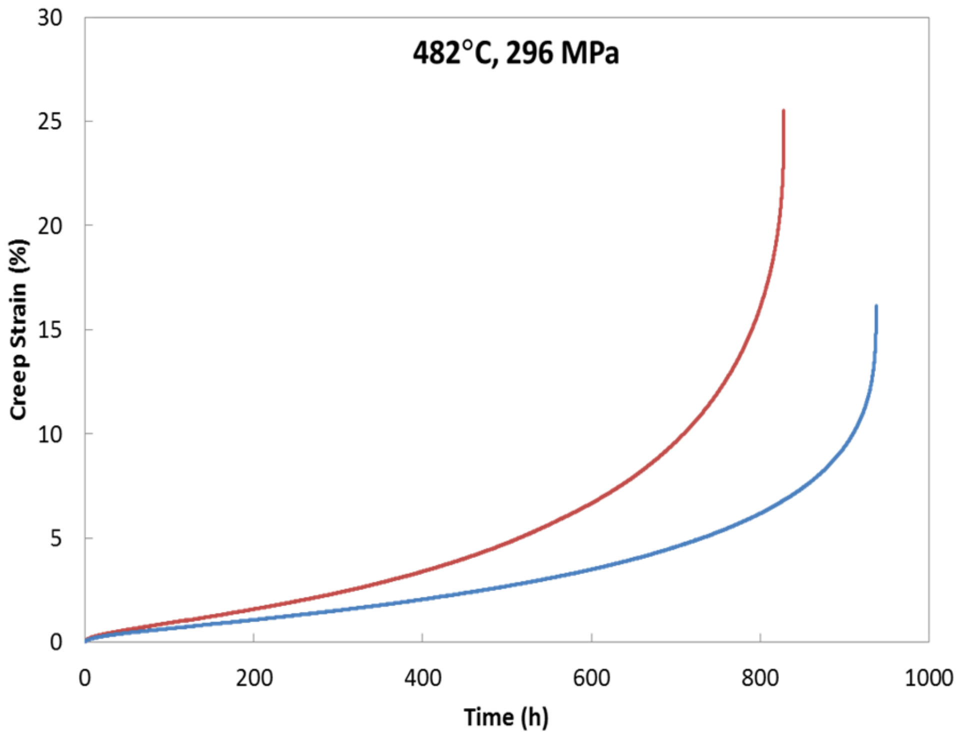


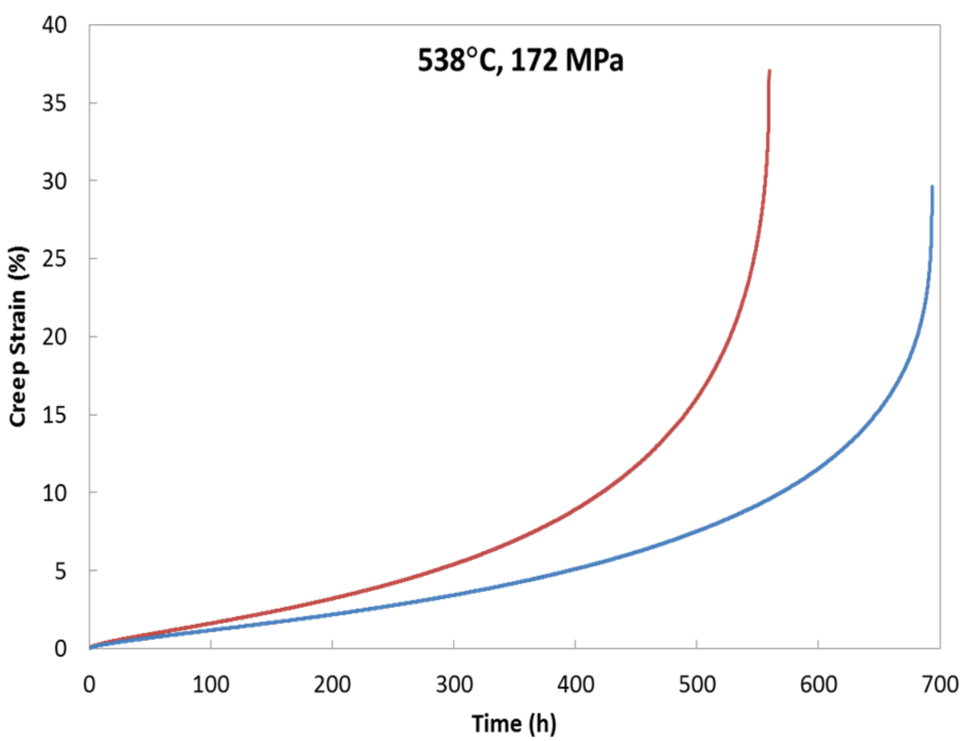

371°C
483 MPa
517 MPa
Creep Strain (%)
Time (h)
0
2
4
6
8
10
12
14
16
18
20
0
1000
2000
3000
4000
5000
6000
7000

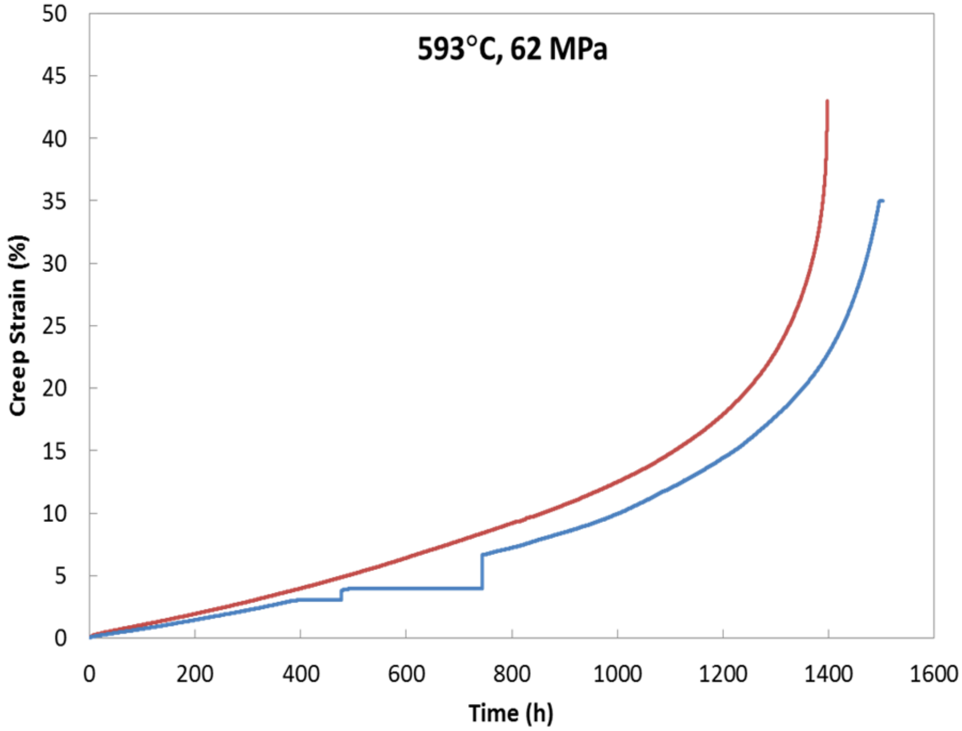

371°C, 483 MPa
Creep Strain (%)
Time (h)
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000
6000
7000
8000


390°C
448 MPa
483 MPa
Strain (%)
Time (h)


427°C, 414 MPa
Creep Strain (%)
Time (h)


482°C, 296 MPa
Creep Strain (%)
Time (h)
0
5
10
15
20
25
30
0
200
400
600
800
1000


538°C, 172 MPa
Creep Strain (%)
Time (h)
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
700


593°C, 62 MPa
Creep Strain (%)
Time (h)
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000
1200
1400
1600