ASME STANDARDS TECHNOLOGY, LLC

STP-PT-080

DEVELOPMENT OF AVERAGE ISOCHRONOUS STRESS-STRAIN CURVES AND EQUATIONS AND EXTERNAL PRESSURE CHARTS AND EQUATIONS FOR 9CR-1MO-V STEEL

STP-PT-080

DEVELOPMENT OF AVERAGE ISOCHRONOUS STRESS-STRAIN CURVES AND EQUATIONS AND EXTERNAL PRESSURE CHARTS AND EQUATIONS FOR 9Cr-1Mo-V STEEL

Prepared by:

MAAN JAWAD, Ph.D., P.E.
Global Engineering & Technology, LLC

ROBERT SWINDEMAN
MICHAEL SWINDEMAN, Ph.D.
Cromtech, Inc.

DONALD GRIFFIN, Ph.D.
Consultant

ASME STANDARDS TECHNOLOGY, LLC

Date of Issuance: June 30, 2016

This report was prepared as an account of work sponsored by ASME Pressure Technology Codes & Standards and ASME Standards Technology, LLC (ASME ST-LLC).

ASME Standards Technology, LLC
Two Park Avenue, New York, NY 10016-5990

ISBN No. 978-0-7918-7124-9

TABLE OF CONTENTS

LIST OF FIGURES

FOREWORD

The purpose of this project is to develop isochronous stress-strain curves and external pressure charts in the creep regime for 9Cr-1Mo-V steel taking into consideration updated information and data available in the literature. The temperature range is 800ºF to 1200ºF. The time range is Hot Tensile up to 300,000 hours. The project is divided into four parts in order to accomplish the required tasks.

PART 1. In this part creep model equations are generated for 9Cr-1Mo-V steel. The equations and applicable current data are gathered from many sources as detailed and explained in this part.

PART 2. The physical data of Part 1 are converted in this part to equation form and combined with the stress-strain creep model equations in order to have a unified system usable for generating isochronous curves. Examples are given to demonstrate the feasibility of generating isochronous curves directly from equations for any temperature and time within the scope of this project. Isochronous stress-strain charts are also drawn for reference purposes.

PART 3. In this part equations are developed for the purpose of constructing external pressure curves and charts for the 9Cr-1Mo-V steel. These curves and charts, which are constructed from equations for various temperatures and times, are verified for accuracy against charts drawn directly from the isochronous curves by the graphical and finite difference methods.

PART 4. The equations derived in this part for designing components in the creep regime are applicable to all materials. They are included in this report to show the integration of design equations with equations used to construct external pressure curves in the creep range.

Reference is made throughout this document to the ASME BPVC Section III-NH Code. Presently all of the current contents in III-NH are also in Section III, Division 5 of the ASME BPV Code for nuclear class NB applications. However, it should be noted that Section III-NH is slated for elimination in the middle of 2017. At that time the material tables and charts in III-NH will be transferred to the ASME BPV Code Section II-D. Similarly, a revised text of the rules in III-NH will appear in ASME Code Case 2843 for Section VIII applications.

The authors extend their thanks to various members of ASME BPV I, II, III, and VIII Committees for their support of this project. It is hoped that the results generated in this report will benefit all of these codes. Special thanks are given to Dr. Kevin Jawad for obtaining the derivatives of some of the complicated equations in PART 3 of the report. Thanks are also given to reviewers Dr. Peter Carter, Mr. Don Kurle, Mr. Benjamin Hantz, Dr. John Grubb, and Mr. Robert Mikitka for their thoughtful comments and to Ms. Colleen O'Brien and Mr. Steve Rossi of ASME for coordinating various phases of this project.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 135,000 members and volunteers promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit www.asme.org for more information.

ASME Standards Technology, LLC (ASME ST-LLC) is a not-for-profit Limited Liability Company, with ASME as the sole member, formed in 2004 to carry out work related to new and developing technology. The ASME ST-LLC mission includes meeting the needs of industry and government by providing new standards-related products and services, which advance the application of emerging and newly commercialized science and technology, and providing the research and technology development needed to establish and maintain the technical relevance of codes and standards. Visit www.stllc.asme.org for more information.

SUMMARY

The following tasks are accomplished for this project.

1. Isochronous stress-strain equations are developed for 9Cr-1Mo-V steel that take into account the elastic, plastic, and creep strain - prepared by Robert W. Swindeman and Michael J. Swindeman, Ph.D.

2. Isochronous stress-strain charts are developed from equations for 9Cr-1Mo-V steel. The temperature coverage is 800ºF to 1200ºF in increments of 50ºF. Curves in the charts cover time increments of Hot Tensile, 1 hour, 10 hours, 100 hours, 1000 hours, 10,000 hours, 100,000 hours, and 300,000 hours. In addition, equations are given to assist in plotting individual curves at any temperature and time within the scope of this project – prepared by Maan H. Jawad, Ph.D., P.E.

3. External pressure charts are generated from isochronous stress-strain equations for 9Cr-1Mo-V steel. The temperature coverage is 800ºF to 1200ºF in increments of 100ºF. Curves in the charts cover time increments of Hot Tensile, 10 hours, 100 hours, 1000 hours, 10,000 hours, 100,000 hours, and 300,000 hours. In addition, equations are given to assist in plotting individual external pressure curves at any temperature and time within the scope of this project – prepared by Maan H. Jawad, Ph.D., P.E. and Donald Griffin, Ph.D.

4. Equations are developed for designing components in the creep range under compressive stress for all materials. The equations cover axial compression in cylinders, external pressure in spherical components, external pressure in cylindrical shells, and axial compression in structural columns (Euler's buckling) – prepared by Maan H. Jawad, Ph.D., P.E. and Donald Griffin, Ph.D.

ABBREVIATIONS AND ACRONYMS (PART 1)

A = Parameter in the Ellis form of the creep equation, essentially the Monkman-Grant strain (mm/mm)
a_0, a_1, a_2, a_3 = Coefficients used in a Larson-Miller parametric expression
α = Creep rate acceleration term used in fitting the tertiary portion of the curve in the Ellis Model
α_1 = Creep rate deceleration term used in fitting the primary creep portion of the curve
α_3 = Creep rate acceleration term used in fitting the tertiary portion of the curve
B = Parameter in the Ellis form of the Creep Equation (1/hour)
(1/b) = a factor in the Voce equation adjusted to force the yield curve to pass through the Y-1, S_{y1}, or S_{ys} (%)
C = term in the Larson-Miller parametric expression, corresponding to the Larson-Miller Constant
Δ = an increment of stress that represents the difference between the minimum and average plastic flow curves and is equal to 0.25 Y-1 or 0.25 S_{y1}
e_p = plastic strain (%)
ε = Creep strain for any stage of the creep curve
ε_1 = Primary component of creep strain in a linear combined model
ε_3 = Tertiary component of creep strain in a linear combined model
ε_c = Combined primary and tertiary creep
ε_r = Total creep strain at rupture
$\dot{\varepsilon}$ = Creep strain rate (1/hour)
$\dot{\varepsilon}_0$ = Initial creep rate based on a fit to the tertiary stage of the creep curve in the Ellis Model (1/hour)
$\dot{\varepsilon}_{03}$ = Initial creep rate based on a fit to the tertiary stage of the creep curve (1/hour)
$\dot{\varepsilon}_1$ = Creep rate (1/hour)
$\dot{\varepsilon}_{01}$ = Initial creep rate based on a fit to the primary stage of the creep curve
F = Parameter used in the Ellis Model, the integration constant, which is related to the total Initial creep strain at time t = 0
K = Coefficient in the Andrade form for primary creep ($1/hr^{p+1}$)
p = Time exponent in the Andrade form for primary creep, normally 1/3
S_{pl} = proportional limit of tensile curve: minimum, average, or typical curve of concern (ksi)
S_u = stress value from Table NH-3225-1 in Section III Subsection NH which covers temperatures above 1000°F(ksi)
S_{uts} = ultimate tensile strength of the "average" curve (ksi)
S_{ys} = 0.2% offset yield strength of the "average" curve (ksi)
S_{y1} = Stress value from Table I-14.5 in Section III Subsection NH which covers temperatures Above 1000°F (ksi)
σ = Applied Stress (MPa)
t = Time at a specified stress (hours)
$t_{\varepsilon r}$ = Time to reach rupture strain (hours)
t_r = Rupture time (hours)
$(t_r)_3$ = Rupture time based on a fit to the tertiary portion of the curve (hours)
T = Temperature (°C)
U = stress value from Table U in ASME BPVC Section II Part D which covers temperatures to 1000°F (ksi)
Y-1 = stress value from Table Y-1 in ASME BPVC Section II Part D which covers temperatures to 1000°F (ksi)

1 GENERATION OF CREEP MODELS FOR 9CR-1MO-V STEEL (GRADE 91) ISOCHRONOUS CURVES

1.1 Introduction

The intent of this report is to describe the development of a creep model for use in producing isochronous curves for grade 91. The basis for the other component of strain, the plasticity or "hot tensile" curve, has been described elsewhere. Values of creep strain are needed over a wide range of conditions. At some temperatures, stresses, and times, the creep strain is dominated by the primary component; at other conditions tertiary creep is important. The model must in some cases be predictive of conditions for which there are no available data, specifically estimating creep strains at very low stresses, high temperatures, and long times.

In describing the model, we try to maintain a distinction between terms such as condition, parameter, constant, and coefficient. The conditions are the inputs to the model: stress, temperature, and time. The parameters of the model are the values that are used to describe the shape of the creep curve at a specific set of conditions. For example, the stress exponent, *n*, is a parameter, and the time to rupture, t_r, may also be considered a parameter. The model coefficients are used in describing the parameters as functions of stress and temperature. The term constant is only used for specific coefficients that take on a special role in a time-temperature parameterization. In this report, the term constant is exclusively used for the Larson-Miller constant. It is highly desirable to keep the number of parameters low to minimize the effort of determining the coefficients.

Many have come to view the classic three stage description of creep as the result of a primary stage where hardening mechanisms result in diminishing creep rates and a tertiary creep stage where damage and aging mechanisms produce an increasing creep rate. The second stage, where creep rate appears to be constant, is simply the transition between the two stages. Primary-tertiary forms for creep models often involve four parameters, two each for the primary and tertiary stages.

To determine these parameters, three approaches are possible. The first is to fit the entire curve. This can be quite difficult depending on the creep model since it involves non-linear regression. The second is to fit either the tertiary creep or primary creep and then make adjustments for the missing component. The third is to fit each separately and look for a method to combine the curves. The model proposed below seeks to use information contained within the tertiary creep portion of the curve to provide an estimate of the primary creep strain.

1.2 Logarithmic Creep Rate Formulation

<u>Description of Tertiary Creep</u>

The model expression for tertiary creep is[1]

$$\ln(\dot{\varepsilon}) = \ln(\dot{\varepsilon}_{03}) + \alpha_3 \varepsilon \quad (1.1)$$

where ε is the creep strain, $\dot{\varepsilon}$ is the creep strain rate, $\dot{\varepsilon}_{03}$ represents the initial creep rate at zero strain and α_3 provides the dependence of the strain rate on the creep strain. In the present paper, we refer to this form of the creep law as the logarithmic-rate form.

[1] The use of the term α is intentional and is used to distinguish the resultant values in the present approach from those values tabulated for aged material in ASME FFS-1 / API-579.

Upon integration, assuming there is no initial strain or other stages of creep, equation (1.1) becomes[2]

$$\varepsilon_3 = \varepsilon = -\frac{1}{\alpha_3}\ln\left(1-\dot{\varepsilon}_{03}\alpha_3 t\right) \tag{1.2}$$

Then, the time to reach the rupture strain is

$$t_{\varepsilon_r} = \frac{1-\exp\left(-\alpha\varepsilon_r\right)}{\dot{\varepsilon}_{03}\alpha_3} \tag{1.3}$$

Which for any combination,

$$\alpha_3\varepsilon_r > 3 \tag{1.4}$$

can be approximated within 5% simply by the limit,

$$t_r \approx \frac{1}{\dot{\varepsilon}_{03}\alpha_3} \tag{1.5}$$

At some conditions, the initial creep rate and the actual minimum creep rate are of the same order. In these situations, equation (1.5) provides an estimate of the value of α from minimum creep rate and time to rupture; furthermore, in such situations, $1/\alpha_3$ can be regarded as the Monkman-Grant strain.

Description of Primary Creep and Combined Creep Strain

It is recognized that primary creep is important under many conditions of practical interest. Neglecting the early part of the creep curve could lead to significant errors, since the difference between the initial creep rate as derived from the latter stages of the creep curve and the actual minimum creep rate measured in a test can be orders of magnitude.

A candidate expression for the primary creep rate may be expressed in a similar form[3]:

$$\ln\left(\dot{\varepsilon}\right) = \ln\left(\dot{\varepsilon}_{01}\right) - \alpha_1\varepsilon \tag{1.6}$$

which leads to an expression for creep as

$$\varepsilon_1 = \varepsilon = \frac{1}{\alpha_1}\ln\left(1+\dot{\varepsilon}_{01}\alpha_1 t\right) \tag{1.7}$$

In this case, the creep rate decreases with time and strain accumulation.

Treating the tertiary and primary creep terms as independent contributions to the total creep strain leads to the following creep model:

$$\varepsilon_c = \frac{1}{\alpha_1}\ln\left(1+\dot{\varepsilon}_{01}\alpha_1 t\right) - \frac{1}{\alpha_3}\ln\left(1-\dot{\varepsilon}_{03}\alpha_3 t\right) \tag{1.8}$$

---

[2] An early example of this equation can be found in Sandstrom, R. and Kondyr, "Model for Tertiary Creep in Mo- and Cr-Mo-Steels," pp. 275-284 in *Mechanical Behavior of Metals*, Vol.2 Pergamon Press, New York, NY, 1976.

[3] Such a procedure was proposed in Cleh, J-P. "An extension of the omega method to primary and tertiary creep of lead-free solders," *Electronic components and technology conference*, 2005.

1.3 Ellis Creep Form

Ellis took a related but subtly different approach to fitting a creep model. Starting with equation (1.1) he expressed the creep strain in the tertiary region as[4]:

$$\varepsilon = -A\ln\left(F - Bt\right) \tag{1.9}$$

where,

$$A = \frac{1}{\alpha} \tag{1.10}$$

and

$$AB = \dot{\varepsilon}_0 \tag{1.11}$$

which, when combined with equation (1.10) leads to

$$B = \alpha\dot{\varepsilon}_0 \tag{1.12}$$

Other than the integration constant, *F*, Ellis's form of the equation is identical to equation (1.7). As will be shown, this integration constant is quite important in matching the tertiary creep parameters to the time to rupture. Ellis linearized the equation as

$$\exp\left(-\varepsilon / A\right) = \left(F - Bt\right) \tag{1.13}$$

The parameters are determined by adjusting the parameter *A* to minimize the R^2 value of a linear regression to the tertiary portion of the creep curve.

As might be expected, Ellis found that the rupture life corresponds very closely to the ratio *F*/*B*. To show this, consider failure to occur at a finite strain, then equation (1.10) becomes

$$\varepsilon_r = -A\ln\left(F - Bt_r\right) \tag{1.14}$$

and

$$t_r = \frac{1}{B}\left(F - \exp\left(-\frac{\varepsilon_r}{A}\right)\right) \tag{1.15}$$

which, upon substitution of the equivalent tertiary creep parameters is identical to equation (1.3) if *F* = 1. As *A* greatly exceeded the rupture strain, equation (1.15) becomes

$$t_r \approx \frac{F}{B} \tag{1.16}$$

Or, from equation (1.12)

$$t_r \approx \frac{F}{\dot{\varepsilon}_0\alpha} \tag{1.17}$$

Thus this new parameter, *F*, appears in the rupture calculation.

Using equation (1.16) allowed Ellis to make the substitution

$$B = F / t_r \tag{1.18}$$

$$\varepsilon = -A\ln\left(F - Ft / t_r\right) \tag{1.19}$$

and, finally,

[4] Originally, Ellis used the symbol *C* for the integration constant, but here, to avoid confusion with the Larson-Miller constant, we use the symbol *F*.

$$\varepsilon = -A\ln(F) - A\ln(1 - t/t_r) \tag{1.20}$$

Ellis then approximates the tertiary strain as

$$\varepsilon_3 = -A\ln(1 - t/t_r) \tag{1.21}$$

Though the first term in equation (1.20), $-A\ln(F)$, is constant, it can be replaced by the primary creep component. Ellis then used the Andrade form of the creep equation to characterize the primary creep:

$$\varepsilon_c = Kt^{1/3} - A\ln(1 - t/t_r) \tag{1.22}$$

This form has the limitation of predicting an infinite strain rate at time=0.

This model has three parameters, *K*, *A*, and t_r; but rupture time has already been measured. Using the known time to rupture, Ellis fit the parameters, *K* and *A*, to all the actual creep curves using a least squares regression and then derived parametric expressions for each using the Dorn parametric fit.

It is important to note that the constant, *A*, though conceptually the same in equations (1.9) and (1.22) are in practice different because they are determined in different ways. The *A*-parameter in equation (1.22) is affected by the primary creep term, and as such it does not necessarily produce the best possible fit to the tertiary portion of the curve. Ellis did not attempt to determine a separate fit to the primary portion of the curve, but if he had, it should be expected that the value of *K* would also be different.

Non-linear combination model

Both equations (1.8) and (1.22) represent linear combinations of primary and tertiary creep where the two creep strain functions do not interact. In the case of the Ellis approach, the whole curve is fit at once. In the case of the logarithmic rate model, the tertiary creep and primary creep parameters are derived separately.

The non-linear combination approach uses the form of the tertiary logarithmic rate relationship with a different method for accounting for primary creep and its effect on rupture life. From equation (1.17)

$$F = \dot{\varepsilon}_0 \alpha t_r \tag{1.23}$$

or,

$$F = \frac{t_r}{(t_r)_3} \tag{1.24}$$

where $(t_r)_3$ is calculated from equation (1.5). Thus one way to consider the parameter *F* is that it is the ratio of the actual rupture time to the rupture estimate that is derived from estimating the life based on the tertiary portion of the curve. Ellis recorded the *F* parameter from as little as 0.31 to nearly 0.82 which provides a rough indication of the fraction of life in tertiary creep.

F is also related to the computed initial strain that comes as a result of a fit to the tertiary portion of the curve. And in this sense it has the most relevance to the problem of isochronous curve generation.

From equations (1.9) and (1.10), at time zero:

$$\varepsilon_0 = -\frac{1}{\alpha}\ln(F) \tag{1.25}$$

Of course the initial strain is actually zero. If, instead of considering "F" as a fixed value, but instead as a consequence of the primary creep, we can use equation (1.25) to derive a time-dependent value of F. For example, using the logarithmic rate description of primary creep

$$\frac{1}{\alpha_1}\ln\left(1+\alpha_1\dot{\varepsilon}_{01}t\right)=-\frac{1}{\alpha}\ln\left(F\right) \tag{1.26}$$

or, using an Andrade type form:

$$kt^p=-\frac{1}{\alpha}\ln\left(F\right) \tag{1.27}$$

In most cases, either equation is sufficient, both employ two parameters, but equation (1.26) has a strategic advantage in its consistency with the tertiary creep form and a practical advantage in that the influence of the primary creep at long times is much less at relatively long times. Using (1.26), the F parameter becomes

$$F=\left(1+\alpha_1\dot{\varepsilon}_{01}t\right)^{-\frac{\alpha}{\alpha_1}} \tag{1.28}$$

and then substituting into equation (1.20) and replacing the constants, A, α, and B with their logarithmic rate equivalents leads to

$$\varepsilon=-\frac{1}{\alpha_3}\ln\left(\left(1+\alpha_1\dot{\varepsilon}_{01}t\right)^{-\frac{\alpha_3}{\alpha_1}}-\dot{\varepsilon}_0\alpha_3 t\right) \tag{1.29}$$

As before, when determining the rupture time from the expressions for creep, it follows that:

$$\left(1+\alpha_1\dot{\varepsilon}_{01}t_r\right)^{-\frac{\alpha_3}{\alpha_1}}=\dot{\varepsilon}_0\alpha_3 t_r \tag{1.30}$$

This equation provides a relation between all the model parameters required to match the observed rupture time, t_r.

1.4 Determination of Model Parameters

Preliminary comparison of Logarithmic Rate and Power-Law forms for Creep

In order to derive the parameters, we first consider the shape of the creep curve. The NIMS datasheets for grade 91 provide high quality data to perform data analysis.

We first note that power law behavior appears linear on (a) Logarithmic strain versus logarithmic time, (b) Logarithmic strain rate versus logarithmic time, and (c) Logarithmic strain rate versus logarithmic strain, since

$$\varepsilon=kt^p \tag{1.31a}$$

$$\log\left(\varepsilon\right)=\log\left(k\right)+p\log\left(t\right) \tag{1.32a}$$

$$\dot{\varepsilon}=kpt^{p-1} \tag{1.31b}$$

$$\log\left(\dot{\varepsilon}\right)=\log\left(kp\right)+\left(p-1\right)\log\left(t\right) \tag{1.32b}$$

$$\dot{\varepsilon}=k^{\frac{1}{p}}p\varepsilon^{\frac{p-1}{p}} \tag{1.31c}$$

$$\log(\dot{\varepsilon}) = \log\left(k^{\frac{1}{p}} p\right) + \left(\frac{p-1}{p}\right)\log(\varepsilon) \qquad (1.32c)$$

The Andrade form is a particular case of the power law equation with p = 1/3.

In regions where the creep behavior obeys the Logarithmic Rate form – Equations (1.1) and (1.7) – a plot of the logarithm of the creep rate versus linear strain would appear linear.

Inspection of the creep curve shapes would seem to be a simple way of distinguishing between power law and logarithmic rate-type behavior. The published NIMS datasheets provide creep curves in different formats for a variety of heats designated as MGA, MGB, MGC, MgC. Over a particular range of either time or strain, curve fits from either form may provide very reasonable results. It can be observed for the NIMS curves that the power law form for the primary creep works well for most curves over several orders of magnitude in time (Figure 1.1(a) and (b)), but at very small strains it tends to break down as a limit to the creep rate is reached (Figure 1.1(c)). The logarithmic rate-type formulation generally holds for the tertiary portion of the curve, but some curves tend to bend down slightly (Figure 1.1(d)). In primary creep, it is difficult to find an appropriate region to perform a regression for logarithmic rate parameters.

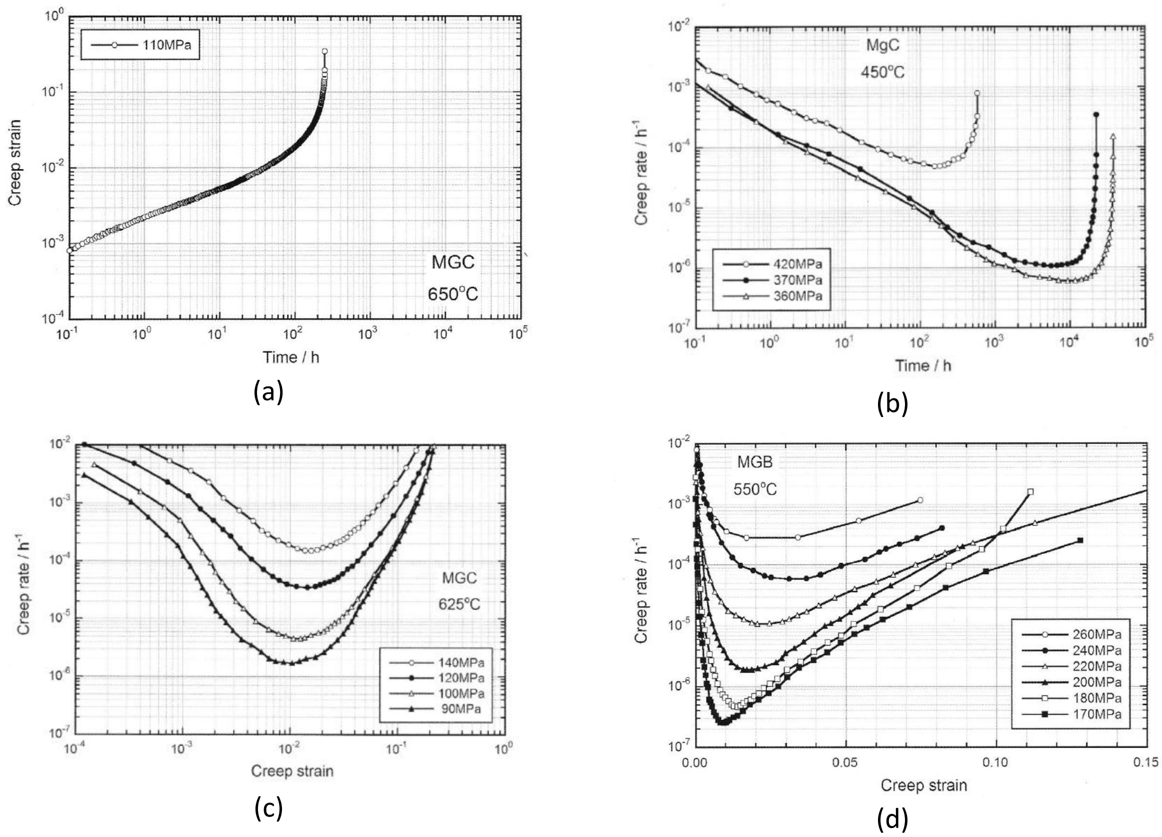

Figure 1.1. Examples of formats of creep data from NIMS

Attempts to fit Primary and Tertiary Separately

Best Fits for Primary Creep

Fits for the primary creep region were performed from digitization of the log creep-rate versus log time NIMS charts using a power law formulation and the standard trendline option in Microsoft Excel. An example is shown in Figure 1.2. The coefficients and R^2 value for the trendline of each material and condition were recorded.

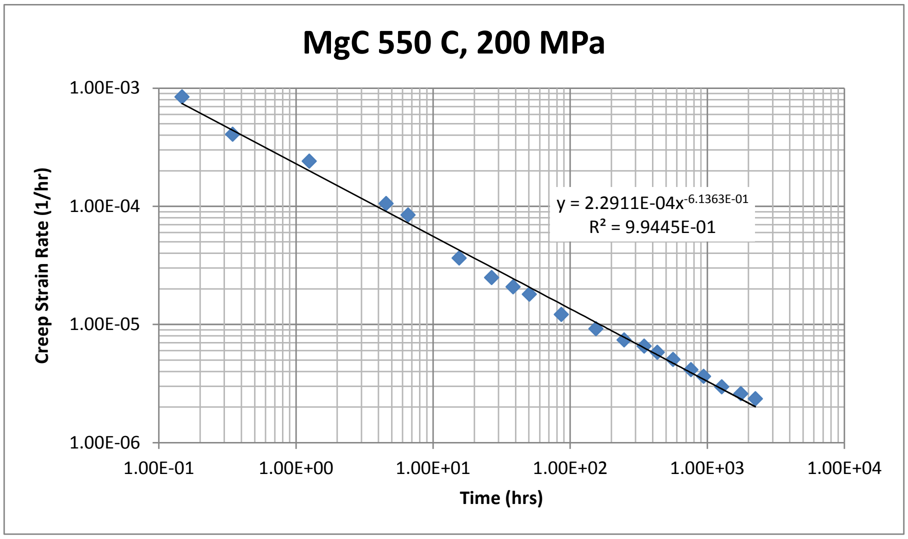

Figure 1.2. Example fit of a power-law equation to the primary creep portion of the curve

Equations to describe the Primary-Creep Parameters

There are two parameters to describe power law creep, *k* and *p*. The first, *k*, can be described adequately through a Larson-Miller expression as shown in Figure 1.3. The second (Figure 1.4), the time exponent, shows significant scatter and can only be roughly described as linear in stress. The effect of the temperature appears to be to shift the stress range. These trends are visible, but the inconsistency of the test results does not allow for complex models to be winnowed from the available data.

In order to describe the *p*-parameter in terms of stress and temperature, it is first assumed that the stress dependency is the same for all temperatures. Or,

$$p = b(\bar{T}) + a\sigma \tag{1.33}$$

Best fit linear equations are developed for the *p*-vs-stress curve at each temperature for which there is sufficient data and then the slope, weighted and averaged over all the temperatures, is used. Next the stress dependency portion of the curve is subtracted out, to find a best-fit expression for the temperature dependency:

$$b(\bar{T}) = p - a\sigma \tag{1.34}$$

In this manner the experimental data is fit in a completely phenomenological manner.

A comparison of the temperature function, $b(T)$, and the data used to generate it is shown in Figure 1.5. The scatter in the data is about +/- 0.1 about the mean. The equation (1.33) is expected to have limited validity beyond the range of experimental data. Nonsensical values of *p*, below zero for example, are possible under certain conditions. Predicted values of *p* greater than 0.5 or less than 0.2 should be considered suspect.[5] That being said, a value of 1/3 for *p*, consistent with the Andrade equation, seems to provide a "good-enough" fit without the additional complexity.

[5] An adjustment to the *p*-parameter is possible using more complex functions such as an inverse hyperbolic tangent to restrict the range of outcomes. The final model, however, does not make use of the power-law form of initial creep rate.

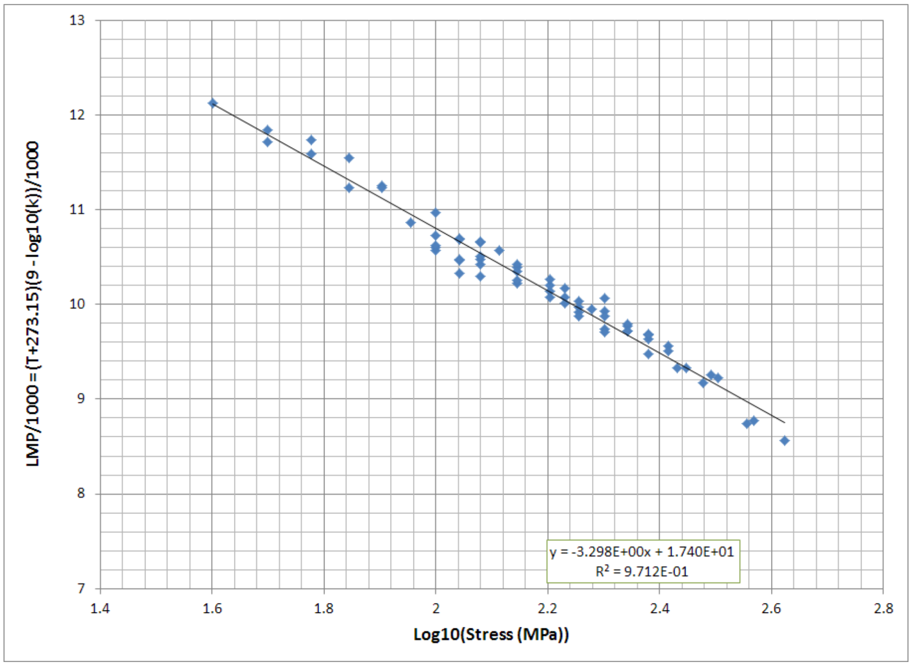

Figure 1.3. A Larson-Miller representation of the primary creep parameter, k

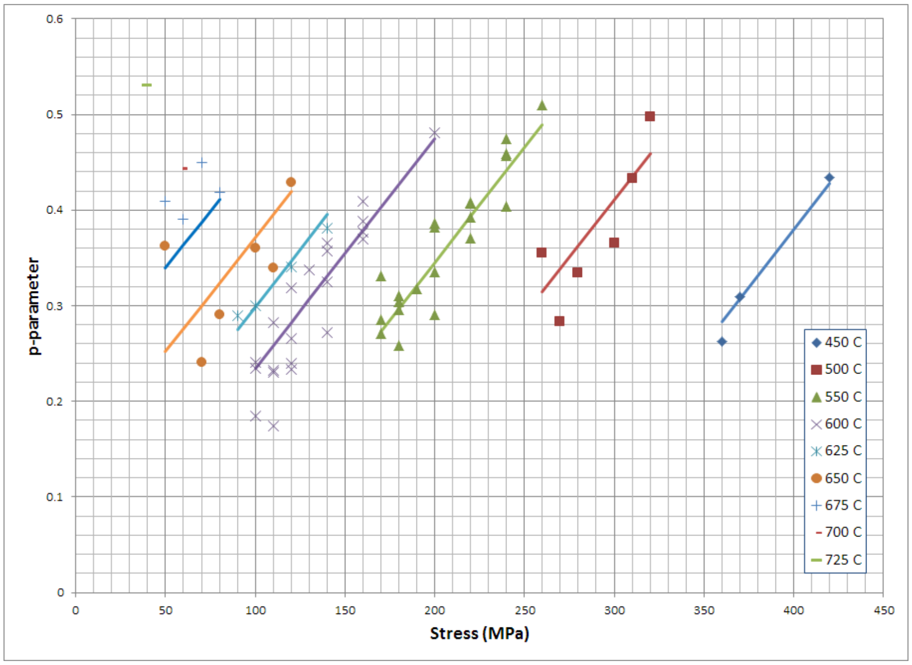

Figure 1.4. Isothermal representation of the primary creep stress exponent, p

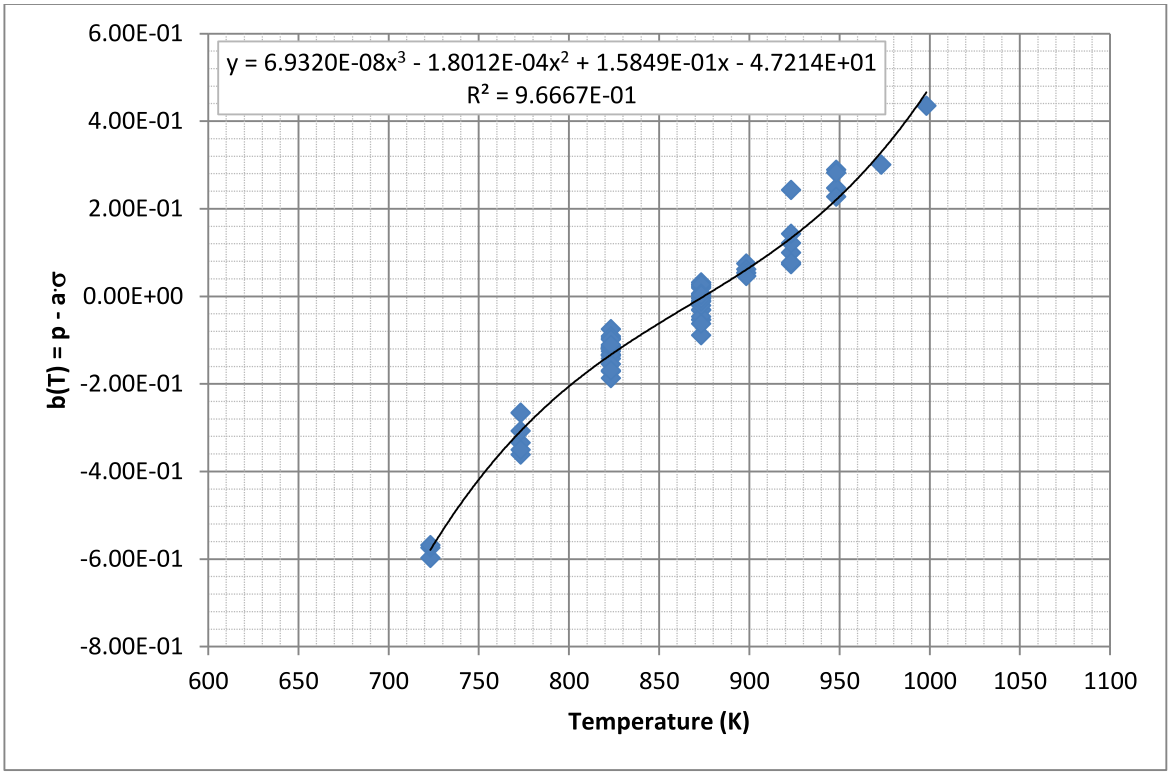

Figure 1.5. Temperature dependent term for the primary creep stress exponent

Best Fits for Tertiary Creep

Fits for the primary creep region were performed from digitization of the log creep-rate versus linear strain NIMS charts using an exponential-law formulation and the built in trend-line option in Microsoft Excel. An example is shown in Figure 1.6. The coefficients and R^2 value for the trendline of each material and condition were recorded. Note that the strain measure is engineering strain, not the true strain. The error associated with this is less than 5% up to 10% strain.

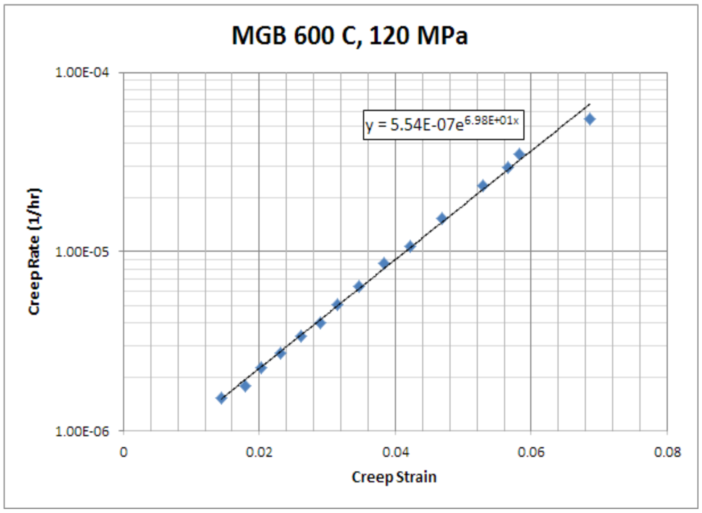

Figure 1.6. Example of an omega-type fit to the tertiary creep portion of the curve

Equations to Describe the Tertiary Creep Parameters

The two parameters used for the tertiary creep are the initial creep rate and α. As can be seen in Figure 1.7, the initial creep rate is fairly well-behaved within the data range and well represented by a Larson-Miller type expression. Extrapolation, especially to very low stress values, could prove problematic.

The α-parameter displays significantly more variability as can be seen in Figure 1.8. In addition, the values generated from the NIMS and those reported in the Ellis tables seem to form two distinct populations.

The ASME FFS-1 tertiary creep equation is of the same form as the Ellis equation and the parameters, initial creep rate and omega, have nearly consistent meaning as the initial creep rate and alpha in this study. Both parameters in ASME FFS-1 are related to time and stress using Larson-Miller type expressions, though the Larson-Miller expressions are presented in logarithmic form. On this basis, we can compare the initial creep rate and alpha parameter determined from the regressions of the digitized NIMS data for "virgin" material to the published curves in ASME FFS-1 recommended for service aged material. In order to make the comparison, we must use the same Larson-Miller Constants for the data set as the ASME FFS-1 tables, which differ slightly from the constants we found, optimized the current data set. The resultant parametric fit determined for the initial creep rate in this study is similar to the curve developed for ASME FFS-1 curve (see Figure 1.9). This was not expected since the ASME FFS-1 curves were based on service aged materials. The Larson-Miller constants in the parametric fits are remarkably close. The sensitivity of the R^2 value to the constant is very low within the range of 30-40 and so either a value of 35.5 (current study) or 34 produce nearly the same results. The ASME FFS-1 expression appears to be better suited for extrapolation, but is less accurate a description of this data set.

The values for Omega in ASME FFS-1 and the α-parameter in the current study have also been compared. Using a Larson-Miller Constant of 2 for α-parameter results in a poor fit for the NIMS and Ellis data (Figure 1.10) and the predicted Omega parameter at the test data conditions is, on average, about 40% of the α-parameter.

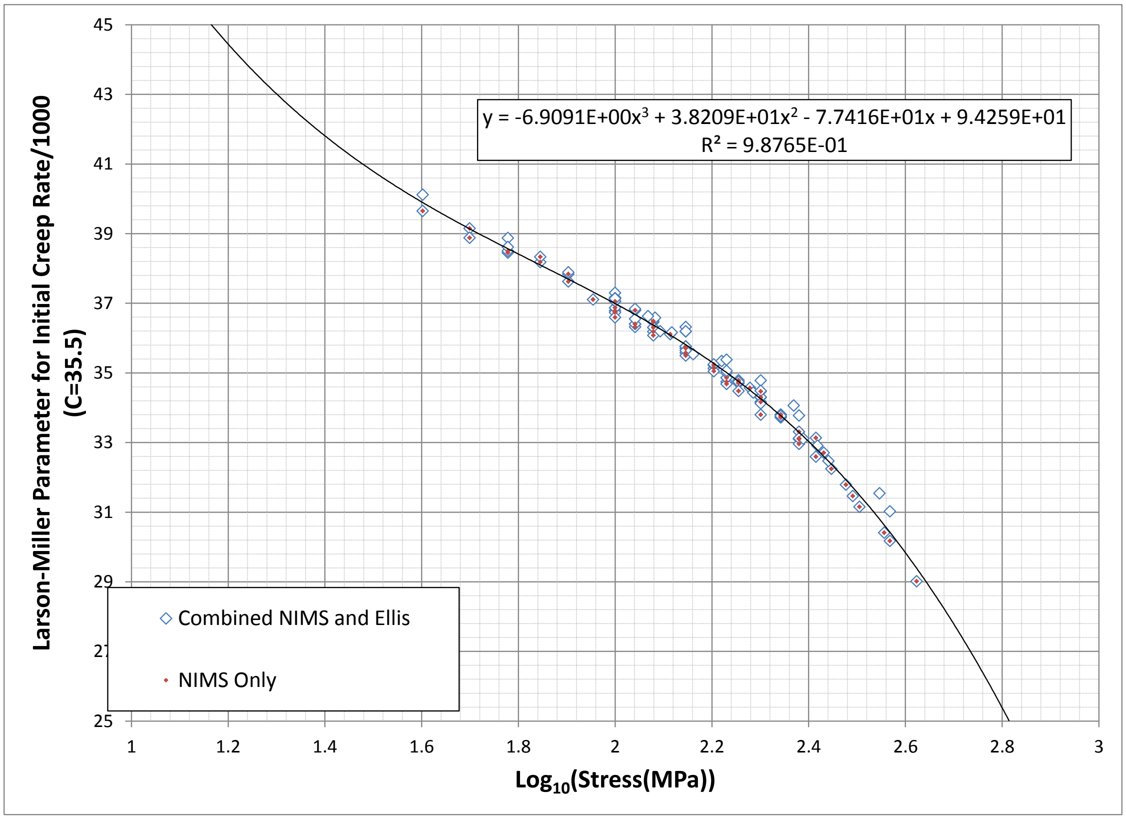

Figure 1.7. A Larson-Miller representation of the initial creep rate for tertiary creep

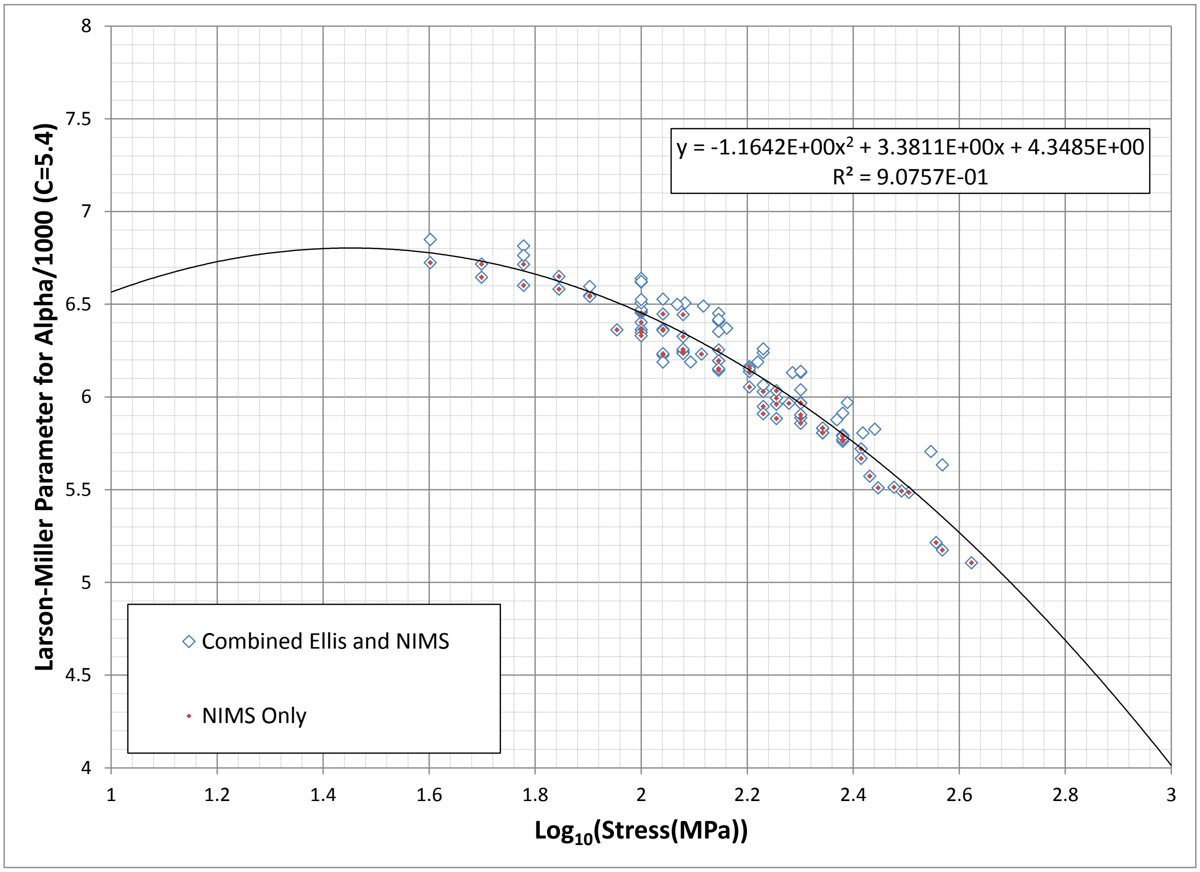

Figure 1.8. A Larson-Miller representation of the α-parameter for tertiary creep. In general, the model slightly over-predicts α for NIMS and under-predicts the α-parameter for the Ellis data set. The values do not extrapolate well to low stresses.

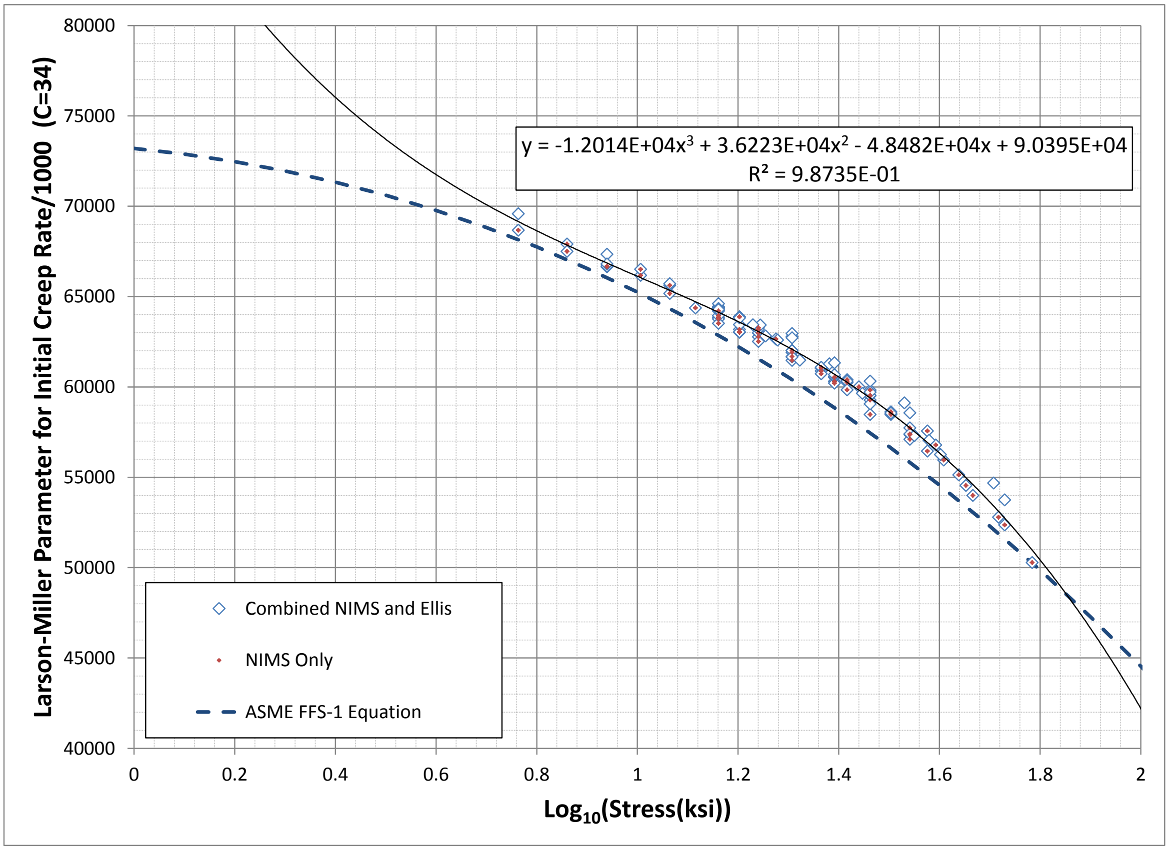

Figure 1.9. Comparison of ASME FFS-1 (API-579) initial creep rates with values found in the present study. ASME FFS-1 would slightly under-predict the present data set. The extrapolation to low stresses is uncertain.

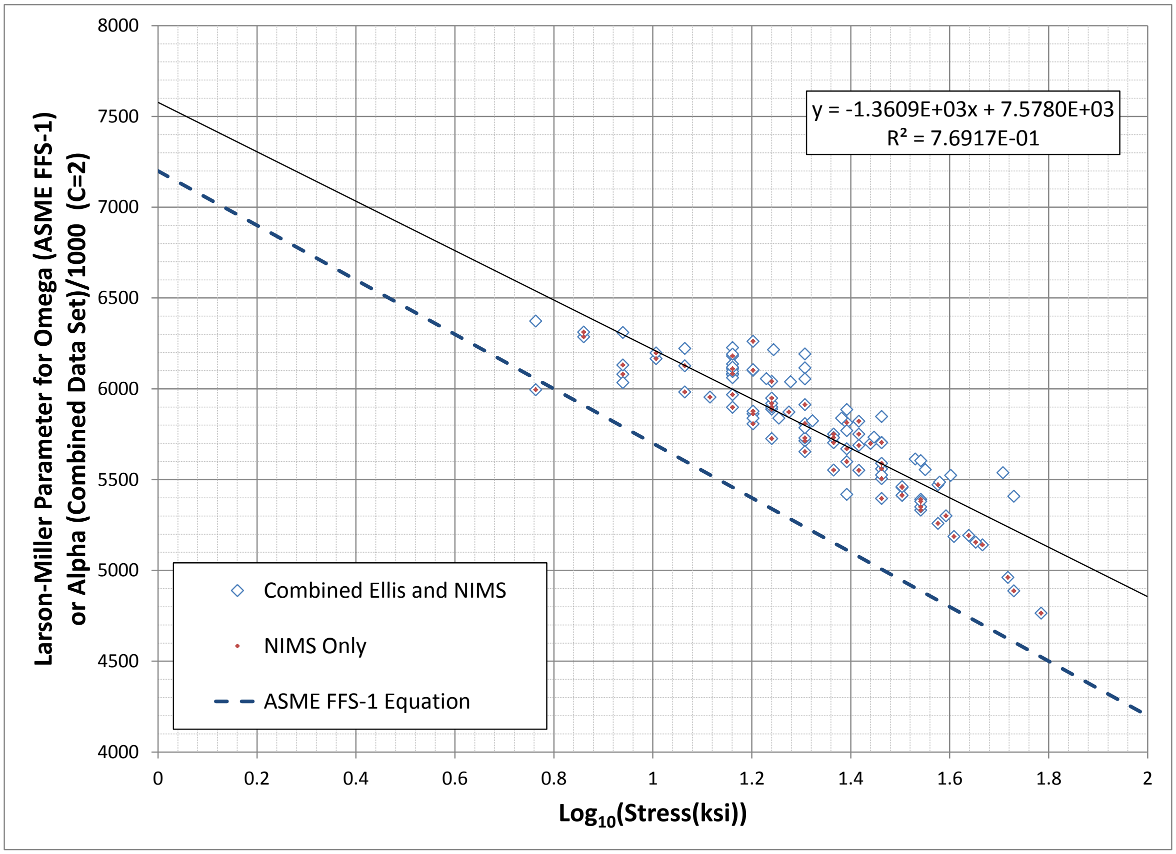

Figure 1.10. Comparison of ASME FFS-1 (API-579) parametric equation for Omega with the α-parameters found in the present study. ASME FFS-1 would under-predict the present data set.

Results of Combinations

Simple Combination Models

There is more than one way to combine the primary and tertiary creep expressions. Figure 1.11 illustrates the difficulty of combining individually fitted portions of the curve to form a complete curve.

The tertiary creep fit of the form of equation (1.9), "tertiary (with F)," provides the best fit of the final part of the creep curve (strains above 2-3%). The "tertiary only" fit ignores the integration constant, F, but uses the same parameters for initial creep rate and α in equation (1.2). This fit over-predicts the time to rupture and under-predicts strain. The "primary only" fit is the power-law model and it performs well at low strains (less than 2%) but, of course, does not include rupture.

Simple attempts to fit the primary creep into the tertiary creep curve tend to cause the rupture time to either become consistently over-conservative or consistently under-conservative. A linear combination model of the two models fits well up to 3% strain but afterwards deviates from the true behavior. A simple first attempt of the non-linear combination fit which uses the primary creep to predict the integration constant under-predicts the time to rupture and over-predicts the strain and begins to deviate at around 2% strain.

Only one example is shown here, but the same results hold true for all the cases investigated. The linear combination under-predicts strains and the non-linear combination over-predicts strains. The true creep strain over the range of interest is not represented by a simple combination of the primary and tertiary creep components fit individually. The fit to either or both of the tertiary and primary portions must be adjusted to account for the interaction region where both are of the same magnitude.

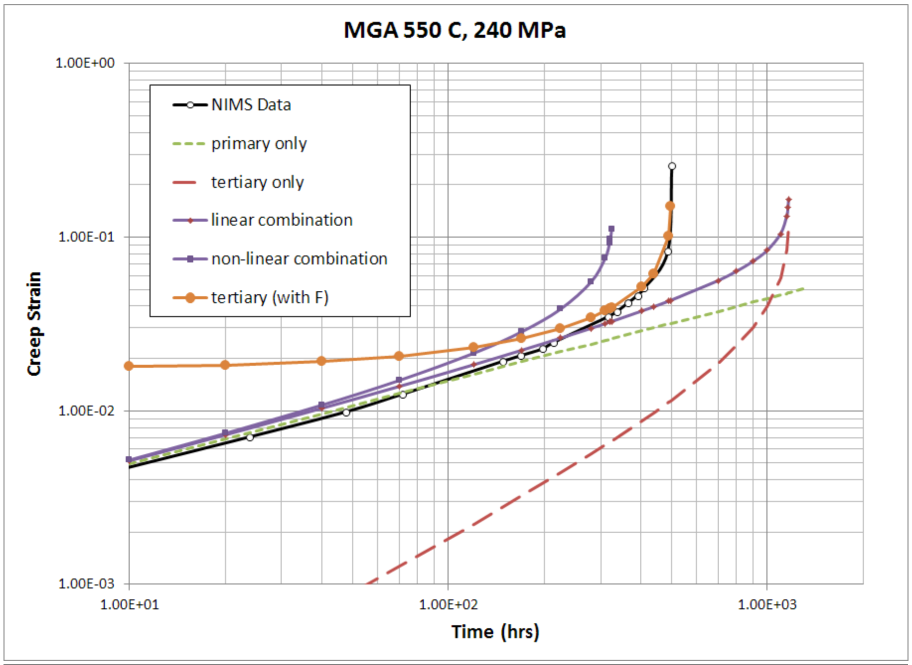

Figure 1.11. Example of comparisons of individual data fits to the overall curve

Fitting Tertiary Creep and Adjusting Primary Creep through the F-Parameter
The over-prediction of strain and a shorter rupture life suggests that the effect of primary creep in the non-linear combined model is excessive. Recognizing that equation (1.30) can be used to determine one of the two creep parameters to properly match the rupture life, the other parameter can be chosen to yield the best fit to the primary creep portion of the curve. Figure 1.12 shows an example of a curve constructed in this manner.

This method of adjusting one of the primary creep parameters works well on an individual curve; applying it to a general creep model is more difficult and requires additional steps.

First, in order to estimate the initial creep rate in primary, the predicted creep rate at 0.1 hrs is used.[6] As shown in Figure 1.13, a first order Larson-Miller fit works well in describing the stress-temperature dependency of creep rate at 0.1-hr. Using this fit for initial creep rate, a value of the α-parameter for each condition that satisfied equation (1.30) was determined. A Larson-Miller parametric fit was constructed for the resulting values of the primary logarithmic-rate term as shown in Figure 1.14.
This method was used to construct a non-linear combination model that better predicted the final rupture time while capturing the early stages pf primary creep. A summary of the methodology is presented in the following section.

[6] An attempt to correlate the initial creep rate in primary with the initial creep rate in tertiary yielded very poor results. This is likely because of the significant difference in the activation energies for primary and tertiary creep.

Overlay plot comparisons of predicted creep curves against the corresponding NIMS creep curves are shown in Figure 1.15 through Figure 1.18.

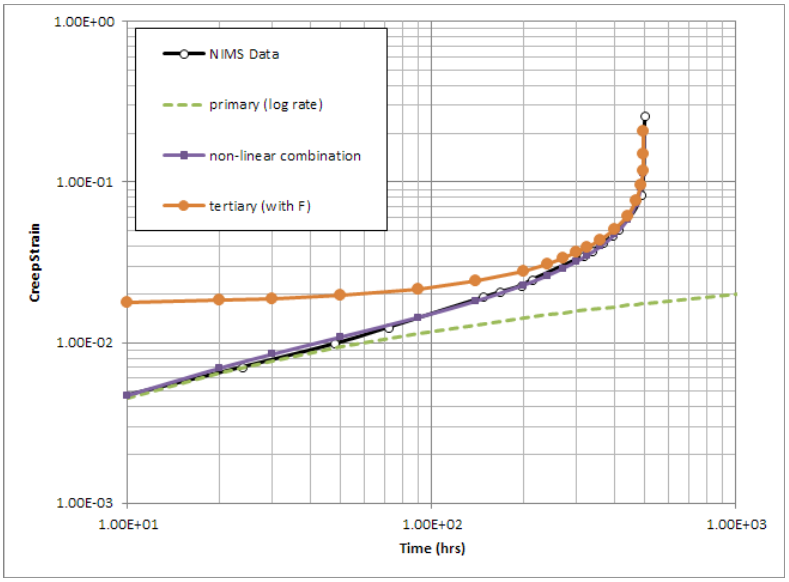

Figure 1.12. Example of the NLCM with primary creep adjusted to match data

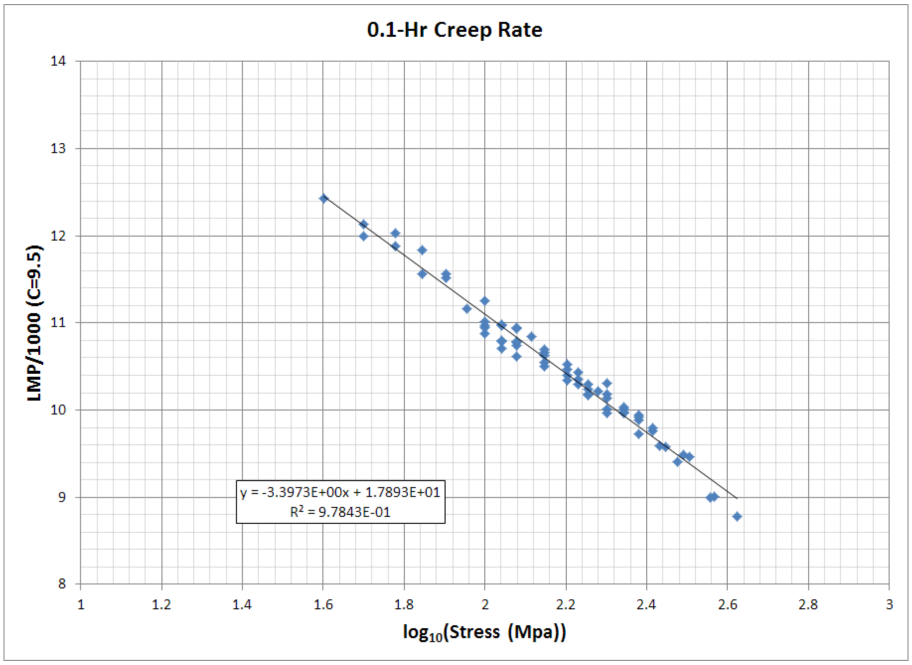

Figure 1.13. A Larson-Miller expression for Creep Rate at 0.1 hr based on Power-Law fit to primary creep portion of curve

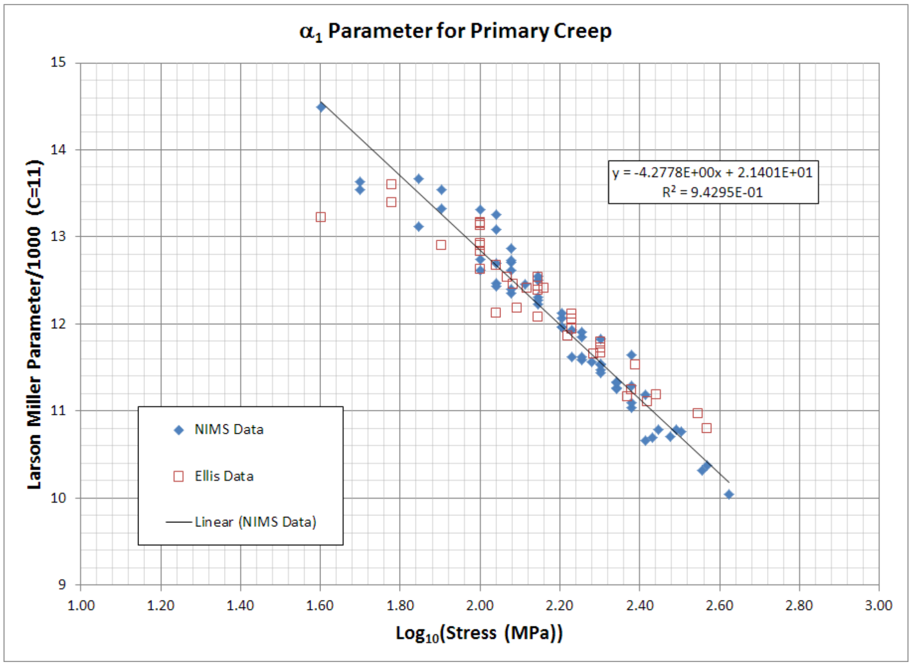

Figure 1.14. A Larson-Miller expression for the α_1 parameter based on consistency of time to rupture and estimated initial creep rate

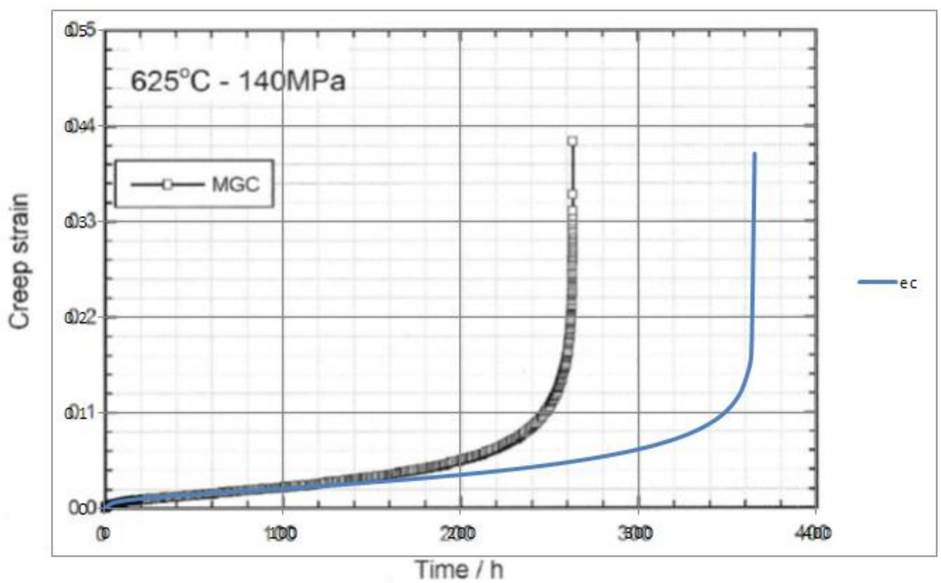

Figure 1.15. Example of the NLCM global fit

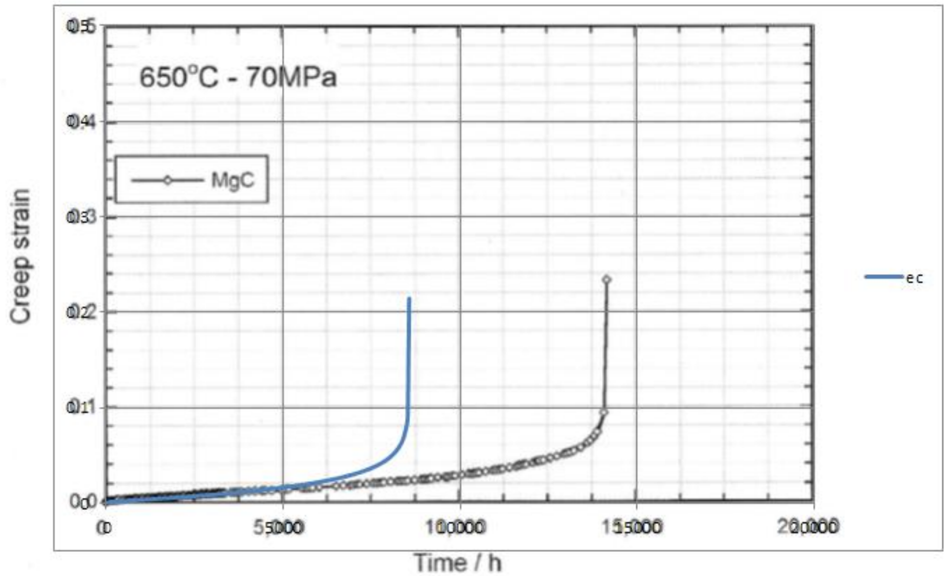

Figure 1.16. Example of the NLCM global fit

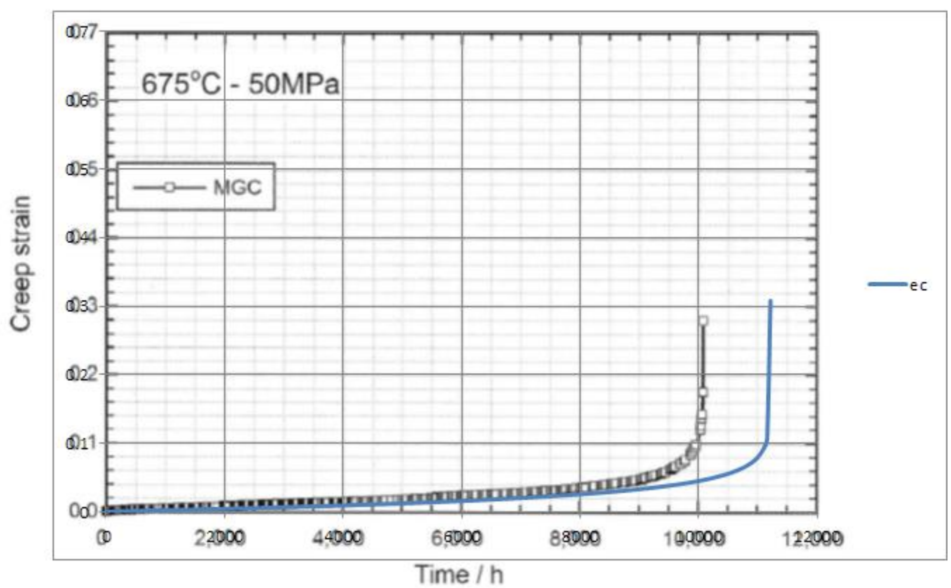

Figure 1.17. Example of the NLCM global fit

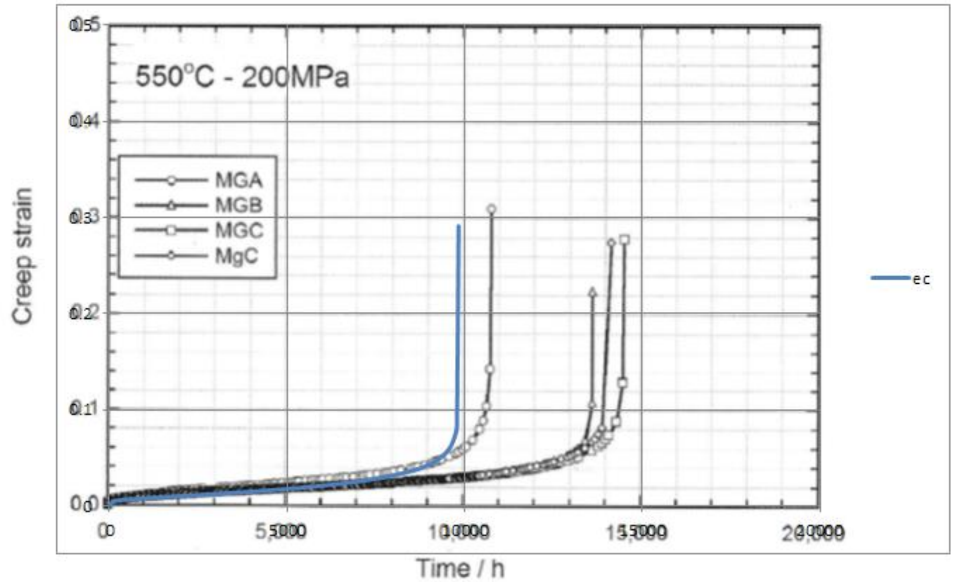

Figure 1.18. Example of the NLCM global fit

1.5 Summary of Model Equations and Coefficients

In summary the proposed non-linear combination model was constructed in the following way.

- A logarithmic-rate fit was calculated for the tertiary portion of the curve.
- Larson-Miller Relationships were determined for the two tertiary creep parameters.
- A power-law fit was constructed for the primary part of the curve.
- The 0.1-hr creep rate was determined from power law fits to the primary region of each creep curve.
- The 0.1-hr creep rate was taken to be the initial creep rate for primary creep, and expressed in terms of a Larson-Miller equation.
- From equation (1.30) a value of the α-parameter for primary creep was determined at each condition.

The NLCM equations are

$$\varepsilon_c = -\frac{1}{\alpha_3}\ln\left(\left(1+\alpha_1\dot{\varepsilon}_{01}t\right)^{-\frac{\alpha_3}{\alpha_1}} - \dot{\varepsilon}_{03}\alpha_3 t\right) \quad (1.35)$$

$$\frac{(T+273.15)}{1000}\left(C+\log_{10}(\alpha)\right) = a_0 + a_1\log_{10}(\sigma) + a_2\left[\log_{10}(\sigma)\right]^2 + a_3\left[\log_{10}(\sigma)\right]^3 \quad (1.36)$$

$$\frac{(T+273.15)}{1000}\left(C-\log_{10}(\dot{\varepsilon}_0)\right) = a_0 + a_1\log_{10}(\sigma) + a_2\left[\log_{10}(\sigma)\right]^2 + a_3\left[\log_{10}(\sigma)\right]^3 \quad (1.37)$$

Where stresses are in MPa and temperatures in Celsius.

	tertiary		primary	
	α_3	ε_{03}	α_1	ε_{01}
C	5.4	35.5	11	9.5
a_0	4.3485	94.259	21.401	17.893
a_1	3.3811	-77.416	-4.2778	-3.3973
a_2	-1.1642	38.209	0	0
a_3	0	-6.9091	0	0

1.6 Plasticity

The hot tensile curves needed for the isochronous stress-strain curves were developed from the modulus data provided in ASME BPVC Section II-D while the plasticity model was based on a modified Voce equation developed previously.[7]

The moduli data for Gr 91 steel are provided in the table below and are given in both customary and metric units. A polynomial is provided that permits the estimation of modulus values for temperatures not included in the table.

Moduli values for Gr 91 steel

Temp deg F	ASME II-D 1000 ksi	Polynomial Fit 1000 ksi	Temp deg C	ASME II-D GPa	Polynomial fit GPa
700	27.5	27.5	350	191	191
750		27.2	375		189
800	26.9	26.9	400	187	187
850		26.6	425		185
900	26.2	26.2	450	183	183
950		25.8	475		181
1000	25.4	25.4	500	179	179
1050		24.9	525		177
1100	24.4	24.4	550	174	174
1150		23.9	575		171
1200	23.3	23.3	600	168	168
			625		165
			650	161	161

CU units $E = 30.048 - 0.0031984\,T + 1.3095\,10^{-6}\,T^2 - 2.7778\,10^{-9}\,T^3$

SI units $E = 247.31 - 0.29484\,T + 0.0005381\,T^2 - 4.4444\,10^{-7}\,T^3$

The modified Voce equation for the "minimum" strength material is given by:

$$e_p = (1/b)\,\{\ln[(S_{pl} - S_U/1.1)/(S - S_U/1.1)]\}^2 \quad (1.38)$$

where the terms are described in the Abbreviations, above.

[7] Swindeman, R. W., "Construction of Isochronous Stress-Strain Curves for 9Cr-1Mo-V Steel," pp. 95-100 in PVP-Vol. 391, *Advances in Life Prediction Methodology*, American Society of Mechanical Engineers, New York, NY, 1999.

The coefficients of the modified Voce equation were evaluated by first inspecting the tensile yield curves for several heats and at several temperatures. The ratio of the proportional limit stress to the 0.2% offset yield stress was determined for temperatures from 700 to 1200°F. Using the ratios, the S_{pl} for the minimum strength curve was determined from the product of the ratio and *Y-1* or S_{Y1} provided Table Y-1 in ASME BPVC Section II-D or Table I-14.5 Section III, Subsection NH. Then, the *U* and S_U values from the Code tables were reduced by a factor of 1/1.1 to approximate the "minimum" ultimate strength.

The *Y-1* or S_{Y1} values were inserted into equation (1.38) and 0.2 replaced e_p. The equation was solved for (1/b). This completed the modified Voce equation for "minimum" strength material. Values for the coefficients are provided in the table below for the minimum strength hot tensile curve. Note that (1/b) in the supplied table is given in percent, hence e_p is in percent. A factor of 0.01 is needed to convert to in/in or m/m units.

Voce coefficients for minimum strength hot tensile CU units

Temp deg F	Spl ksi	S_{y1} ksi	$S_u/1.1$ ksi	1/b %
700	34.96	53.2	72.727	0.45965
750	33.913	52	70.545	0.43163
800	32.612	50.4	67.909	0.4069
850	31.361	48.5	64.636	0.38182
900	29.304	46.1	60.818	0.34503
950	27.036	43.4	56.545	0.30586
1000	23.274	40.2	51.818	0.24752
1050	19.188	36.6	46.727	0.19985
1100	15.607	32.7	41.364	0.16847
1150	12.537	28.6	35.818	0.14584
1200	10.014	24.2	30.182	0.1354

$e_p = (1/b)\{\ln[(S_{pl} - S_U/1.1)/(S - S_U/1.1)]\}^2$

note: for 1000°F and below S_U is replaced by *U* from ASME II-D

note: for 1000°F and below S_{Y1} is replaced by *Y-1* from ASME II-D

note: e_p is in %

For the "average" hot tensile curve, the ***Y-1*** and $\boldsymbol{S_{Y1}}$ values were increased by the factor 1.25 and were identified as S_{ys}. The increment associated with this increase, Δ, was given by 0.25 ***Y-1*** or 0.25 $\boldsymbol{S_{Y1}}$. The Δ was added to the S_{pl}, ***U***/1.1, and $\boldsymbol{S_U}$/1.1 values to become new S_{pl} and S_{uts}. The (1/b) values were then calculated by inserting 0.2 for e_p in the modified equation (1.39) and solving for (1/b). A table of values for the average hot tensile curves is provided below. Note that the (1/b) values are the same as those for the minimum strength hot tensile curves. Again, the strains are in percent. The average curve is produced by equation (1.39).

$$e_p = (1/b)\,[\ln[(S_{pl} - S_{uts})/(S - S_{uts})]\}^2 \qquad (1.39)$$

A typical tensile curve is shown in Figure 1.19 for a test at 1000°F and the curve may be compared to a calculated curve representing the minimum strength shown in Figure 1.20. The ***Y-1*** for 1000°F is 40.2 ksi which is well below the typical yield strength of 58 ksi. The "average" yield strength used for the hot tensile curve in equation (1.39) is 50.2 ksi is still below the typical value. The calculated curve exhibits more hardening than the typical curve as it increases toward the U/1.1 stress value. However, the average ultimate strength (61.9 ksi) is close to the typical strength (62 ksi). For Gr 91, it appears that the 1.25 factor is too low to represent the average yield strength at high temperatures.

Voce coefficients for average strength hot tensile CU units

Temp deg F	S_{pl} ksi	S_{ys} ksi	S_{uts} ksi	(1/b) %
700	48.26	66.5	86.03	0.4596
750	46.91	65.00	83.55	0.4316
800	45.21	63.0	80.51	0.4069
850	43.49	60.63	76.77	0.3818
900	40.83	57.63	72.35	0.3450
950	37.89	54.25	67.40	0.3059
1000	33.32	50.25	61.87	0.2475
1050	28.34	45.75	55.88	0.1998
1100	23.79	40.88	49.54	0.1685
1150	19.69	35.75	42.97	0.1458
1200	16.06	30.25	36.23	0.1354

$e_p = (1/b)\{\ln[(S_{pl} - S_{uts})/(S - S_{uts})]\}^2$

Note e_p is in percent

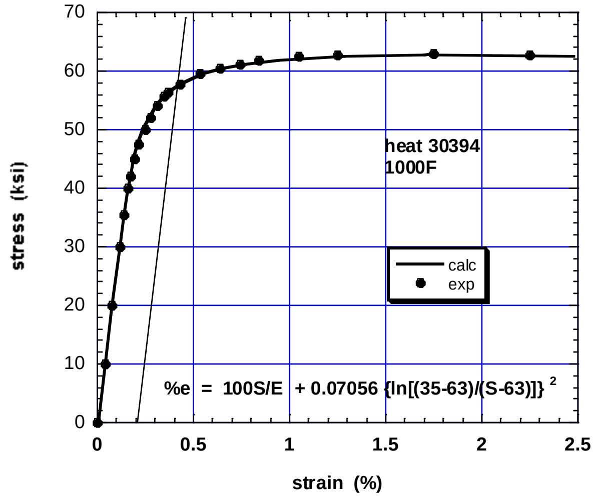

Figure 1.19. Fit of modified Voce equation to typical data

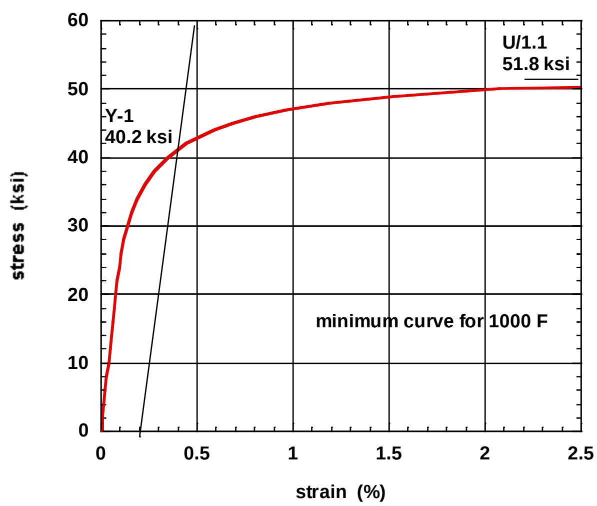

Figure 1.20. Calculated minimum strength tensile curve

1.7 Limitations of the Non-Linear Combination Model (NLCM) for Creep

It is the opinion of the authors that the question about which model provides the best fit to the data is beyond the expertise of any individual contributor. Here we present the data and methods, and remain open to criticism. Consideration should not only be given to the quality of the fit for the NIMS data but the quality of fit of other data sets, the robustness of the data (when it comes to extrapolation), the simplicity of expression, and, most importantly, the appropriateness of the model for its intended application. This requires the free and open exchange of ideas and the participation of engineers with different skills and backgrounds which we welcome.

One key limitation of the model comes in the description of the tertiary parameters. Outside the range of the data, the extrapolations appear to be suspect. This applicable stress range is roughly 30 MPa to 400 MPa (4.5 ksi to 60 ksi). A second limitation is that the parameters for the primary creep description are built entirely upon the NIMS data set. The results were compared against the Ellis data, but we did not attempt to find the best expression to fit both Ellis and NIMS data. Third, this data were digitized from scans, and though the accuracy of the digitization process is good, it does introduce small errors.

Though not limitations of the model per se other points deserve more consideration.

It is recognized that the NLCM has quite a bit of added complexity. It is hoped that the explanation in this report of the F-parameter provides a sufficient explanation as to why this form (equation 1.35) was chosen. Whether the Larson-Miller expression is "best" for the various parameters is subject to debate. Some small effort was made to explore the use of alternative parametric forms and stress functions beyond what has been presented here, but this avenue has not been fully explored.

Finally, the approach presented here was to build the method on the tertiary creep parameters and adjust the primary creep parameters to produce as accurate of rupture times as possible. This was done because the primary creep parameters appeared to be more problematic. However, in comparing the model with the BPV III-NH isochronous curves it appears that the NH curves have more strain at high temperatures and low stresses. Starting with the primary creep parameters and then adjusting the tertiary creep parameters may provide a different fit in this important region of the curve. Further investigation is recommended.

ABBREVIATIONS AND ACRONYMS (PART 2)

α_1 = initial creep factor
α_3 = creep factor
1/b = strain factor
Δ = 0.25 S_y
E = modulus of elasticity, ksi, obtained from ASME BPVC Section II-D
ε = total strain
ε_c = creep strain
ε_e = elastic strain
ε_p = plastic strain
ε_{pa} = plastic strain based on average stress values
ε_{pm} = plastic strain based on minimum stress values
$\dot{\varepsilon}_0$ = strain rate
$\dot{\varepsilon}_{01}$ = initial strain rate
F = temperature, °F
S = effective stress, ksi
S_{pl} = proportional stress limit, ksi
S_{pa} = S_{pl} + Δ, Average proportional stress limit, ksi
S_{pm} = minimum proportional stress limit, ksi
S_u/1.1 = minimum tensile strength, ksi, obtained from ASME BPVC Sections II-D and NH
S_{ua} = S_u/1.1 + Δ, Average tensile strength, ksi
S_y = minimum yield stress, ksi, obtained from ASME BPVC Sections II-D and NH.
t = time, hours

2 DEVELOPMENT OF ISOCHRONOUS CURVES AND CHARTS FOR 9CR-1MO-V STEELS

2.1 Basic Equations for Generating Isochronous Curves

The basic equations for generating isochronous stress-strain curves are derived by Swindeman and shown in Part 1. It consists of expressing the elastic, plastic, and creep strains as a function of stress. The strain expression is given by

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_c \qquad (2.1)$$

2.1.1 Elastic Strain

The elastic strain, ε_e, based on design values of modulus of elasticity, E, obtained from the ASME BPVC Section II-D Code is expressed as

$$\varepsilon\varepsilon = \Sigma/E \qquad (2.2)$$

The design values of modulus of elasticity, E, in Eq. (2.2) is a function of temperature. PART I gives a table showing the variation of E with respect to temperature taken from Section II-D of the ASME BPV Code. The data are also shown below in Table 2.1. An equation developed from regression analysis that represents the values in Table2.1 is given by

$$E = 31{,}430 - (6.5941)F + (0.003534)F^2 - (3.0247\text{x}10^{-6})F^3 \qquad (2.3)$$

Table 2.1. Design values of modulus of elasticity, E, at various temperatures from Table TM-1 of ASME BPVC Section II-D.

Temperature, ºF	E, ksi	Temperature, ºF	E, ksi
70	30958	800	26856
100	30797	850	26519
200	30260	900	26162
300	29719	950	25780
400	29176	1000	25370
500	28627	1050	24925
600	28067	1100	24443
700	27483	1150	23917
750	27176	1200	23343

2.1.2 Plastic Strain

The minimum plastic strain, ε_{pm}, is obtained from Eq. (1.38) of Part I and is expressed as

$$\varepsilon_{pm} = (1/b)\{\ln[(S_{pm} - S_u/1.1)/(S - S_u/1.1)]\}^2 \qquad S > S_{pl} \qquad (2.4a)$$

$$\varepsilon_{pm} = 0 \qquad S \le S_{pm} \qquad (2.4b)$$

The values of S_{pm}, S_u, and (1/b) are a function of the temperature, ºF. Part 1 gives a table showing the variation of S_{pm} , S_u , S_y, and (1/b) with respect to temperature. The values of S_u and S_y are obtained from Sections II-D and NH of the ASME BPV Code while the values of S_{pm} and (1/b) are taken from other references listed in Part 1. These values are also shown below in Table 2.2. Equations developed from regression analysis that represents the values in the table as a function of temperature are given by

$$S_{Pm} = -132.6445 + (0.56111)F - (0.00058894)F^2 + (1.8345\times10^{-7})F^3 \quad (2.5)$$

$$S_u/1.1 = -3.12091 + (0.29143)F - (0.00032029)F^2 + (8.37762\times10^{-8})F^3 \quad (2.6)$$

$$1/b = -0.0257828 + (0.00010860)F - (1.2357\times10^{-7})F^2 + (4.32502\times10^{-11})F^3 \quad (2.7)$$

$$S_y = 11.19394 + 0.14974F - 0.00014580F^2 + 2.50194\times10^{-8}F^3 \quad (2.8)$$

Table 2.2. Values of S_{pl} , S_y, S_u, and (1/b) at various temperatures

Temperature °F	S_{Pm} ksi	S_y Ksi	$S_u/1.1$ Ksi	1/b In/in
700	34.96	53.2	72.727	0.0045965
750	33.913	52.0	70.545	0.0043163
800	32.612	50.4	67.909	0.004069
850	31.361	48.5	64.636	0.0038182
900	29.304	46.1	60.818	0.0034503
950	27.036	43.4	56.545	0.0030586
1000	23.274	40.2	51.818	0.0024752
1050	19.188	36.6	46.727	0.0019985
1100	15.607	32.7	41.364	0.0016847
1150	12.537	28.6	35.818	0.0014584
1200	10.014	24.2	30.182	0.0013540

The units of the strain expression (1/b) in Eq. (2.7) are expressed in inch/inch. They differ from the units of the strain in Part 1 which are given as a percentage.

Similarly, the average plastic strain, ε_{pa}, is obtained from Eq. (1.39) of Part 1 and is expressed as

$$\varepsilon_{pa} = (1/b)\{\ln[((S_{pm} + \Delta) - (S_u/1.1 + \Delta))/(S - (S_u/1.1 + \Delta))]\}^2 \qquad S > (S_{pm} + \Delta) \quad (2.9a)$$

$$\varepsilon_{pa} = (1/b)\{\ln[(S_{pa} - S_{ua})/(S - S_{ua})]\}^2 \qquad S > S_{pa} \quad (2.9b)$$

$$\varepsilon_{pa} = 0 \qquad S \leq S_{pa} \quad (2.9c)$$

Where, $\Delta = 0.25S_y$.

2.1.3 Creep Strain

The creep strain, ε_c, is based on average creep data and is obtained from Appendix A shown at the end of this part.

$$\varepsilon_c = (-1/\alpha_3)\ln[(1 + \alpha_1 \dot{\varepsilon}_{01} t)^{-\alpha_3/\alpha_1} - \alpha_3 \dot{\varepsilon}_0 t)] \quad (2.10)$$

The values of α_1, α_3, $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$ are derived in Appendix A and are given by

$$\alpha_1 = EXP\{ K_6 + (K_2)[K_7 + K_8 \ln S]\} \quad (2.11)$$

$$\alpha_3 = EXP\{ K_1 + (K_2)[K_3 + K_4 \ln S + K_5(\ln S)^2]\} \quad (2.12)$$

$$\dot{\varepsilon}_0 = EXP\{ K_9 - (K_2)[K_{10} + K_{11} \ln S + K_{12}(\ln S)^2 + K_{13}(\ln S)^3]\} \quad (2.13)$$

$$\dot{\varepsilon}_{01} = EXP\{ K_{14} - (K_2)[K_{15} + K_{16} \ln S]\} \quad (2.14)$$

Where,

K_1 = -12.4338	K_2 = 1800/(F + 460)	K_3 = 14.6558
K_4 = 1.4278	K_5 = - 0.5056	K_6 = - 25.3281
K_7 = 41.0177	K_8 = -4.2777	K_9 = 81.7407
K_{10} = 120.0467	K_{11} = - 27.9095	K_{12} = 9.0461
K_{13} = -1.3030	K_{14} = 21.8743	K_{15} = 34.6401
K_{16} = -3.3972		

Equations (2.1), (2.2), (2.4), and (2.10) are the necessary equations needed to construct isochronous curves with minimum plastic strain for a given temperature and time. These isochronous curves with the minimum plastic strain are used in Part 3 to construct external pressure charts.

Similarly, Eqs. (2.1), (2.2), (2.9), and (2.10) are the necessary equations needed to construct average isochronous curves for a given temperature and time. These average isochronous curves are constructed here in Part 2.

Example 2.1
Determine the average isochronous curve for 9Cr-1Mo-V steel at 1070°F for 75 hours.

Solution:
From Eqs.(2.3) and (2.5) through (2.8) calculate the values at 1070°F:

E = 24,382 ksi	S_{pm} = 18.25 ksi	S_u/1.1 = 44.64 ksi
1/b = 0.001927	S_y = 35.14 ksi	Δ = 8.78 ksi
S_{pa} = 27.03 ksi	S_{ya} = 43.92 ksi	S_{ua} = 53.42 ksi

The elastic strain, ε_e , is obtained from Eq.(2.2) and the average plastic strain, ε_{pa}, is obtained from Eq.(2.9). These values are shown in Table 2.3.

Table 2.3 elastic and plastic strains

S, ksi	ε_e Eq. (2.2)	ε_{pa} Eq. (2.9)
0	0	0
0.1	4.101E-06	9.532E-04
1	4.101E-05	9.076E-04
2	8.203E-05	8.574E-04
4	1.641E-04	7.585E-04
6	2.461E-04	6.619E-04
8	3.281E-04	5.681E-04
10	4.101E-04	4.778E-04
12	4.922E-04	3.916E-04
14	5.742E-04	3.103E-04
16	6.562E-04	2.350E-04
18	7.383E-04	1.669E-04
20	8.203E-04	1.075E-04
22	9.023E-04	5.866E-05
23	9.433E-04	3.893E-05
24	9.843E-04	2.277E-05
26	1.066E-03	2.827E-06
28	1.148E-03	2.699E-06
30	1.230E-03	2.746E-05
32	1.312E-03	8.387E-05

The creep strain ε_c is calculated from Eq. (2.10) in conjunction with Eqs. (2.11) through (2.14). The calculated values are shown in Table 2.4.

Table 2.4. Creep strains

S, ksi	α_3 Eq.(2.12)	α_1 Eq.(2.11)	$\dot{\varepsilon}_0$ Eq.(2.13)	$\dot{\varepsilon}_{01}$ Eq.(2.14)	ε_c Eq.(2.10)
0	0	0	0	0	0
0.1	0.109	9.775E+14	4.966E-92	6.373E-13	1.015E-14
1	122.525	9.068E+09	1.457E-26	6.325E-09	9.227E-10
2	294.965	2.770E+08	1.119E-18	1.010E-07	2.761E-08
4	400.946	8.464E+06	6.652E-14	1.612E-06	8.189E-07
6	368.127	1.100E+06	5.069E-12	8.149E-06	5.920E-06
8	307.731	2.586E+05	6.554E-11	2.573E-05	2.404E-05
10	250.241	8.412E+04	4.172E-10	6.277E-05	7.117E-05
12	202.246	3.361E+04	1.877E-09	1.301E-04	1.726E-04
14	163.791	1.547E+04	6.956E-09	2.409E-04	3.649E-04
16	133.361	7.901E+03	2.289E-08	4.107E-04	6.979E-04
18	109.307	4.368E+03	6.959E-08	6.577E-04	1.237E-03
20	90.220	2.570E+03	2.002E-07	1.002E-03	2.068E-03
22	74.984	1.591E+03	5.527E-07	1.467E-03	3.303E-03
23	68.532	1.272E+03	9.071E-07	1.752E-03	4.119E-03
24	62.738	1.027E+03	1.478E-06	2.077E-03	5.100E-03
26	52.825	6.863E+02	3.852E-06	2.860E-03	7.712E-03
28	44.744	4.727E+02	9.824E-06	3.845E-03	1.162E-02
30	38.112	3.340E+02	2.460E-05	5.066E-03	1.795E-02
32	32.633	2.414E+02	6.059E-05	6.557E-03	3.003E-02

The total strain is calculated from Eq. (2.1) and is shown in Table 2.5.

Table 2.5. Total strain

S	ε Eq.(2.1)	ε_p excluded
0	0	yes
0.1	4.101E-06	yes
1	4.102E-05	yes
2	8.206E-05	yes
4	1.649E-04	yes
6	2.520E-04	yes
8	3.521E-04	yes
10	4.813E-04	yes
12	6.648E-04	yes
14	9.391E-04	yes
16	1.354E-03	yes
18	1.975E-03	yes
20	2.888E-03	yes
22	4.205E-03	yes
23	5.062E-03	yes
24	6.085E-03	yes
26	8.779E-03	yes
28	1.277E-02	No
30	1.918E-02	No
32	3.142E-02	No

A plot of the isochronous curve with average plastic strain at 1070ºF and 75 hours is shown in Figure 2.1.

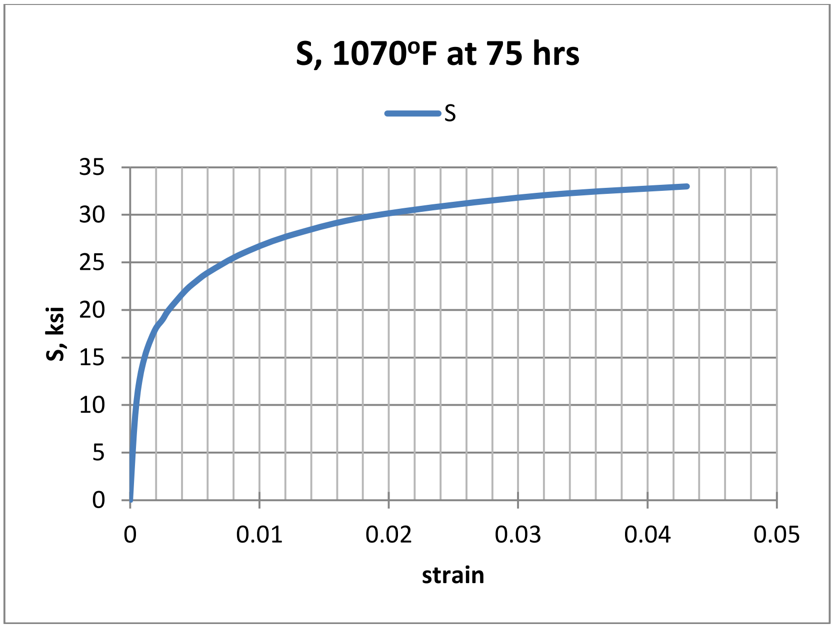

Figure 2.1. Average Isochronous curve at 1070ºF and 75 hours

Example 2.2
Compare the isochronous curve for 1000ºF at 10,000 hours using the average isochronous curve equations shown above and data shown in Section III-NH of the ASME BPV Code.

Solution
From Eqs. (2.1), (2.2), (2.9), and (2.10), the stress-strain values are calculated as shown in the first two columns of Table 2.4. The stress–strain values measured from the chart in NH for 9Cr-1Mo-V steel at 1000ºF at 10,000 hours are shown in the third and fourth columns of Table 2.6.

Table 2.6. Stress-strain relationship at 1000ºF for 10,000 hours

Equation 2.1	Equation 2.1	Section NH	Section NH
Total ε	Stress, ksi	Total ε	Stress, ksi
0	0	0	0
4.03E-06	0.1	0.0005	11.00
4.03E-05	1	0.001	14.38
8.05E-05	2	0.0015	17.00
0.000161	4	0.002	19.00
0.000243	6	0.0025	20.40
0.000329	8	0.003	21.50
0.000425	10	0.0035	22.50
0.000542	12	0.004	23.13
0.000694	14	0.0045	23.75
0.000905	16	0.005	24.38
0.001208	18	0.0055	24.75
0.001649	20	0.006	25.25
0.0023	22	0.007	25.88
0.002739	23	0.008	26.38
0.003285	24	0.009	26.88
0.004867	26	0.01	27.25
0.006064	27	0.011	27.50
0.007747	28	0.012	27.88
0.014484	30	0.014	28.63
0.017871	30.5	0.016	29.13
0.023097	31	0.018	29.63
0.032956	31.5	0.02	30.00
		0.022	30.38

The isochronous curves for the above two sets of data are shown in Fig. 2.2 below.

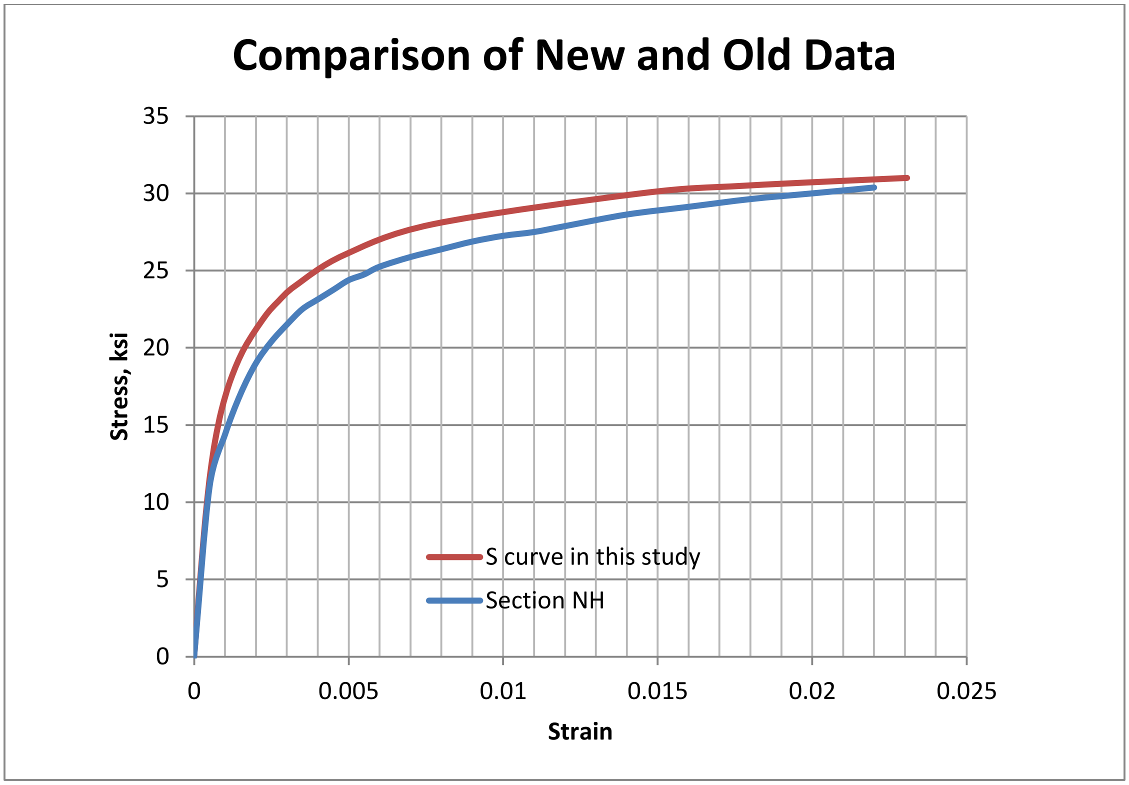

Figure 2.2. Isochronous curves for 1000°F and 10,000 hours

The figure indicates the curve in III-NH gives higher strain at a given stress (lower stress at a given strain) than the curve obtained from the equations above for a large range of stress values. This difference is due, in part, to the additional data available presently for 9Cr-1Mo-V steel compared to the data used when the original curves were constructed, and to the different methodology used in constructing the new isochronous curves.

2.2 Modified Equations for Developing Miscellaneous Isochronous Curves

Occasions arise where the basic isochronous curves discussed above may have to be adjusted upwards or downwards in order to take care of some special design conditions such as heat treating, upset conditions, and earthquake loading. In such cases a modification factor "f" can be inserted in the equations to accomplish such increase or decrease. The "f" factor is defined as follows.

$f = 1/(\text{increase or decrease in stress value}) \quad \text{for } S > S_{pl}$ (2.15a)

$f = 1.0 \quad \text{for } S \leq S_{pl}$ (2.15b)

Accordingly, if the isochronous stress-strain curve obtained from Eqs. (2.2), (2.4), and (2.10) or from Eqs. (2.2), (2.9), and (2.10) needs to be decreased by 20%, then f = 1/(1-0.2) = 1.25. Similarly, if the isochronous curve needs to be increased by 15%, then f = 1/(1 + 0.15) = 0.87.
Hence, the above strain equations can be modified as follows.

$\varepsilon_e = S/E$ (2.16)

$\varepsilon_{pm} = (1/b)\{\ln[(S_{pm} - S_u/1.1)/(fS - S_u/1.1)]\}^2 \quad \text{for } S > S_{pl}/f$ (2.17)

$\varepsilon_{pa} = (1/b)\{\ln[((S_{pm} + \Delta) - (S_u/1.1 + \Delta))/(fS - (S_u/1.1 + \Delta))]\} \quad \text{for } S > S_{pl}/f$ (2.18)

$\alpha_1 = \text{EXP}\{K_6 + (K_2)[K_7 + K_8 \ln(fS)]\}$ (2.19)

$\alpha_3 = \text{EXP}\{K_1 + (K_2)[K_3 + K_4 \ln(fS) + K_5(\ln(fS))^2]\}$ (2.20)

$$\dot{\varepsilon}_0 = EXP\{ K_9 - (K_2)[K_{10} + K_{11} \ln (f S) + K_{12}(\ln (f S))^2 + K_{13}(\ln (f S))^3]\} \quad (2.21)$$

$$\dot{\varepsilon}_{01} = EXP\{ K_{14} - (K_2)[K_{15} + K_{16} \ln (f S)]\} \quad (2.22)$$

Example 2.3
A vessel is operating at 1000°F. Determine the following isochronous curves for 5 hour duration.
Average isochronous curve.
Isochronous curve that is 15% higher than the average curve.
Isochronous curve that is 20% lower than the average curve.

Solution
a. strain values for the average curve are obtained from Eqs, (2.1), (2.2), (2.9), and (2.10). The values are summarized in the first two columns of Table 2.5
b. the stress-strain relationship is obtained from Eqs. (2.1), (2.2), (2.10), (2.16), (2.18) through (2.22) with an f value of 0.87. The values are summarized in column three of Table 2.5.
c. the stress-strain relationship is obtained from Eqs. (2.1), (2.2), (2.10), (2.16), (2.18) through (2.22) with an f value of 1.25. The values are summarized in column four of Table 2.7.

Table 2.7. Stress-strain relationship at 1000ºF for 5 hours

Stress	Average Iso curve	Iso curve 15% higher than average	Iso curve 20% lower than average
0	0	0	0
0.1	3.95E-06	3.9455E-06	3.9455E-06
1	3.95E-05	3.9455E-05	3.9455E-05
2	7.89E-05	7.8911E-05	7.8917E-05
4	0.000158	0.00015786	0.00015805
6	0.000237	0.00023701	0.00023846
8	0.000318	0.00031683	0.00032291
10	0.000402	0.00039818	0.00041658
12	0.000491	0.00048245	0.00052778
14	0.000591	0.00057169	0.00066858
16	0.000706	0.00066873	0.00085545
18	0.000844	0.00077722	0.00110973
20	0.001013	0.0009018	0.00145825
22	0.001226	0.00104818	0.00193388
23	0.001352	0.00113163	0.00223145
24	0.001495	0.00122319	0.00257623
26	0.001836	0.00143491	0.00343303
28	0.002269	0.00186719	0.00457555
30	0.002813	0.00212487	0.0061169
32	0.003494	0.00246111	0.00820026
33	0.003895	0.00266349	0.00952199
34	0.004345	0.00289154	0.01110368
36	0.005422	0.00343408	0.01549677
38	0.006784	0.00410945	0.02328971
40	0.008516	0.00494227	0.04117631
42	0.010766	0.00596313	0.11395816
44	0.013832	0.00721303	
46	0.018376	0.00875264	
48	0.026038	0.01068204	
50	0.041571	0.01318373	

The isochronous curves for the above three sets of data are shown in Fig. 2.3 below.

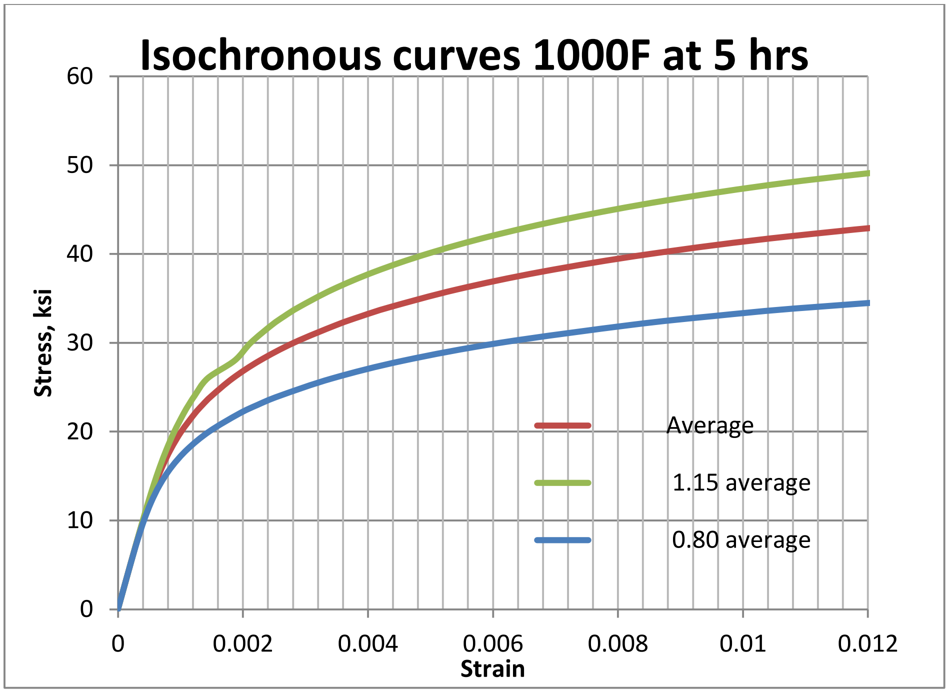

Figure 2.3. Isochronous curves for 1000ºF and 5 hours

A comparison of an isochronous curve obtained from the methodology described in this report with that from ASME-FFS1 for this material at 1000ºF and 10,000 hours is shown in Fig. 2.4. The figure shows that the difference between the two curves is small for values of strain larger than 0.25% but significant for strains less than 0.25%.

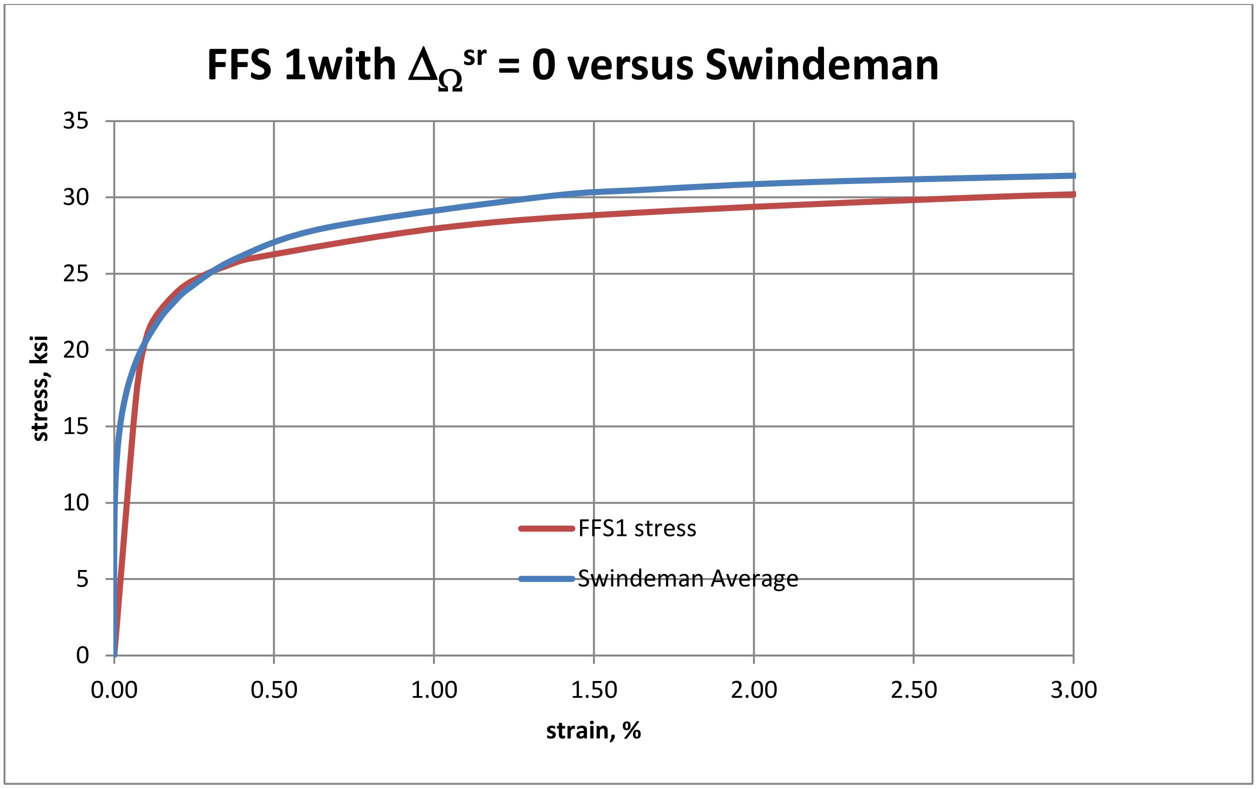

Figure 2.4 Comparison of an isochronous curve obtained from the methodology in this report versus that in ASME-FFS1

2.3 Summary of Procedure

The procedure for obtaining average isochronous curve for a given temperature and time is as follows.

1. For any given stress, determine the elastic strain ε_e from Eq. (2.2). The modulus of elasticity E in Eq. (2.2) is a function of temperature and is given by Eq. (2.3).
2. For any stress value above the proportional limit S_{pa}, determine the average plastic strain from Eq. (2.9). The values of S_{pl}, S_u, S_y, and (1/b) given in Eq. (2.9) are a function of temperature as given by Eqs. (2.5) through (2.8).
3. For any given stress, determine the creep strain ε_c from Eq. (2.10). The values of α_1, α_3, $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$ are given by Eqs. (2.11) through (2.14) and are a function of stress, temperature, and time.
4. The total strain ε is obtained from Eq. (2.1) and is the sum of the elastic, plastic, and creep strains.

2.4 Average Isochronous Curves

Section NH of the Nuclear Code and the newly developed Code Case 284383 for Section VIII-2 show isochronous curves with average values. Also, the design methodologies in NH and the newly developed Code Case are based on the average isochronous curves. Accordingly, in this part average isochronous stress-strain charts for 9Cr-1Mo-V (Grade 91) steel in increments of 50ºF from 800ºF to 1200ºF are developed as shown in Appendix B. These charts and tables were developed by Mike Swindeman and Robert Swindeman from the equations and data shown above.

- Figure B.1. Average isochronous curves at 800ºF
- Table B.1. Tabular values for average isochronous curves at 800ºF
- Figure B.2. Average isochronous curves at 850ºF
- Table B.2. Tabular values for average isochronous curves at 850ºF
- Figure B.3. Average isochronous curves at 900ºF
- Table B.3. Tabular values for average isochronous curves at 900ºF
- Figure B.4. Average isochronous curves at 950ºF
- Table B.4. Tabular values for average isochronous curves at 950ºF
- Figure B.5. Average isochronous curves at 1000ºF
- Table B.5. Tabular values for average isochronous curves at 1000ºF
- Figure B.6. Average isochronous curves at 1050ºF
- Table B.6. Tabular values for average isochronous curves at 1050ºF
- Figure B.7. Average isochronous curves at 1100ºF
- Table B.7. Tabular values for average isochronous curves at 1100ºF
- Figure B.8. Average isochronous curves at 1150ºF
- Table B.8. Tabular values for average isochronous curves at 1150ºF
- Figure B.9. Average isochronous curves at 1200ºF
- Table B.9. Tabular values for average isochronous curves at 1200ºF

APPENDIX A CONVERSION OF α_1, α_3, $\dot{\varepsilon}_0$, AND $\dot{\varepsilon}_{01}$ VALUES

The values of α_1, α_3, $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$ are defined in Part 1 of the report in terms of stress MPa, temperature °C, and logarithm to the base 10, $\log_{10}$, as:

$$\frac{(C+273.15)}{1000}(11.0 + \log_{10}(\alpha_1)) = 21.401 - 4.2778 \log_{10}(S) \quad \text{(A1)}$$

$$\frac{(C+273.15)}{1000}(5.4 + \log_{10}(\alpha_3)) = 4.3485 + 3.3811 \log_{10}(S) - 1.1642[\log_{10}(S)]^2 \quad \text{(A2)}$$

$$\frac{(C+273.15)}{1000}(35.5 - \log_{10}(\dot{\varepsilon}_0)) = 94.259 - 77.416 \log_{10}(S) + 38.209[\log_{10}(S)]^2 - 6.9091[\log_{10}(S)]^3 \quad \text{(A3)}$$

$$\frac{(C+273.15)}{1000}(9.5 - \log_{10}(\dot{\varepsilon}_{01})) = 15.04606 - 1.47542 \log_{10}(S) \quad \text{(A4)}$$

In order to facilitate further calculations, the above four equations are rewritten in terms of stress in ksi, temperature in °F, and natural log, ln, by substituting

$$F = 1.8C + 32$$
$$S_{ksi} = S_{MPa}/6.895$$
$$\text{Log}_{10}(x) = \ln(x)/\ln 10 = \ln(x)/2.3026$$

Equations (A1) through (A4) become

$$\frac{(F+460)}{1800}(11.0 + 0.4343 \ln \alpha_1) = 17.8140 - 1.8578 \ln S \quad \text{(A5)}$$

$$\frac{(F+460)}{1800}(5.4 + 0.4343 \ln \alpha_3) = 6.3650 + 0.6201 (\ln S) - 0.2196 (\ln S)^2 \quad \text{(A6)}$$

$$\frac{(F+460)}{1800}(35.5 - 0.4343 \ln \dot{\varepsilon}_0) = 52.1363 - 12.1211 (\ln S) + 3.9287 (\ln S)^2 - 0.5659(\ln S)^3 \quad \text{(A7)}$$

$$\frac{(F+460)}{1800}(9.5 - 0.4343 \ln \dot{\varepsilon}_{01}) = 15.0442 - 1.4754 \ln S \quad \text{(A8)}$$

Equations (A5) through (A8) can be solved for of α_1, α_3, $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$ to give

$$\alpha_1 = \text{EXP}\{-25.3281 + \left(\frac{1800}{F+460}\right)[41.0177 - 4.2777 \ln S]\} \quad \text{(A9)}$$

$$\alpha_3 = \text{EXP}\{ -12.4338 + \left(\frac{1800}{F + 460}\right)[14.6558 + 1.4278 \ln S - 0.5056(\ln S)^2]\} \qquad \text{(A10)}$$

$$\dot{\varepsilon}_0 = \text{EXP}\{ 81.7407 - \left(\frac{1800}{F + 460}\right)[120.0467 - 27.9095 \ln S + 9.0461(\ln S)^2 - 1.3030(\ln S)^2]\} \qquad \text{(A11)}$$

$$\dot{\varepsilon}_{01} = \text{EXP}\{ 21.8743 - \left(\frac{1800}{F + 460}\right)[34.6401 - 3.3972 \ln S]\} \qquad \text{(A12)}$$

Let

$K_1 = -12.4338$	$K_2 = 1800/(F + 460)$	$K_3 = 14.6558$
$K_4 = 1.4278$	$K_5 = - 0.5056$	$K_6 = - 25.3281$
$K_7 = 41.0177$	$K_8 = -4.2777$	$K_9 = 81.7407$
$K_{10} = 120.0467$	$K_{11} = - 27.9095$	$K_{12} = 9.0461$
$K_{13} = -1.3030$	$K_{14} = 21.8743$	$K_{15} = 34.6401$
$K_{16} = -3.3972$		

Equations (A9) through (A12) become

$$\alpha_1 = \text{EXP}\{ K_6 + (K_2)[K_7 + K_8 \ln S]\} \qquad \text{(A13)}$$

$$\alpha_3 = \text{EXP}\{ K_1 + (K_2)[K_3 + K_4 \ln S + K_5(\ln S)^2]\} \qquad \text{(A14)}$$

$$\dot{\varepsilon}_0 = \text{EXP}\{ K_9 - (K_2)[K_{10} + K_{11} \ln S + K_{12}(\ln S)^2 + K_{13}(\ln S)^3]\} \qquad \text{(A15)}$$

$$\dot{\varepsilon}_{01} = \text{EXP}\{ K_{14} - (K2)[K_{15} + K_{16} \ln S]\} \qquad \text{(A16)}$$

APPENDIX B AVERAGE ISOCHRONOUS STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES

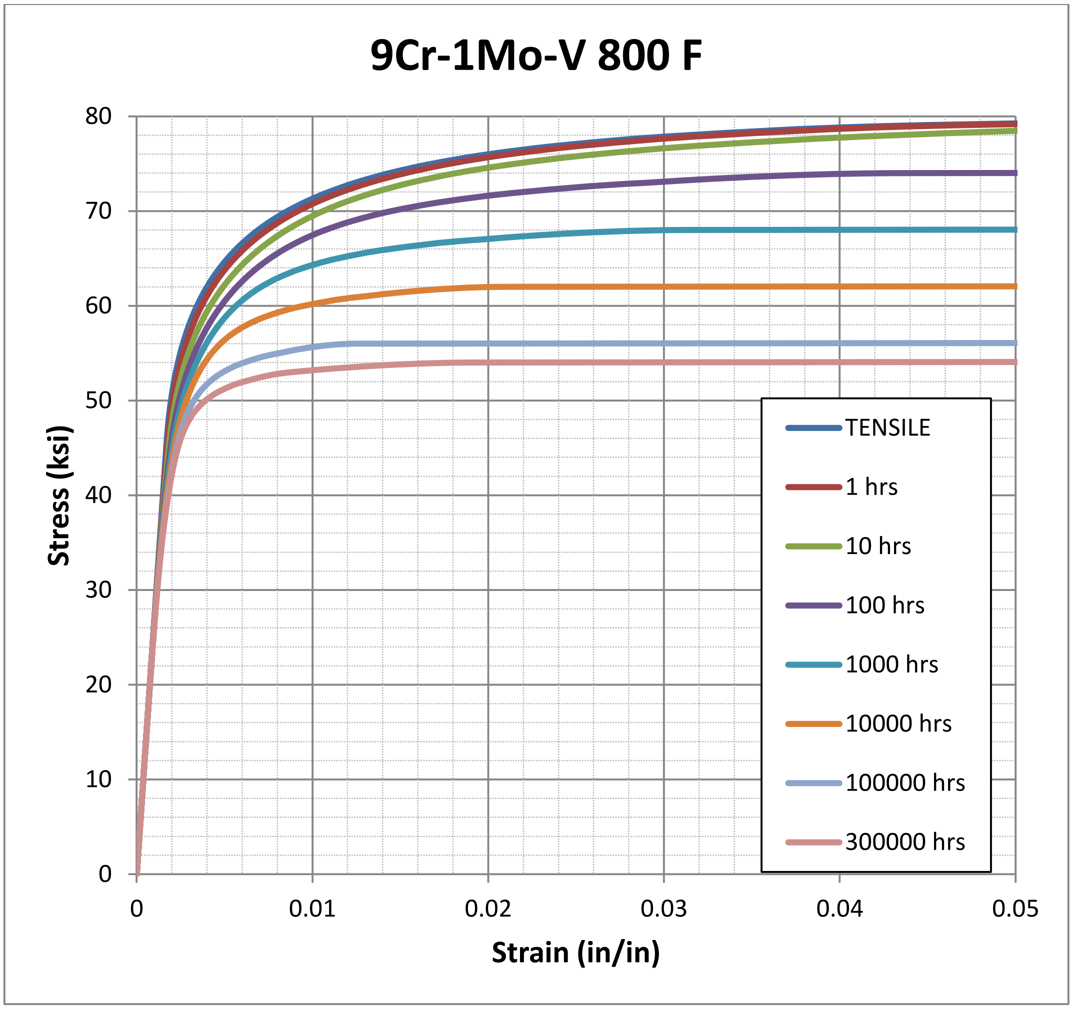

Figure B.1. Average isochronous curves at 800ºF

Table B.1. Tabular values for average isochronous curves at 800ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	7.44713E-05	7.44713E-05	7.44713E-05	7.44713E-05
4	0.000148943	0.000148943	0.000148943	0.000148943
6	0.000223414	0.000223414	0.000223415	0.000223415
8	0.000297885	0.000297889	0.000297891	0.000297894
10	0.000372356	0.000372369	0.00037238	0.00037239
12	0.000446828	0.000446864	0.000446895	0.000446928
14	0.000521299	0.000521386	0.000521466	0.000521549
16	0.00059577	0.000595955	0.000596135	0.000596322
18	0.000670241	0.0006706	0.000670966	0.00067135
20	0.000744713	0.000745359	0.000746052	0.00074678
22	0.000819184	0.000820282	0.000821514	0.000822818
24	0.000893655	0.000895433	0.000897516	0.000899734
26	0.000968126	0.000970894	0.000974268	0.000977881
28	0.001042598	0.00104676	0.00105203	0.001057709
30	0.001117069	0.00112315	0.001131126	0.001139776
32	0.00119154	0.001200199	0.001211949	0.001224771
34	0.001266011	0.001278069	0.001294968	0.001313525
36	0.001340483	0.001356945	0.001380739	0.001407032
38	0.001414954	0.001437039	0.001469914	0.001506469
40	0.001489425	0.001518589	0.001563247	0.001613218
41	0.001526661	0.001559994	0.00161174	0.001669826
42	0.001563896	0.001601867	0.001661608	0.001728882
43	0.001601132	0.001644246	0.00171298	0.001790625
44	0.001638368	0.001687172	0.001765992	0.001855313
45	0.001675603	0.001730688	0.001820789	0.001923218
46	0.001714923	0.001776925	0.00187961	0.00199672
47	0.001761094	0.001830694	0.001947385	0.002080897
48	0.001814894	0.001892826	0.002025067	0.002176864
49	0.001877036	0.001964083	0.002113551	0.002285691
50	0.001948312	0.002045314	0.002213825	0.002408557
51	0.002029616	0.002137468	0.002326988	0.002546767
52	0.002121949	0.002241608	0.00245426	0.002701773
53	0.002226446	0.00235893	0.002597007	0.002875203
54	0.002344392	0.002490783	0.00275676	0.003068888
55	0.002477252	0.002638702	0.002935245	0.003284914
56	0.002626699	0.002804433	0.003134419	0.003525679
57	0.00279466	0.002989975	0.003356512	0.003793983
58	0.002983358	0.003197635	0.003604087	0.004093143
59	0.00319538	0.003430082	0.003880107	0.00442717

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
60	0.003433747	0.003690432	0.004188028	0.004801021
61	0.00370202	0.003982346	0.004531928	0.005220975
62	0.004004418	0.004310159	0.004916667	0.005695195
63	0.004345987	0.004679051	0.00534811	0.006234583
64	0.004732819	0.005095271	0.005833444	0.006854091
65	0.005172337	0.005566445	0.006381606	0.007574781
66	0.005673692	0.006101984	0.007003907	0.008427083
67	0.006248316	0.006713672	0.007714928	0.009456122
68	0.006910692	0.007416487	0.00853384	0.0107307
69	0.007679491	0.008229802	0.009486373	0.012359206
70	0.008579246	0.009179188	0.010607827	0.014519792
71	0.009642958	0.010299176	0.011947757	0.01752364
72	0.010916245	0.011637684	0.013577482	0.021968869
73	0.012464322	0.013263399	0.015602534	0.029215791
74	0.014384383	0.015278782	0.018184236	0.043705766
75	0.016829222	0.01784465	0.02157945	1.016829222
76	0.020056668	0.021231097	0.026220012	
77	0.024547167	0.025937382	0.032891123	
78	0.031341082	0.033032864	0.043208304	
79	0.043361738	0.045485867	0.061328609	
80	0.076034071	0.078791874	0.106069881	

Table B.1. Tabular values for average isochronous curves at 800°F (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
2	7.44713E-05	7.44713E-05	7.44713E-05	7.44713E-05
4	0.000148943	0.000148943	0.000148943	0.000148943
6	0.000223416	0.000223416	0.000223417	0.000223417
8	0.000297897	0.000297899	0.000297902	0.000297903
10	0.000372401	0.000372411	0.000372422	
12	0.00044696	0.000446992	0.000447025	
14	0.000521632	0.000521714	0.000521797	
16	0.000596509	0.000596696	0.000596884	
18	0.000671734	0.000672119	0.000672504	
20	0.000747513	0.000748246	0.000748979	0.000372427
22	0.000824129	0.000825442	0.000826754	0.00044704
24	0.000901966	0.000904199	0.000906433	0.000521837
26	0.000981521	0.000985164	0.000988807	0.000596973
28	0.001063433	0.001069163	0.001074895	0.000672688
30	0.001148503	0.001157237	0.001165978	0.000749329
32	0.001237716	0.001250674	0.001263651	0.000827381

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
34	0.001332273	0.001351045	0.00136987	0.000907499
36	0.001433616	0.001460245	0.001487024	0.000990547
38	0.001543462	0.001580541	0.001618051	0.001077633
40	0.001663832	0.00171463	0.001766657	0.00117016
41	0.001728688	0.001787828	0.001849036	0.001269875
42	0.001797091	0.001865729	0.001937838	0.001378949
43	0.001869399	0.001948843	0.002034101	0.00150009
44	0.001945995	0.002037744	0.002139209	0.001636788
45	0.002027297	0.002133087	0.002255081	0.001793893
46	0.00211584	0.002237725	0.00238659	0.001882313
47	0.002216882	0.002357356	0.002542692	0.001979105
48	0.002331745	0.002493933	0.00273067	0.002086317
49	0.002461743	0.002649712	0.002961596	0.00220699
50	0.002608356	0.002827605	0.00325321	0.002345788
51	0.002773277	0.003031535	0.003634913	0.002512177
52	0.00295847	0.00326699	0.004157492	0.002722921
53	0.003166274	0.003541945	0.004913943	0.00299886
54	0.003399547	0.003868372	0.006091	0.003375415
55	0.003661889	0.004264823	0.008130745	0.00391642
56	0.003957991	0.004760921	0.012533812	0.004746369
57	0.004294189	0.005405634	1.00279466	0.00614338
58	0.004679321	0.006283546		0.008925386
59	0.00512613	0.007550483		0.019254317
60	0.005653531	0.009524997		1.002477252
61	0.006290421	0.012994844		
62	0.007082271	0.020999575		
63	0.00810313	1.004345987		
64	0.009479143			
65	0.011439842			
66	0.014449656			
67	0.019648222			
68	0.031411164			
69	1.007679491			

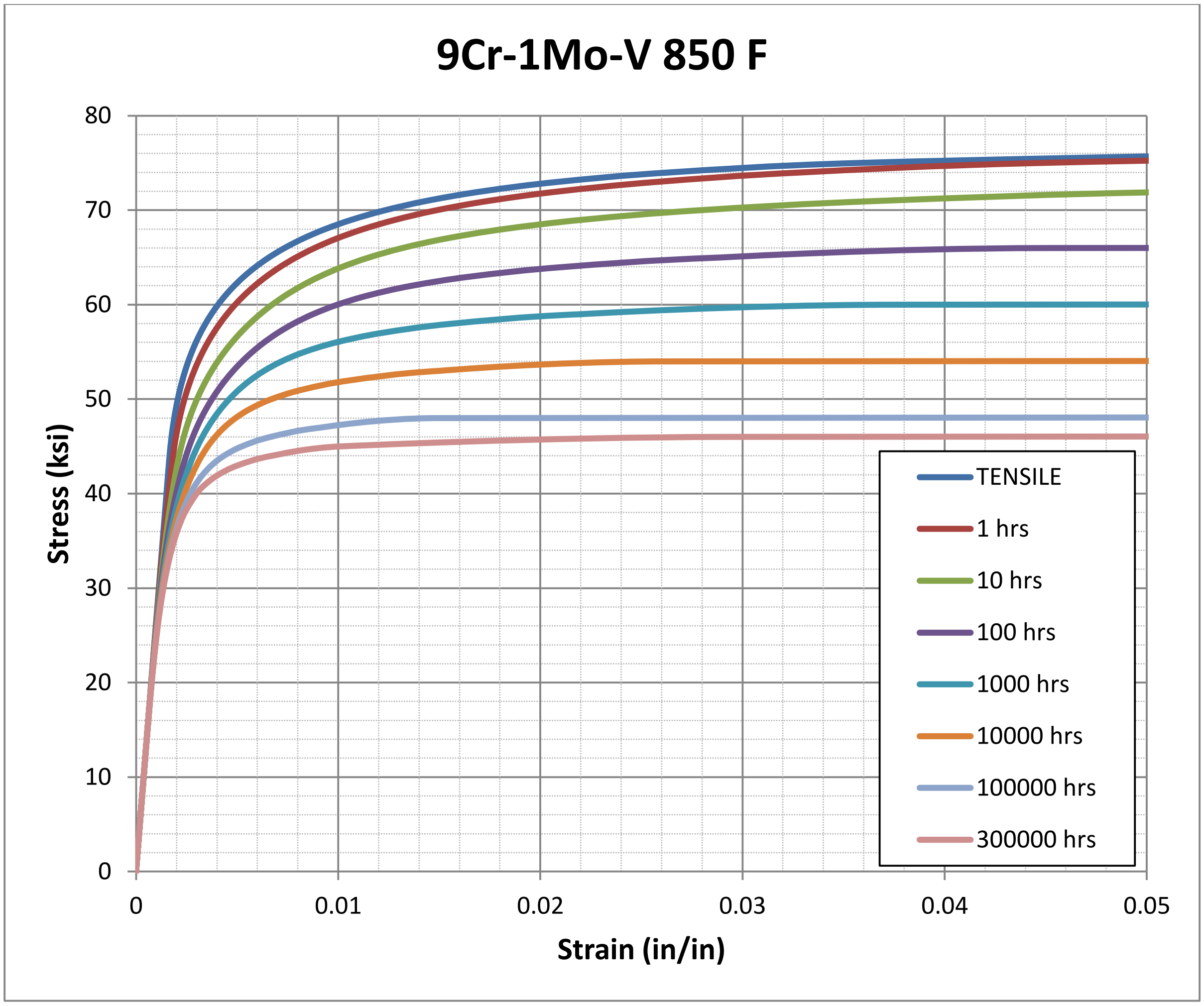

Figure B.2. Average isochronous curves at 850ºF

Table B.2. Tabular values for average isochronous curves at 850ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	7.54176E-05	7.54176E-05	7.54176E-05	7.54176E-05
4	0.000150835	0.000150836	0.000150836	0.000150836
6	0.000226253	0.000226257	0.00022626	0.000226263
8	0.000301671	0.00030169	0.000301705	0.000301721
10	0.000377088	0.000377154	0.00037721	0.000377268
12	0.000452506	0.000452682	0.000452845	0.000453014
14	0.000527923	0.000528329	0.00052873	0.000529147
16	0.000603341	0.000604174	0.000605046	0.00060596
18	0.000678759	0.000680324	0.000682053	0.000683878
20	0.000754176	0.000756924	0.000760111	0.000763498
22	0.000829594	0.000834155	0.000839692	0.000845618
24	0.000905012	0.000912245	0.000921407	0.000931281

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
26	0.000980429	0.000991469	0.001006019	0.001021811
28	0.001055847	0.001072156	0.001094471	0.001118861
30	0.001131264	0.00115469	0.001187902	0.001224455
32	0.001206682	0.001239522	0.001287672	0.001341039
34	0.0012821	0.001327164	0.001395384	0.001471526
36	0.001357517	0.001418199	0.001512906	0.001619356
38	0.001432935	0.001513286	0.0016424	0.001788544
40	0.001508353	0.00161316	0.001786337	0.001983753
41	0.001546061	0.001665144	0.001864588	0.002092766
42	0.00158377	0.001718638	0.001947533	0.002210366
43	0.001621479	0.001773757	0.002035583	0.002337356
44	0.001660098	0.001831534	0.002130084	0.002475517
45	0.001705129	0.001897596	0.002236998	0.002631293
46	0.001758084	0.001973589	0.00235833	0.002807228
47	0.001819745	0.002060434	0.002495385	0.00300525
48	0.001890992	0.002159159	0.002649601	0.00322753
49	0.00197282	0.002270911	0.00282257	0.003476558
50	0.002066356	0.002396978	0.003016069	0.003755241
51	0.002172882	0.002538814	0.003232089	0.004067065
52	0.002293866	0.002698069	0.003472886	0.004416329
53	0.002430994	0.002876622	0.003741044	0.004808511
54	0.002586211	0.003076632	0.004039561	0.005250831
55	0.002761778	0.003300597	0.004371972	0.005753126
56	0.002960335	0.003551424	0.004742518	0.00632923
57	0.003184987	0.003832536	0.005156405	0.006999171
58	0.00343941	0.004147997	0.005620156	0.007792717
59	0.003727996	0.004502688	0.006142161	0.008755255
60	0.004056034	0.004902545	0.006733469	0.009957846
61	0.004429956	0.005354886	0.007408999	0.01151528
62	0.004857677	0.005868867	0.008189375	0.013620779
63	0.005349053	0.006456136	0.009103755	0.016619787
64	0.005916531	0.007131763	0.010194266	0.021192046
65	0.006576096	0.007915625	0.011523092	0.028922292
66	0.007348653	0.008834465	0.013184137	0.04513618
67	0.008262167	0.009925041	0.015323022	1.008262167
68	0.009355028	0.011239083	0.018173296	
69	0.010681649	0.01285132	0.022127524	
70	0.012322246	0.014873069	0.02789383	
71	0.014401113	0.017476566	0.036906821	
72	0.017123909	0.020942042	0.05277884	
73	0.020863109	0.025759553	0.091362257	
74	0.026389751	0.032889352	1.026389751	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
75	0.035696072	0.044637738		
76	0.057027712	0.069797343		

Table B.2. Tabular values for average isochronous curves at 850°F (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
2	7.54176E-05	7.54177E-05	7.54177E-05	7.54177E-05
4	0.000150836	0.000150837	0.000150837	0.000150837
6	0.000226265	0.000226268	0.000226271	0.000226273
8	0.000301736	0.000301752	0.000301768	0.000301775
10	0.000377326	0.000377384	0.000377442	0.000377469
12	0.000453183	0.000453353	0.000453522	0.000453603
14	0.000529566	0.000529986	0.000530405	0.000530605
16	0.000606878	0.000607797	0.000608716	0.000609155
18	0.000685714	0.00068755	0.000689387	0.000690264
20	0.000766907	0.000770319	0.000773732	0.000775363
22	0.000851587	0.000857561	0.000863541	0.000866402
24	0.000941235	0.000951198	0.000961178	0.000965968
26	0.001037744	0.001053695	0.001069695	0.00107742
28	0.00114349	0.001168157	0.001192968	0.001205084
30	0.0012614	0.001298425	0.001335879	0.001354583
32	0.001395028	0.001449202	0.001504631	0.001533543
34	0.00154864	0.001626201	0.001707396	0.001753331
36	0.001727305	0.001836397	0.001955895	0.002033707
38	0.001937014	0.002088506	0.002269517	0.00241581
40	0.002184866	0.002394102	0.002686583	0.003000552
41	0.002325691	0.002571971	0.002958019	0.003443523
42	0.002479397	0.002770396	0.003296516	0.004077495
43	0.002647393	0.00299357	0.003737058	0.005054752
44	0.002832226	0.003248389	0.004341873	0.006726507
45	0.003041358	0.003549232	0.005230693	0.010193634
46	0.003278734	0.003911229	0.00663991	0.029623154
47	0.003548282	0.004356684	0.009148742	1.001819745
48	0.003855127	0.004921517	0.014921961	
49	0.004206224	0.005665728	1.00197282	
50	0.004611381	0.00669435		
51	0.005084914	0.00820431		
52	0.005648396	0.010608866		
53	0.006335296	0.01497958		
54	0.00719911	0.026058955		
55	0.008328363	1.002761778		

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
56	0.009876407			
57	0.012127622			
58	0.015671661			
59	0.022013285			
60	0.037554236			
61	1.004429956			

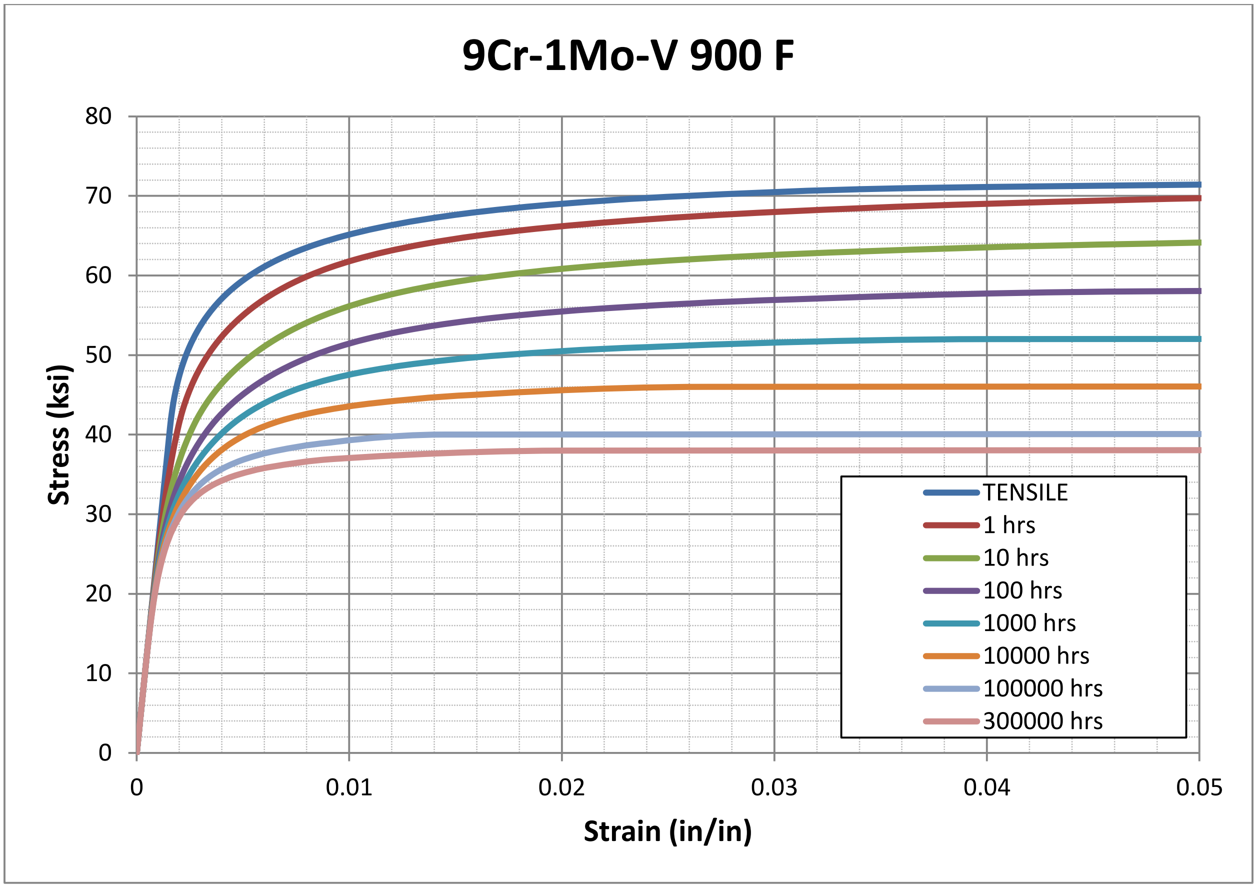

Figure B.3. Average isochronous curves at 900ºF

Table B.3. Tabular values for average isochronous curves at 900ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	7.64468E-05	7.64468E-05	7.64468E-05	7.64469E-05
4	0.000152894	0.000152896	0.000152897	0.000152899
6	0.00022934	0.00022936	0.000229375	0.000229391
8	0.000305787	0.000305878	0.000305955	0.000306034
10	0.000382234	0.000382526	0.000382795	0.000383074
12	0.000458681	0.000459434	0.000460185	0.000460968

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
14	0.000535127	0.000536802	0.000538584	0.000540455
16	0.000611574	0.000614908	0.000618669	0.000622651
18	0.000688021	0.000694122	0.000701385	0.000709135
20	0.000764468	0.000774923	0.000787994	0.000802052
22	0.000840914	0.0008579	0.000880124	0.000904214
24	0.000917361	0.000943773	0.000979826	0.001019212
26	0.000993808	0.001033396	0.001089619	0.001151523
28	0.001070255	0.001127769	0.001212551	0.001306633
30	0.001146701	0.001228047	0.00135225	0.001491158
31	0.001184925	0.001280806	0.001429692	0.00159686
32	0.001223148	0.001335549	0.001512976	0.001712977
33	0.001261371	0.001392467	0.001602744	0.001840713
34	0.001299595	0.001451764	0.001699683	0.001981376
35	0.001337818	0.001513654	0.00180453	0.002136376
36	0.001376042	0.001578363	0.001918072	0.002307242
37	0.001414265	0.001646129	0.002041152	0.002495628
38	0.001452488	0.001717204	0.002174665	0.002703336
39	0.001490712	0.001791851	0.00231957	0.002932338
40	0.001528935	0.001870347	0.002476888	0.003184815
41	0.001567259	0.001953083	0.002647812	0.003463315
42	0.001610318	0.002045	0.002838148	0.003775276
43	0.00166116	0.002149465	0.003052209	0.004127048
44	0.001720593	0.002267626	0.00329218	0.004523458
45	0.001789531	0.002400759	0.003560498	0.004970504
46	0.001869017	0.002550287	0.00385991	0.005475924
47	0.001960236	0.002717812	0.004193571	0.00605009
48	0.002064549	0.002905148	0.004565179	0.006707428
49	0.002183525	0.003114372	0.004979172	0.0074687
50	0.002318979	0.003347882	0.005441039	0.008364718
51	0.002473028	0.003608487	0.005957769	0.009442503
52	0.002648149	0.003899517	0.006538553	0.010775852
53	0.002847271	0.004224989	0.007195843	0.012484235
54	0.003073872	0.00458983	0.007946996	0.014768895
55	0.003332126	0.005000201	0.00881683	0.017988569
56	0.003627083	0.005463956	0.009841651	0.022842261
57	0.003964918	0.005991313	0.011075723	0.03092008
58	0.004353271	0.006595843	0.012601906	0.047212167
59	0.004801718	0.007295926	0.014549801	0.153303347
60	0.005322441	0.008116932	0.017128315	1.005322441
61	0.005931211	0.009094532	0.02068847	
62	0.006648858	0.010279776	0.025857955	
63	0.007503554	0.011747047	0.033877689	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
64	0.008534496	0.013606802	0.047683093	
65	0.009798151	0.016026677	0.077599791	
66	0.011379458	0.019267965	1.011379458	
67	0.013413517	0.023752582		
68	0.016131846	0.0301966		
69	0.019975337	0.039909757		
70	0.025931661	0.055597416		
71	0.036960715	0.084261229		
72	0.072634458	0.159353229		

Table B.3. Tabular values for average isochronous curves at 900°F (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
2	7.64469E-05	7.64469E-05	7.6447E-05	7.6447E-05
4	0.0001529	0.000152902	0.000152904	0.000152904
6	0.000229406	0.000229422	0.000229437	0.000229445
8	0.000306113	0.000306192	0.000306271	0.000306309
10	0.000383354	0.000383634	0.000383915	0.000384048
12	0.000461754	0.00046254	0.000463327	0.000463703
14	0.000542336	0.000544219	0.000546103	0.000547006
16	0.000626657	0.000630666	0.000634683	0.000636616
18	0.000716938	0.00072475	0.000732591	0.000736386
20	0.000816221	0.00083041	0.000844694	0.000851692
22	0.000928518	0.000952874	0.000977531	0.000989886
24	0.001058989	0.001098897	0.001139746	0.001161078
26	0.001214113	0.001277047	0.001342837	0.001379861
28	0.001401885	0.001498069	0.001602765	0.001669667
30	0.00163204	0.001775489	0.001943951	0.002074892
31	0.001766596	0.001940607	0.002157329	0.002348118
32	0.001916333	0.00212682	0.002410123	0.002696887
33	0.00208311	0.0023374	0.002715768	0.00316143
34	0.002268981	0.002576424	0.003095526	0.003814114
35	0.002476242	0.002849182	0.003584484	0.004795742
36	0.002707495	0.003162863	0.004243308	0.006418352
37	0.002965745	0.003527678	0.005183504	0.009577034
38	0.00325456	0.003958767	0.006629899	0.020069404
39	0.003578322	0.004479487	0.00911598	1.001490712
40	0.00394263	0.005127244	0.014447606	
41	0.004355055	0.005964445	1.001567259	
42	0.00483063	0.00710456		

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
43	0.005387478	0.008753879		
44	0.006049062	0.011335652		
45	0.006851475	0.015920631		
46	0.007852153	0.02688046		
47	0.009145922	1.001960236		
48	0.010896783			
49	0.013407892			
50	0.017303094			
51	0.024145137			
52	0.040187871			
53	1.002847271			

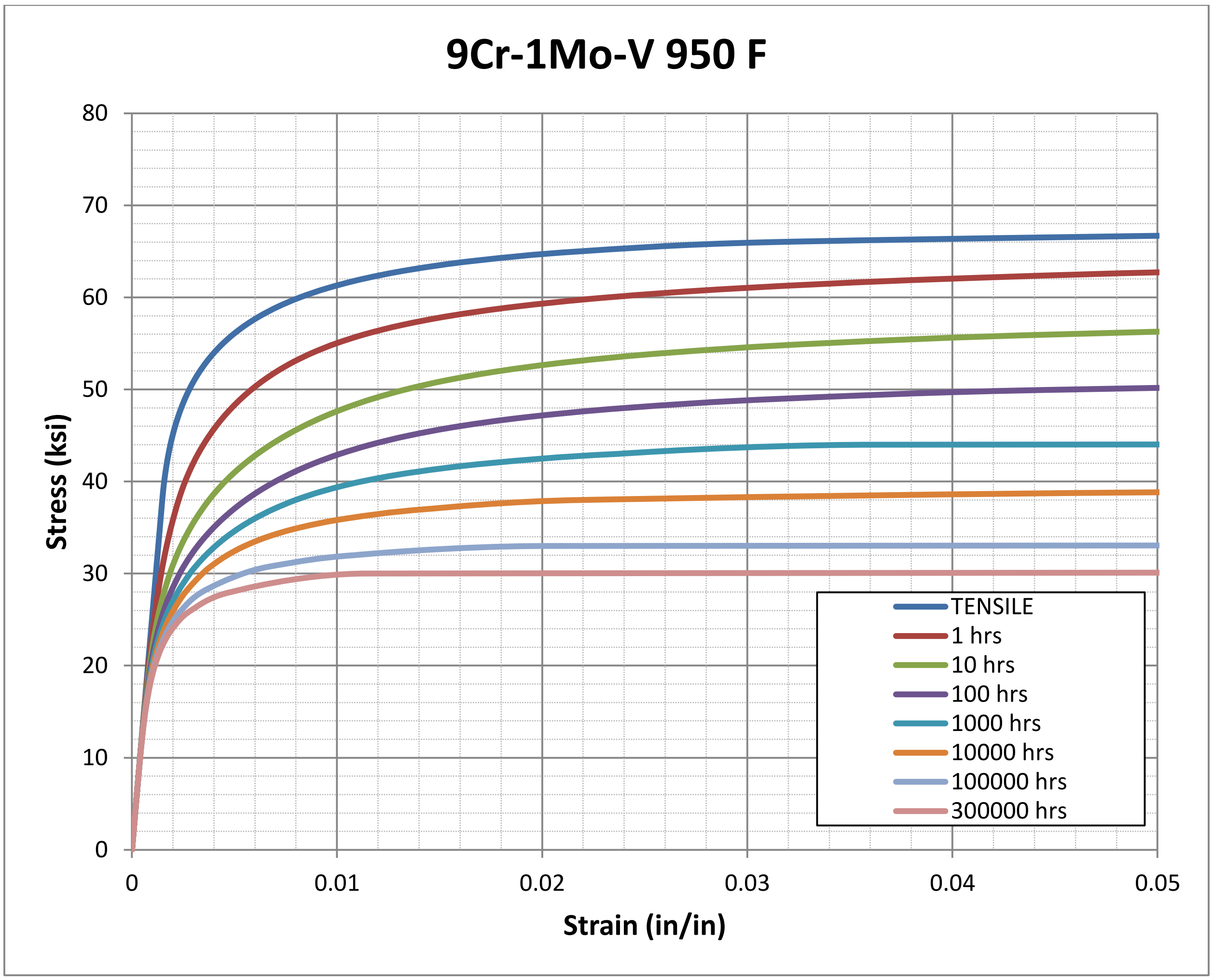

Figure B.4. Average isochronous curves at 950ºF

Table B.4. Tabular values for average isochronous curves at 950°F

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	7.75795E-05	7.75798E-05	7.758E-05	7.75802E-05
4	0.000155159	0.00015517	0.000155178	0.000155186
6	0.000232739	0.000232827	0.000232899	0.000232973
8	0.000310318	0.000310697	0.000311042	0.000311398
10	0.000387898	0.000389061	0.000390216	0.00039142
12	0.000465477	0.000468369	0.000471465	0.000474719
14	0.000543057	0.000549277	0.000556389	0.000563933
16	0.000620636	0.000632673	0.000647272	0.000662897
18	0.000698216	0.000719707	0.000747208	0.000776902
20	0.000775795	0.000811813	0.000860221	0.000912953
22	0.000853375	0.000910733	0.000991394	0.001080039
24	0.000930954	0.001018536	0.001146992	0.001289414
26	0.001008534	0.001137637	0.001334584	0.001554888
28	0.001086113	0.001270814	0.001563167	0.001893158
30	0.001163693	0.001421224	0.001843297	0.002324212
31	0.001202483	0.001503986	0.002006453	0.00258182
32	0.001241272	0.001592423	0.002187235	0.002871936
33	0.001280062	0.001687043	0.002387473	0.003198334
34	0.001318852	0.001788384	0.00260913	0.003565237
35	0.001357642	0.001897012	0.002854319	0.003977437
36	0.001396431	0.002013525	0.003125319	0.004440502
37	0.001435221	0.002138553	0.003424603	0.004961091
38	0.001474054	0.002272805	0.003754928	0.005547503
39	0.001517297	0.002421358	0.004123676	0.006214759
40	0.001568424	0.002588444	0.004537734	0.006980672
41	0.001628314	0.002775763	0.005001951	0.007866235
42	0.00169797	0.002985222	0.005522093	0.008901743
43	0.001778545	0.003218987	0.006105232	0.010132489
44	0.001871366	0.003479551	0.006760354	0.011628458
45	0.001977971	0.003769845	0.007499285	0.01350149
46	0.002100155	0.004093379	0.008338141	0.015937389
47	0.002240019	0.004454458	0.009299593	0.019261115
48	0.002400049	0.004858494	0.010416443	0.024086288
49	0.002583199	0.005312467	0.011737357	0.031729129
50	0.002793013	0.005825606	0.013336238	0.045798986
51	0.003033785	0.006410405	0.015328006	0.086166123
52	0.003310764	0.007084143	0.017896345	1.003310764
53	0.003630448	0.007871187	0.021345504	
54	0.004000981	0.008806497	0.02620595	
55	0.004432726	0.009941015	0.03347928	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
56	0.004939101	0.011350114	0.045330188	
57	0.005537822	0.013147077	0.067853183	
58	0.006252842	0.015505289	0.139456422	
59	0.00711747	0.018696262	1.00711747	
60	0.008179644	0.023158626		
61	0.009511377	0.029633656		
62	0.011226963	0.039463526		
63	0.013521647	0.05536937		
64	0.016765354	0.084145742		
65	0.021779467	0.154077168		
66	0.030980239	1.030980239		
67	0.059179259			

Table B.4. Tabular values for average isochronous curves at 950°F (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hour
0	0	0	0	0
2	7.75804E-05	7.75806E-05	7.75808E-05	7.75808E-05
4	0.000155194	0.000155203	0.000155211	0.000155215
6	0.000233048	0.000233122	0.000233196	0.000233232
8	0.000311756	0.000312113	0.000312472	0.000312644
10	0.000392629	0.000393839	0.000395054	0.000395644
12	0.000477991	0.000481267	0.000484571	0.000486199
14	0.000571525	0.000579133	0.000586856	0.000590763
16	0.00067864	0.000694436	0.000710657	0.000719225
18	0.000806857	0.000836982	0.000868569	0.000886504
20	0.000966224	0.001020012	0.00107858	0.001115944
22	0.001169748	0.001261009	0.001367333	0.00144811
24	0.001433893	0.001582969	0.001778407	0.001966256
26	0.001779203	0.002016969	0.002395668	0.002878486
28	0.002231248	0.002608332	0.003415529	0.004845069
30	0.002822439	0.003433009	0.005410715	0.011458901
31	0.003183135	0.003975029	0.007316544	1.001202483
32	0.003596168	0.004644127	0.01083462	
33	0.004070346	0.00549421	0.020266499	
34	0.004617214	0.0066167	1.001318852	
35	0.005252612	0.008176492		
36	0.005999272	0.0104987		

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
37	0.00689123	0.014328428		
38	0.007981606	0.021997529		
39	0.009360947	0.065585093		
40	0.011179249	1.001568424		
41	0.01370201			
42	0.017453794			
43	0.023648749			
44	0.036211419			
45	1.001977971			

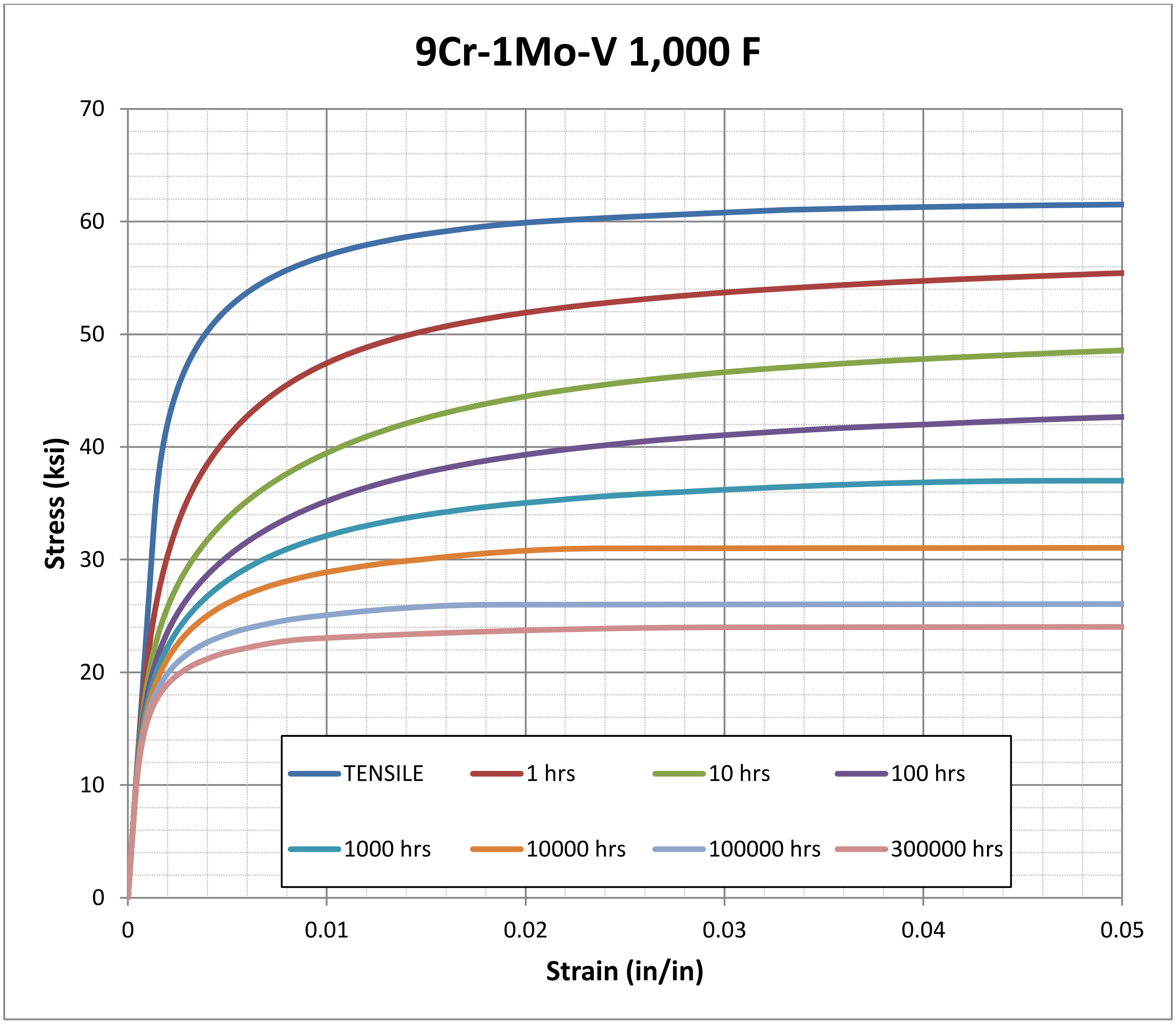

Figure B.5. Average isochronous curves at 1000ºF

Table B.5. Tabular values for average isochronous curves at 1000ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	7.88333E-05	7.88348E-05	7.88358E-05	7.88368E-05
4	0.000157667	0.000157715	0.000157752	0.000157789
6	0.0002365	0.000236853	0.000237162	0.00023748
8	0.000315333	0.000316763	0.000318157	0.000319607
10	0.000394166	0.000398367	0.000402838	0.000407536
11	0.000433583	0.000440223	0.000447573	0.000455334
12	0.000473	0.000483074	0.000494638	0.000506911
13	0.000512416	0.000527184	0.000544721	0.00056343
14	0.000551833	0.000572855	0.000598633	0.000626272
15	0.00059125	0.000620431	0.000657314	0.000697061
16	0.000630666	0.000670296	0.000721844	0.000777676
17	0.000670083	0.000722877	0.000793452	0.000870278
18	0.000709499	0.000778646	0.000873522	0.000977327
19	0.000748916	0.00083812	0.000963608	0.001101601
20	0.000788333	0.000901864	0.001065433	0.001246225
21	0.000827749	0.000970487	0.001180908	0.001414686
22	0.000867166	0.00104465	0.00131213	0.001610868
23	0.000906583	0.001125061	0.001461402	0.001839076
24	0.000945999	0.001212482	0.001631234	0.00210408
25	0.000985416	0.001307723	0.001824355	0.002411166
26	0.001024832	0.001411649	0.00204373	0.002766203
27	0.001064249	0.001525178	0.002292568	0.003175756
28	0.001103666	0.001649283	0.002574345	0.003647239
29	0.001143082	0.001784998	0.002892826	0.004189164
30	0.001182499	0.001933415	0.003252106	0.004811533
31	0.001221916	0.002095691	0.003656656	0.005526454
32	0.001261332	0.002273058	0.004111411	0.006349146
33	0.001300749	0.002466825	0.004621884	0.007299557
34	0.001341604	0.002679837	0.005195799	0.008406469
35	0.001388686	0.002918409	0.005845293	0.009713816
36	0.001443049	0.003185271	0.006580292	0.011281078
37	0.00150555	0.00348316	0.007412761	0.013199822
38	0.001577171	0.003815228	0.008358163	0.015617672
39	0.001659051	0.004185188	0.009437259	0.018784106
40	0.001752514	0.004597535	0.010678966	0.023147883
41	0.001859109	0.005057875	0.012124919	0.029596319
42	0.001980658	0.005573412	0.013836882	0.040196254
43	0.002119326	0.006153688	0.015909041	0.061774188
44	0.002277697	0.006811691	0.018489087	1.002277697
45	0.00245889	0.00756554	0.021816118	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
46	0.0026667	0.008441042	0.026293624	
47	0.002905804	0.009475625	0.032644697	
48	0.003182026	0.010724428	0.04229485	
49	0.003502729	0.01226989	0.058568848	
50	0.003877371	0.014237151	0.092594671	
51	0.004318324	0.016819581	1.004318324	
52	0.00484213	0.020322892		
53	0.00547149	0.025246079		
54	0.006238536	0.032442926		
55	0.007190541	0.043485749		
56	0.008400526	0.061649079		
57	0.009988716	0.095540199		
58	0.012171154	0.187061424		
59	0.015389176	1.015389176		
60	0.020754599			
61	0.032568478			
61.1	0.034719433			
61.2	0.037259434			
61.3	0.040330466			
61.4	0.044163976			
61.5	0.049173044			
61.6	0.056201364			
61.7	0.067409517			
61.8	0.091867703			

Table B.5. Tabular values for average isochronous curves at 1000ºF (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
2	7.88377E-05	7.88387E-05	7.88397E-05	7.88401E-05
4	0.000157827	0.000157865	0.000157902	0.00015792
6	0.0002378	0.000238119	0.000238441	0.0002386
8	0.000321063	0.000322523	0.000324018	0.000324799
10	0.00041226	0.000417012	0.000422009	0.00042487
11	0.000463145	0.000471017	0.000479453	0.000484572
12	0.000519274	0.000531765	0.000545468	0.000554365
13	0.000582292	0.000601414	0.000623021	0.000638186
14	0.000654167	0.000682568	0.000715893	0.000741441
15	0.00073722	0.000778345	0.000828954	0.000871785
16	0.000834163	0.000892449	0.000968621	0.001040464
17	0.000948129	0.001029279	0.00114361	0.001264749
18	0.001082719	0.001194078	0.001366241	0.001572467

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
19	0.001242047	0.001393168	0.001654751	0.002010914
20	0.001430801	0.001634309	0.002037516	0.002665848
21	0.001654322	0.001927299	0.002561117	0.003707393
22	0.001918719	0.00228497	0.003306805	0.005526775
23	0.002231033	0.002724889	0.004427733	0.009342366
24	0.002599503	0.00327232	0.006248288	0.03007158
25	0.003033975	0.00396553	0.009617669	1.000985416
26	0.003546574	0.004865658	0.018347214	
27	0.004152812	0.006076172	1.001064249	
28	0.004873435	0.007784799		
29	0.005737558	0.010367392		
30	0.006788095	0.014712379		
31	0.008091447	0.023817961		
32	0.009755566	1.001261332		
33	0.01196598			
34	0.015066782			
35	0.01976863			
36	0.027840254			
37	0.046307151			
38	1.001577171			

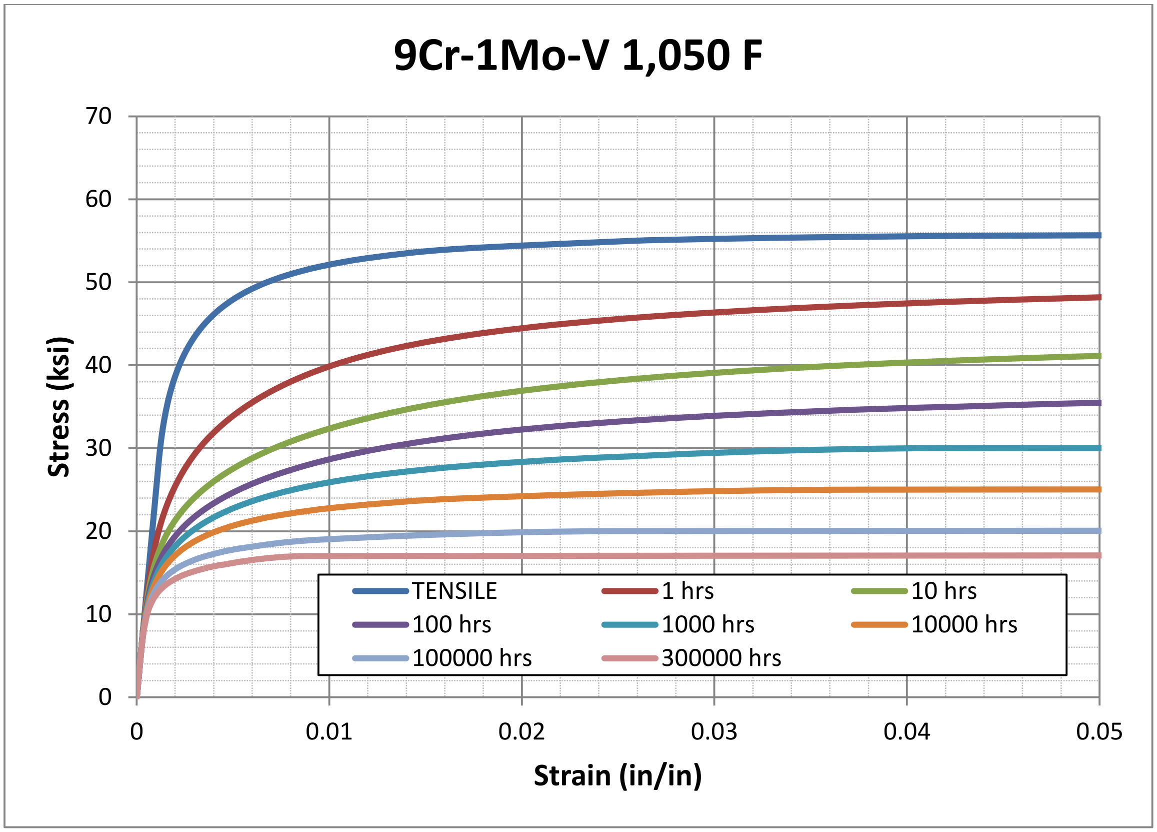

Figure B.6. Average isochronous curves at 1050ºF

Table B.6. Tabular values for average isochronous curves at 1050ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
2	8.02407E-05	8.02476E-05	8.02522E-05	8.02568E-05
4	0.000160481	0.00016067	0.000160824	0.000160981
6	0.000240722	0.000242003	0.000243202	0.000244443
8	0.000320963	0.000325884	0.000331014	0.00033639
10	0.000401204	0.000415077	0.000430876	0.000447634
11	0.000441324	0.000462876	0.000488398	0.000515629
12	0.000481444	0.000513625	0.000553148	0.000595568
13	0.000521565	0.000568051	0.000627119	0.000690899
14	0.000561685	0.00062697	0.000712625	0.000805669
15	0.000601805	0.000691294	0.000812311	0.000944573
16	0.000641926	0.000762034	0.000929185	0.001113006
17	0.000682046	0.0008403	0.001066624	0.001317125
18	0.000722166	0.000927302	0.001228403	0.001563914
19	0.000762287	0.001024354	0.001418712	0.001861275
20	0.000802407	0.001132873	0.001642178	0.00221815
21	0.000842528	0.001254385	0.00190389	0.002644684
22	0.000882648	0.001390525	0.002209436	0.003152489

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
23	0.000922768	0.00154304	0.002564942	0.003755035
24	0.000962889	0.001713796	0.002977133	0.004468283
25	0.001003009	0.001904781	0.00345342	0.005311698
26	0.001043129	0.002118118	0.004002033	0.006309923
27	0.00108325	0.00235608	0.004632216	0.00749553
28	0.00112337	0.002621111	0.005354547	0.008913662
29	0.001164666	0.002917037	0.006182598	0.010631145
30	0.001211335	0.00325097	0.007135555	0.012752321
31	0.001264351	0.003627142	0.008233196	0.015438487
32	0.00132449	0.004050065	0.009500866	0.018961168
33	0.001392649	0.004525045	0.010972914	0.023810469
34	0.001469874	0.005058515	0.012697773	0.030964021
35	0.001557387	0.005658531	0.014746277	0.042737517
36	0.001656628	0.006335537	0.017225611	0.06709518
37	0.001769307	0.007103508	0.020303482	1.001769307
38	0.001897467	0.007981712	0.024252059	
39	0.002043575	0.0089974	0.02953369	
40	0.002210634	0.010189954	0.036986323	
41	0.002402346	0.011617341	0.048292223	
42	0.002623323	0.013366305	0.067505666	
43	0.002879399	0.015568777	0.109358473	
44	0.003178068	0.018429103	1.003178068	
45	0.003529139	0.022271105		
46	0.003945731	0.027624376		
47	0.00444585	0.035396128		
48	0.00505499	0.04725681		
49	0.005810666	0.066676038		
50	0.006770825	0.102693303		
51	0.008030867	0.197586691		
52	0.009762164	1.009762164		
53	0.012314498			
54	0.016567351			
55	0.025903844			
55.1	0.027597207			
55.2	0.029593367			
55.3	0.032001164			
55.4	0.03499673			
55.6	0.044309704			
55.8	0.070430697			

Table B.6. Tabular values for average isochronous curves at 1050^{o}F (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
2	8.02614E-05	8.02659E-05	8.02705E-05	8.02727E-05
4	0.000161139	0.000161297	0.000161456	0.000161534
6	0.00024569	0.000246947	0.000248305	0.000249146
8	0.000341807	0.000347361	0.000354265	0.000360184
10	0.000464584	0.000482439	0.000509302	0.000539757
11	0.000543246	0.000572883	0.000622783	0.000686589
12	0.000638724	0.000686136	0.000776566	0.000905822
13	0.000756037	0.000829748	0.000991113	0.001247725
14	0.000901159	0.001013358	0.001299171	0.001805806
15	0.001081158	0.001249499	0.001755842	0.00277047
16	0.001304371	0.001554962	0.002459816	0.004595734
17	0.001580664	0.001953145	0.003603622	0.008810284
18	0.001921823	0.00247824	0.005617974	1.000722166
19	0.002342174	0.003182952	0.009764068	
20	0.002859595	0.004153443	0.025187558	
21	0.003497211	0.005540475	1.000842528	
22	0.004286283	0.007632108		
23	0.005271251	0.011058129		
24	0.006518774	0.017594547		
25	0.008134624	0.038008878		
26	0.010297235	1.001043129		
27	0.013330885			
28	0.017890649			
29	0.025562122			
30	0.042062718			
31	1.001264351			

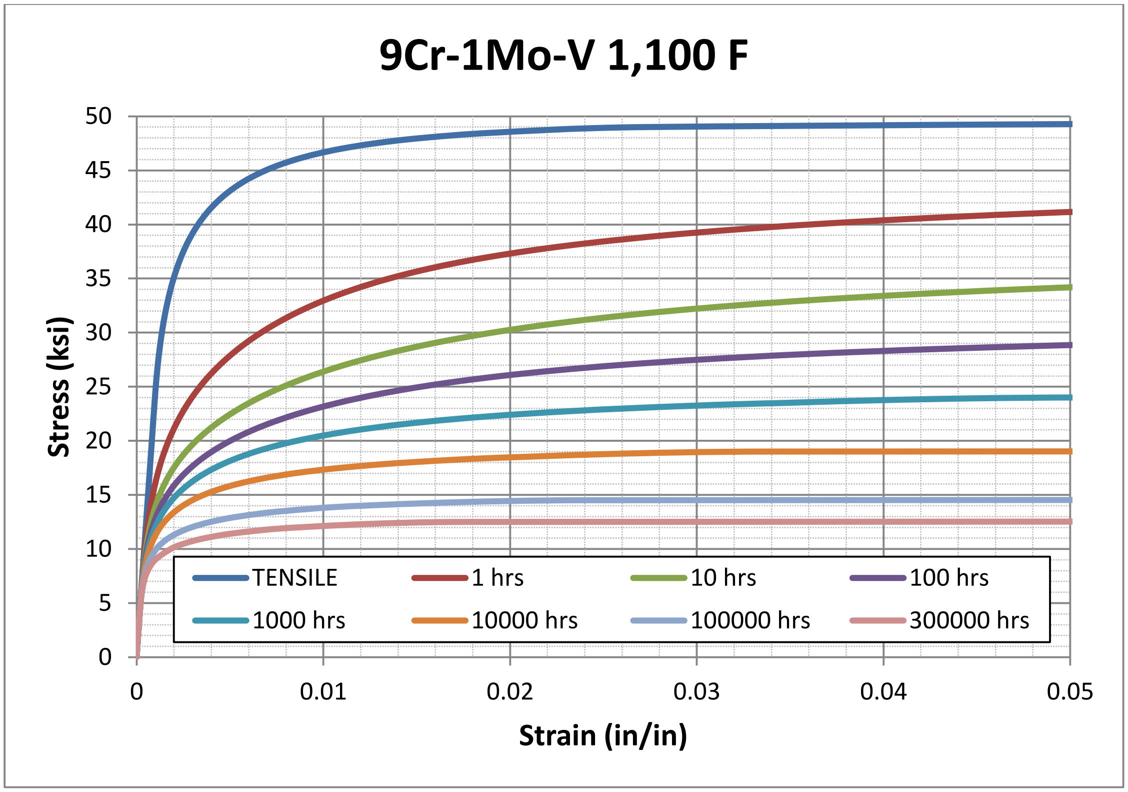

Figure B.7. Average isochronous curves at 1,100ºF

Table B.7. Tabular values for average isochronous curves at 1100ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
1	4.09115E-05	4.09126E-05	4.09132E-05	4.09139E-05
2	8.1823E-05	8.18507E-05	8.18701E-05	8.18897E-05
3	0.000122735	0.000122915	0.000123057	0.000123202
4	0.000163646	0.00016432	0.000164904	0.000165504
5	0.000204558	0.000206421	0.000208164	0.00020997
6	0.000245469	0.00024973	0.000253985	0.000258424
7	0.000286381	0.000294929	0.000303967	0.000313467
8	0.000327292	0.000342876	0.000360219	0.000378585
9	0.000368204	0.00039462	0.000425413	0.000458273
10	0.000409115	0.000451399	0.000502828	0.00055814
10.5	0.000429571	0.000482119	0.00054732	0.000617727
11	0.000450027	0.000514651	0.000596396	0.000685028
11.5	0.000470482	0.000549208	0.000650657	0.000761113
12	0.000490938	0.000586013	0.000710749	0.000847143
12.5	0.000511394	0.000625303	0.000777368	0.00094438
13	0.00053185	0.000667327	0.000851257	0.001054192
13.5	0.000552305	0.00071235	0.00093321	0.001178055
14	0.000572761	0.000760646	0.001024073	0.00131757

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
14.5	0.000593217	0.000812504	0.001124746	0.001474461
15	0.000613673	0.000868229	0.001236184	0.001650597
15.5	0.000634128	0.000928134	0.001359399	0.001848001
16	0.000654584	0.000992552	0.001495462	0.002068866
16.5	0.00067504	0.001061825	0.001645506	0.002315582
17	0.000695496	0.00113631	0.001810731	0.002590761
17.5	0.000715951	0.00121638	0.001992401	0.00289727
18	0.000736407	0.001302421	0.002191856	0.003238281
18.5	0.000756863	0.001394835	0.002410513	0.00361733
19	0.000777319	0.001494037	0.00264987	0.004038385
19.5	0.000797774	0.001600461	0.002911519	0.004505951
20	0.00081823	0.001714555	0.003197153	0.005025196
20.5	0.000838686	0.001836786	0.003508575	0.005602113
21	0.000859142	0.001967638	0.003847718	0.006243746
21.5	0.000879597	0.002107616	0.004216658	0.006958472
22	0.000900053	0.002257246	0.004617645	0.007756391
22.5	0.000920509	0.002417078	0.005053124	0.008649844
23	0.000940965	0.002587686	0.00552578	0.009654113
23.5	0.00096142	0.002769675	0.006038578	0.010788388
24	0.000981989	0.002963797	0.006594945	0.012077224
24.5	0.001003649	0.003171704	0.007199592	0.013553212
25	0.00102669	0.003394409	0.007857061	0.015258209
25.5	0.001051198	0.003632768	0.008572332	0.01724799
26	0.001077265	0.003887708	0.009351194	0.019598916
26.5	0.001104988	0.004160234	0.010200452	0.022418374
27	0.001134476	0.004451449	0.011128188	0.025862587
27.5	0.001165843	0.004762573	0.012144103	0.030169164
28	0.001199214	0.005094962	0.013259967	0.035722159
28.5	0.001234727	0.005450144	0.014490197	0.043199301
29	0.001272527	0.00582985	0.015852633	0.053971751
29.5	0.001312777	0.006236062	0.01736957	0.071577179
30	0.001355652	0.00667107	0.019069156	0.112730847
30.5	0.001401343	0.007137538	0.020987319	1.001401343
31	0.001450061	0.007638593	0.023170459	
31.5	0.001502037	0.008177932	0.025679322	
32	0.001557524	0.008759955	0.028594694	
32.5	0.001616802	0.00938993	0.03202608	
33	0.001680183	0.010074207	0.036125463	
33.5	0.001748008	0.010820474	0.041110216	
34	0.001820661	0.011638091	0.047303735	
34.5	0.001898568	0.012538503	0.055213514	
35	0.001982206	0.013535777	0.06569824	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
35.5	0.002072112	0.014647276	0.080384812	
36	0.002168889	0.015894538	0.102992937	
36.5	0.002273222	0.017304423	0.14602982	
37	0.002385889	0.018910615	1.002385889	
37.5	0.002507777	0.020755634		
38	0.002639907	0.022893564		
38.5	0.002783454	0.025393819		
39	0.002939785	0.028346456		
39.5	0.003110494	0.031869881		
40	0.00329746	0.036122348		
40.5	0.003502907	0.041319797		
41	0.003729497	0.047764764		
41.5	0.003980443	0.055895939		
42	0.004259663	0.066379312		
42.5	0.004571998	0.080291983		
43	0.004923505	0.099543037		
43.5	0.005321882	0.128036509		
44	0.00577709	0.176090743		
44.5	0.006302292	0.296787853		
45	0.006915312	1.006915312		
45.5	0.007641018			
46	0.008515398			
46.5	0.009592976			
47	0.01096144			
47.5	0.012773699			
48	0.01532937			
48.5	0.019335024			
49	0.027166153			
49.5	0.072489558			

Table B.7. Tabular values for average isochronous curves at 1100ºF (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
1	4.09145E-05	4.09152E-05	4.09158E-05	4.09161E-05
2	8.19094E-05	8.19291E-05	8.19488E-05	8.19582E-05
3	0.000123348	0.000123493	0.00012364	0.000123712
4	0.000166107	0.000166715	0.000167369	0.000167772
5	0.000211788	0.000213662	0.000216093	0.000218333
6	0.000262916	0.000267741	0.000275882	0.000286214
7	0.000323147	0.000334157	0.000358468	0.00039608

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
8	0.000397471	0.000420508	0.000485373	0.000599306
9	0.000492442	0.000537651	0.000695412	0.001001094
10	0.000616448	0.000701072	0.001059741	0.001829541
10.5	0.000692545	0.000806784	0.001338306	0.00255538
11	0.000780058	0.000933213	0.001715295	0.003664394
11.5	0.000880729	0.001084923	0.002231754	0.005459624
12	0.00099651	0.001267592	0.002951089	0.008739177
12.5	0.001129593	0.001488373	0.00397729	0.01756617
13	0.001282452	0.0017564	0.005496722	1.00053185
13.5	0.001457893	0.002083505	0.007894162	
14	0.001659123	0.002485268	0.012199898	
14.5	0.001889833	0.00298258	0.024004382	
15	0.00215432	0.00360407	1.000613673	
15.5	0.002457633	0.004389984		
16	0.002805781	0.005398764		
16.5	0.003206008	0.006718897		
17	0.003667166	0.0084922		
17.5	0.004200228	0.010965228		
18	0.004819008	0.014623838		
18.5	0.005541171	0.020658314		
19	0.006389699	0.033868781		
19.5	0.00739506	1.000797774		
20	0.008598516			
20.5	0.010057366			
21	0.01185366			
21.5	0.014109585			
22	0.017016837			
22.5	0.020898964			
23	0.026365151			
23.5	0.034789952			
24	0.050649022			
24.5	1.001003649			

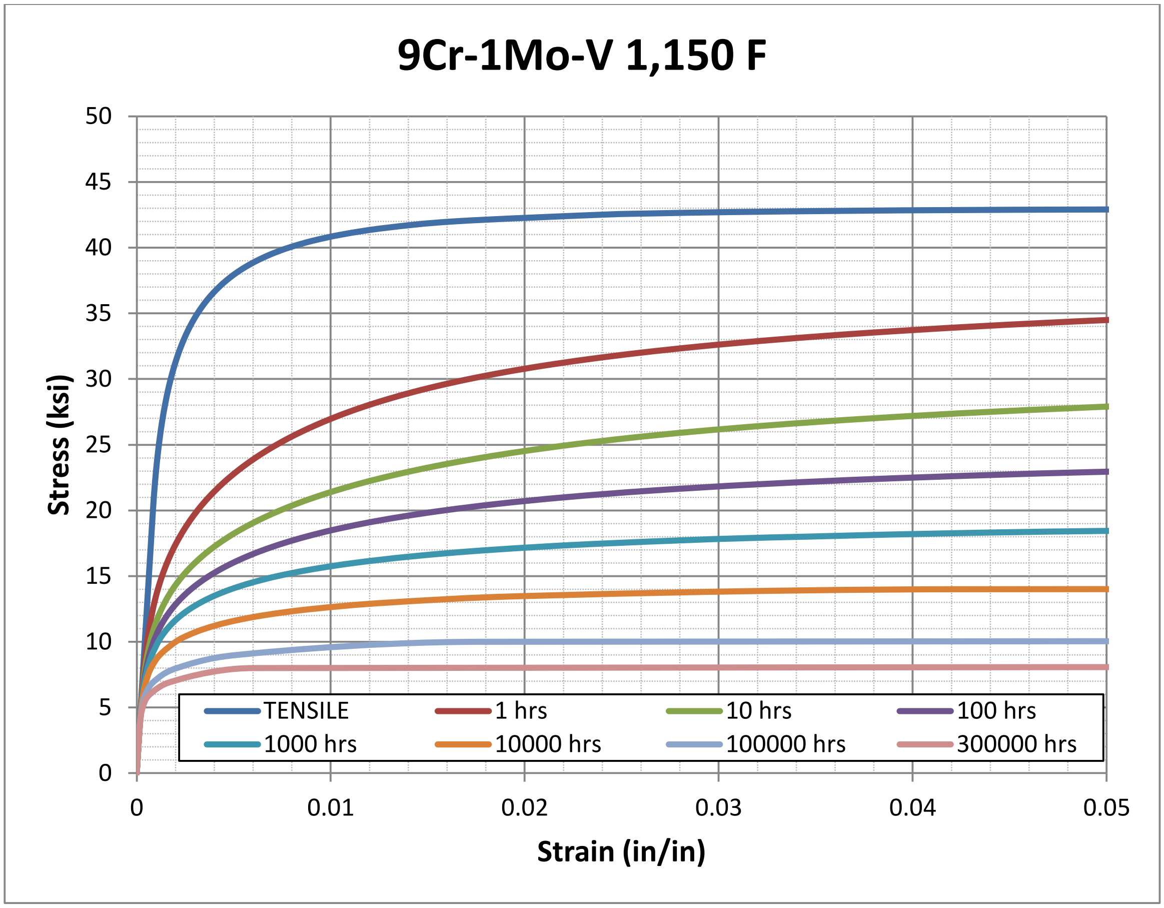

Figure B.8. Average isochronous curves at 1,150°F

Table B.8. Tabular values for average isochronous curves at 1150°F

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
1	4.18113E-05	4.18158E-05	4.18185E-05	4.18213E-05
2	8.36225E-05	8.37242E-05	8.37997E-05	8.38765E-05
3	0.000125434	0.000126053	0.000126573	0.000127107
4	0.000167245	0.000169458	0.000171498	0.00017361
5	0.000209056	0.000214961	0.000220842	0.000226988
6	0.000250868	0.00026398	0.000277929	0.000292669
7	0.000292679	0.000318338	0.000347263	0.000378216
8	0.00033449	0.000380278	0.000434645	0.000493633
9	0.000376301	0.000452468	0.000547272	0.00065172
10	0.000418113	0.000538005	0.000693842	0.000868499
10.5	0.000439018	0.000586864	0.000783013	0.001004925
11	0.000459924	0.000640418	0.000884669	0.0011638
11.5	0.00048083	0.000699177	0.001000372	0.001348343
12	0.000501735	0.000763678	0.001131803	0.001562141
12.5	0.000522641	0.000834487	0.001280766	0.001809214

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
13	0.000543546	0.0009122	0.001449198	0.002094091
13.5	0.000564452	0.000997439	0.001639178	0.002421906
14	0.000585358	0.001090858	0.001852937	0.00279853
14.5	0.000606263	0.001193143	0.002092871	0.003230744
15	0.000627169	0.001305009	0.00236156	0.003726458
15.5	0.000648075	0.001427205	0.002661789	0.004295018
16	0.00066898	0.001560518	0.002996576	0.004947603
16.5	0.000689886	0.00170577	0.003369202	0.005697775
17	0.000710791	0.001863823	0.003783263	0.006562216
17.5	0.000731697	0.002035587	0.004242719	0.007561763
18	0.000752603	0.002222016	0.004751968	0.00872285
18.5	0.000773508	0.002424125	0.005315938	0.010079583
19	0.000794414	0.002642987	0.005940207	0.011676767
19.5	0.00081532	0.002879749	0.006631147	0.013574484
20	0.000836487	0.003135905	0.00739639	0.015855494
20.5	0.00085896	0.003413827	0.008245597	0.018637406
21	0.000882929	0.003715153	0.009189154	0.022091156
21.5	0.000908496	0.004041576	0.010239369	0.026479032
22	0.000935774	0.004394963	0.011411138	0.032230707
22.5	0.000964885	0.0047774	0.0127227	0.040119804
23	0.000995961	0.005191233	0.014196652	0.051764311
23.5	0.001029147	0.00563913	0.01586132	0.071626431
24	0.001064602	0.006124147	0.017752659	0.127028361
24.5	0.001102499	0.006649824	0.019916898	1.001102499
25	0.00114303	0.007220291	0.022414343	
25.5	0.001186406	0.007840414	0.025324959	
26	0.001232859	0.008515964	0.028756834	
26.5	0.001282647	0.009253845	0.032859546	
27	0.001336056	0.010062361	0.037846273	
27.5	0.001393405	0.010951577	0.044032676	
28	0.00145505	0.011933756	0.05191081	
28.5	0.001521389	0.013023929	0.062305017	
29	0.001592872	0.014240626	0.076752801	
29.5	0.001670006	0.015606814	0.098673284	
30	0.001753363	0.017151131	0.138842787	
30.5	0.001843599	0.018909515	1.001843599	
31	0.001941461	0.020927374		
31.5	0.002047809	0.023262551		
32	0.002163636	0.025989413		
32.5	0.002290098	0.029204659		
33	0.002428548	0.033035734		
33.5	0.002580579	0.037653467		

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
34	0.002748086	0.043291723		
34.5	0.002933339	0.050279438		
35	0.003139083	0.059095865		
35.5	0.003368678	0.070473013		
36	0.003626282	0.085604519		
36.5	0.003917116	0.106631503		
37	0.004247837	0.13801895		
37.5	0.00462709	0.192040268		
38	0.005066347	0.342624605		
38.5	0.00558122	1.00558122		
39	0.006193615			
39.5	0.006935451			
40	0.007855506			
40.5	0.009033101			
41	0.010608652			
41.5	0.012863458			
42	0.016485951			
42.5	0.023989025			
42.6	0.02679986			
42.7	0.0307553			
42.8	0.037085699			
42.85	0.042262693			
42.9	0.050970311			
42.95	0.074479826			

Table B.8. Tabular values for average isochronous curves at 1150ºF (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
1	4.18241E-05	4.18269E-05	4.18297E-05	4.1831E-05
2	8.39534E-05	8.40304E-05	8.41074E-05	8.41442E-05
3	0.000127642	0.000128181	0.000128756	0.000129098
4	0.000175743	0.000178019	0.000181723	0.00018626
5	0.000233317	0.000241217	0.000264853	0.000306827
6	0.000308369	0.000332942	0.000447156	0.000680965
7	0.000412748	0.000481502	0.000905002	0.00187888
8	0.000563304	0.000737537	0.002068292	0.005983363
9	0.000783639	0.001191311	0.005180599	1.000376301
10	0.001106952	0.002009274	0.017642028	
10.5	0.001321377	0.002646942	1.000439018	
11	0.001581006	0.003521634		

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
11.5	0.001895542	0.004740054		
12	0.002277109	0.006477853		
12.5	0.00274106	0.00905225		
13	0.003307149	0.013127888		
13.5	0.004001232	0.020541498		
14	0.004857824	0.042705712		
14.5	0.005924043	1.000606263		
15	0.007265979			
15.5	0.008979477			
16	0.011209685			
16.5	0.014189636			
17	0.018326091			
17.5	0.024426733			
18	0.034500912			
18.5	0.057031677			
19	1.000794414			

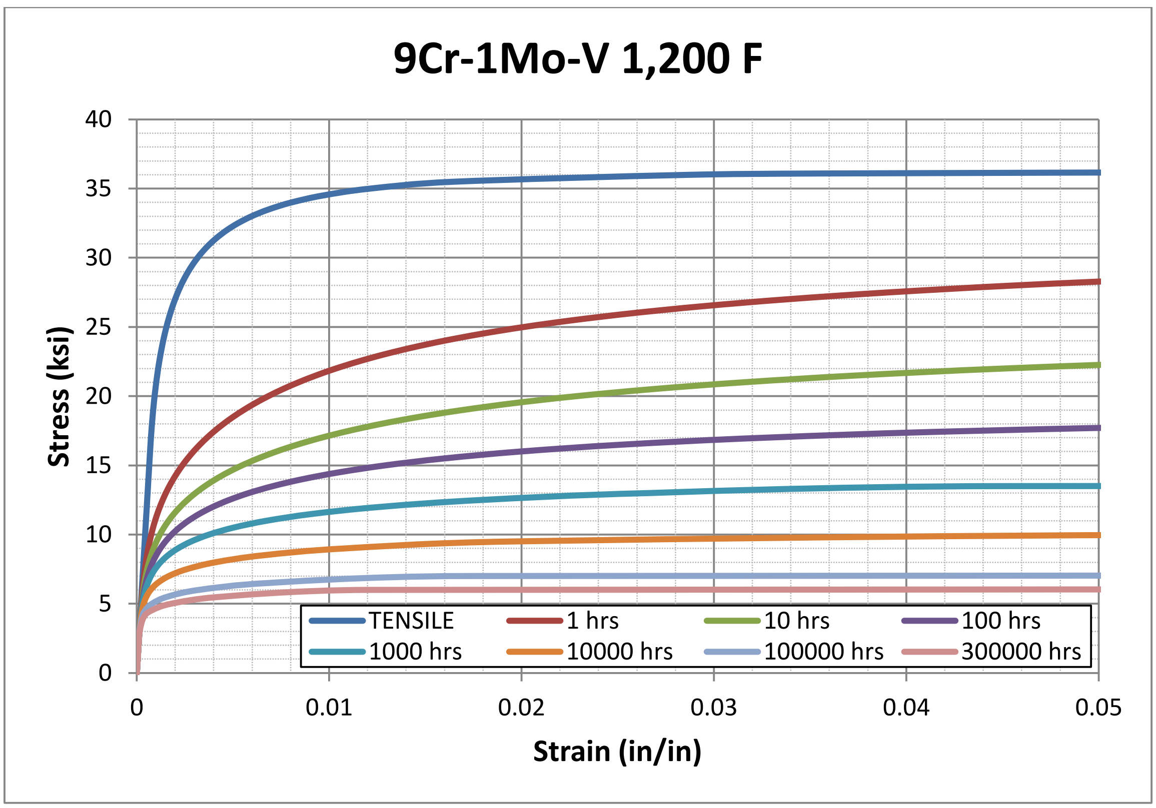

Figure B.9. Average isochronous curves at 1,200ºF

Table B.9. Tabular values for average isochronous curves at 1200ºF

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
0	0	0	0	0
1	4.28394E-05	4.28563E-05	4.28673E-05	4.28784E-05
2	8.56788E-05	8.60229E-05	8.62936E-05	8.65701E-05
3	0.000128518	0.00013049	0.000132247	0.00013406
4	0.000171358	0.000178101	0.00018471	0.000191621
4.5	0.000192777	0.000203906	0.000215268	0.000227269
5	0.000214197	0.000231596	0.000250044	0.000269771
5.5	0.000235617	0.000261656	0.000290257	0.000321296
6	0.000257036	0.000294631	0.000337312	0.000384436
6.5	0.000278456	0.00033112	0.000392812	0.000462255
7	0.000299876	0.000371783	0.000458563	0.000558353
7.5	0.000321295	0.000417337	0.000536587	0.000676939
8	0.000342715	0.000468557	0.000629133	0.00082293
8.5	0.000364135	0.000526276	0.000738691	0.001002075
9	0.000385555	0.000591388	0.00086801	0.00122112
9.5	0.000406974	0.000664847	0.001020113	0.001488029
10	0.000428394	0.000747667	0.00119833	0.00181227
10.5	0.000449814	0.000840928	0.001406325	0.002205217
11	0.000471233	0.000945775	0.001648138	0.002680671
11.5	0.000492653	0.001063422	0.001928234	0.003255605
12	0.000514073	0.001195159	0.002251574	0.003951167
12.5	0.000535492	0.001342353	0.002623698	0.00479412
13	0.000556912	0.001506462	0.003050832	0.005818888
13.5	0.000578332	0.001689038	0.003540035	0.00707057
14	0.000599752	0.001891742	0.004099383	0.008609473
14.5	0.000621171	0.00211636	0.00473821	0.010518193
15	0.000642591	0.002364822	0.005467425	0.012913141
15.5	0.000664011	0.002639225	0.006299933	0.015964356
16	0.00068543	0.002941867	0.007251182	0.019932063
16.5	0.000707509	0.003275941	0.008340564	0.025241321
17	0.000731354	0.00364538	0.0095922	0.032652241
17.5	0.000757118	0.004053509	0.011034886	0.04373472
18	0.000784956	0.004504084	0.012704921	0.062721941
18.5	0.000815039	0.005001402	0.014648744	0.113239212
19	0.000847555	0.005550431	0.016926693	1.000847555
19.5	0.000882713	0.006156959	0.019618539	
20	0.000920743	0.006827805	0.022831858	
20.5	0.000961905	0.007571063	0.02671522	
21	0.001006487	0.008396421	0.031479954	
21.5	0.00105481	0.009315574	0.037438258	
22	0.001107238	0.010342735	0.04507525	

Stress S, ksi	ε hot tensile	ε at 1 hour	ε at 10 hours	ε at 100 hours
22.5	0.00116418	0.011495306	0.05519985	
23	0.0012261	0.012794734	0.069309658	
23.5	0.001293525	0.014267639	0.090692233	
24	0.001367058	0.015947286	0.129415662	
24.5	0.00144739	0.017875554	0.319597117	
25	0.001535321	0.020105599	1.001535321	
25.5	0.001631776	0.022705501		
26	0.001737838	0.025763389		
26.5	0.00185478	0.029394797		
27	0.001984111	0.033753536		
27.5	0.002127631	0.039048321		
28	0.002287512	0.045569306		
28.5	0.002466398	0.05373264		
29	0.002667547	0.064160339		
29.5	0.002895024	0.077836006		
30	0.003153975	0.096444973		
30.5	0.003451032	0.123249508		
31	0.003794901	0.166018221		
31.5	0.004197291	0.253791696		
32	0.004674386	1.004674386		
32.5	0.005249324			
33	0.00595661			
33.5	0.00685055			
34	0.008022981			
34.5	0.009645699			
35	0.012093384			
35.5	0.016435304			
36	0.028643251			
36.1	0.036000582			
36.2	0.058946739			

Table B.9. Tabular values for average isochronous curves at 1200ºF (continued)

Stress S, ksi	ε at 1,000 hours	ε at 10,000 hour	ε at 100,000 hours	ε at 300,000 hours
0	0	0	0	0
1	4.28895E-05	4.29006E-05	4.29118E-05	4.29171E-05
2	8.68472E-05	8.71245E-05	8.74032E-05	8.75389E-05
3	0.000135888	0.000137814	0.000140718	0.000143999
4	0.000198913	0.000209743	0.000256018	0.000347369
4.5	0.000240582	0.000266508	0.000419659	0.000746324
5	0.000293216	0.000353015	0.000785401	0.001774446
5.5	0.000361407	0.000491288	0.001573764	0.004367708

Stress S, ksi	**ε at 1,000 hours**	**ε at 10,000 hour**	**ε at 100,000 hours**	**ε at 300,000 hours**
6	0.000451298	0.000715877	0.003233936	0.012095317
6.5	0.000571015	0.001079758	0.006872856	1.000278456
7	0.000731228	0.001664402	0.017071306	
7.5	0.000945941	0.002598788	1.000321295	
8	0.001233606	0.004099183		
8.5	0.001618758	0.006564883		
9	0.00213445	0.010863785		
9.5	0.002826014	0.019595049		
10	0.003757066	0.060200127		
10.5	0.005019587	1.000449814		
11	0.006751915			
11.5	0.009173596			
12	0.012660821			
12.5	0.017938123			
13	0.026707773			
13.5	0.045104125			
14	1.000599752			

ABBREVIATIONS AND ACRONYMS (PART 3)

A = strain factor associated with the tangent modulus
α = creep factor
α_1 = initial creep factor
α_3 = creep factor
B = compressive stress
1/b = strain factor
E = modulus of elasticity, ksi
E_t = tangent modulus of elasticity, ksi
ε = total strain
ε_c = creep strain
ε_e = elastic strain
ε_{pm} = plastic strain based on minimum stress values
$\dot{\varepsilon}_0$ = strain rate
$\dot{\varepsilon}_{01}$ = initial strain rate
F = temperature, ^{o}F
f = modification factor
S = effective stress, ksi
S_{pl} = proportional stress limit, ksi
S_{pm} = minimum proportional stress limit, ksi
S_u/1.1 = minimum tensile strength, ksi
S_{ua} = S_u/1.1 + Δ, Average tensile strength, ksi
S_y = minimum yield stress, ksi
t = time, hours

3 DEVELOPMENT OF EXTERNAL PRESSURE CHARTS AND EQUATIONS

3.1 External Pressure Curves and Charts Generated from Minimum Isochronous Curves

In this part, external pressure charts were generated between 800ºF and 1200ºF using three different methods. Equations were first developed to construct the charts. A graphical as well as a finite difference method were then used to construct the charts and to verify the equations developed.

3.2 Required Equations for Minimum Isochronous Curves

According to Mandatory Appendix 3 in ASME BPVC Section II-D, the external pressure charts are based on minimum values. Accordingly, in this report the isochronous equations with minimum plastic strain expression are used to develop the external pressure charts. A procedure is also presented for modifying these equations to obtain values other than minimum for use in developing external pressure charts for specific applications.

The equations developed in Part 2 for the minimum stress-strain relationship in the elastic, plastic, and creep regions are given by

$$\varepsilon = \varepsilon_e + \varepsilon_{pm} + \varepsilon_c \quad (3.1)$$

The elastic strain is expressed as

$$\varepsilon_e = S/E \quad (3.2)$$

where, the design E values are expressed by Eq.(2.3) as a function of temperature, ºF.

The minimum plastic strain is given by

$$\varepsilon_{pm} = (1/b)\{\ln[(S_{pm} - S_u/1.1)/(S - S_u/1.1)]\}^2 \qquad S > S_{pm} \quad (3.3a)$$

$$\varepsilon_{pm} = 0 \qquad S \leq S_{pm} \quad (3.3b)$$

where the values of S_{pm}, $S_u/1.1$, (1/b), and S_y are a function of temperature and are given by Eqs. (2.5) through (2.8), respectively.

The average creep strain is given by

$$\varepsilon_c = (-1/\alpha_3)\ln[(1 + \alpha_1 \dot{\varepsilon}_{01}\, t)^{-\alpha 3/\alpha 1} - \alpha_3\, \dot{\varepsilon}_0\, t)] \quad (3.4)$$

Where t is time in hours and α_1, $\dot{\varepsilon}_{01}$, α_3, and $\dot{\varepsilon}_0$ are a function of stress and temperature and are given by

$$\alpha_1 = EXP\{ K_6 + (K_2)[K_7 + K_8 \ln S]\} \quad (3.5)$$

$$\alpha_3 = EXP\{ K_1 + (K_2)[K_3 + K_4 \ln S + K_5(\ln S)^2]\} \quad (3.6)$$

$$\dot{\varepsilon}_0 = EXP\{ K_9 - (K_2)[K_{10} + K_{11} \ln S + K_{12}(\ln S)^2 + K_{13}(\ln S)^3]\} \quad (3.7)$$

$$\dot{\varepsilon}_{01} = EXP\{ K_{14} - (K2)[K_{15} + K_{16} \ln S]\} \quad (3.8)$$

K_1 through K_{16} are defined in Part 2 as

K_1 = -12.4338	K_2 = 1800/(F + 460)	K_3 = 14.6558
K_4 = 1.4278	K_5 = - 0.5056	K_6 = - 25.3281
K_7 = 41.0177	K_8 = -4.2777	K_9 = 81.7407

K_{10} = 120.0467 K_{11} = - 27.9095 K_{12} = 9.0461
K_{13} = -1.3030 K_{14} = 21.8743 K_{15} = 34.6401
K_{16} = -3.3972

Equation (3.3) can be simplified by letting
$K_{17} = 1/b$, $K_{18} = (S_{pm} - S_u/1.1)$, and $K_{19} = (S_u/1.1)$

Hence,

$$\varepsilon_{pm} = K_{17}\{\ln[K_{18}/(S - K_{19})]\}^2 \qquad S > S_{pm} \qquad (3.9a)$$

$$\varepsilon_{pm} = 0 \qquad S \leq S_{pm} \qquad (3.9b)$$

Equations (3.1), (3.2), (3.9), and (3.4) are required in order to plot minimum isochronous curves and thus external pressure charts based on minimum values.

Example 3.1.
Plot the isochronous stress-strain curve for 1000°F at 10,000 hours using
The minimum values obtained from Eqs. (3.1), (3.2), (3.9), and (3.4) above.
The average values obtained from Appendix B of Part 2 (Swindeman).
The average values obtained from Eqs. (2.1), (2.2), (2.9), and (2.10) of Part 2 using regression equations for material properties.
The average values obtained from Section III-NH of the ASME BPV Code
Solution:
The minimum stress-strain values are obtained from Eqs. (3.1), (3.2), (3.9), and (3.4) above. They are tabulated in Table 3.1 below in columns 1 and 4.
The stress-strain values are obtained from Appendix B of Part 2 and are shown in Table 3.1 in columns 1 and 2.
The average stress-strain values are obtained from Eqs. (2.1), (2.2), (2.9), and (2.10) of Part 2. The values are shown in Table 3.1 in columns 1 and 3
The average stress-strain values are obtained from the isochronous chart for Grade 91 in Section III-NH. The values were first obtained graphically from the chart. A regression analysis was then performed to smooth out the obtained x and y values. The resultant equation is given by

$$S = -0.166 - 4560.13(\varepsilon) + 12582.451(\varepsilon)^{1.5} + 605.060(\varepsilon)^{0.5}$$

The resultant stress-strain values are shown in Table 3.1 in columns 5 and 6.

Table 3.1 Isochronous stress-strain values

1 S	2 ε Appendix B	3 ε average	4 ε minimum	5 ε, III-NH	6 S, III-NH
0	0	0	0	0	0
2	7.88387E-05	7.89158E-05	7.8928E-05	0.0005	11.22
4	0.000157865	0.000158019	0.00015845	0.001	14.81
6	0.000238119	0.000238349	0.00024187	0.0015	17.16
8	0.000322523	0.000322823	0.00033846	0.002	18.90
10	0.000417012	0.000417367	0.00046707	0.0025	20.26
11	0.000471017	0.000471392	0.0005529	0.003	21.36
12	0.000531765	0.000532148	0.00066029	0.0035	22.27
13	0.000601414	0.000601792	0.00079631	0.004	23.04
				0.0045	23.70

1 S	2 ε Appendix B	3 ε average	4 ε minimum	5 ε, III-NH	6 S, III-NH
14	0.000682568	0.000682924	0.00096974	0.005	24.27
15	0.000778345	0.000778653	0.00119153	0.0055	24.76
16	0.000892449	0.000892676	0.00147567	0.006	25.19
17	0.001029279	0.001029379	0.00184069	0.007	25.91
18	0.001194078	0.001193986	0.00231252	0.008	26.47
19	0.001393168	0.001392786	0.00293014	0.009	26.94
20	0.001634309	0.001633493	0.00375689	0.01	27.32
21	0.001927299	0.001925821	0.0049046	0.011	27.65
22	0.00228497	0.002282463	0.00658946	0.014	28.43
23	0.002724889	0.00272074	0.00928116	0.016	28.87
24	0.00327232	0.003265482	0.01424907	0.018	29.32
25	0.00396553	0.003954162	0.02680096	0.02	29.79
26	0.004865658	0.00484642	1.00	0.023	30.60
27	0.006076172	0.006042743			
28	0.007784799	0.007724397			
29	0.010367392	0.010251175			
30	0.014712379	0.014460399			
31	0.023817961	0.023071826			
32	1.001261332	1.0000			

A plot of the above four curves is shown in Fig. 3.1. The isochronous stress-strain values from Appendix B and the Average Values are shown by the top two lines in the figure which lie on top of each other. This indicates the regression equations developed for S_{pm}, S_u, S_y, and (1/b) are a good approximation of the actual tabulated values listed in Section II-D. The Minimum isochronous stress-strain curve is shown as the bottom line in Fig.3.1 and is about 80% of the value of the Average curve.

The line second from the bottom in Fig.3.1 represents the isochronous curve obtained from III-NH. It differs from the Average curve obtained from current data by about 14% at a strain of about 0.0015 in/in. This difference, which is relatively small, is based in part on different data base used in this report which contains more data.

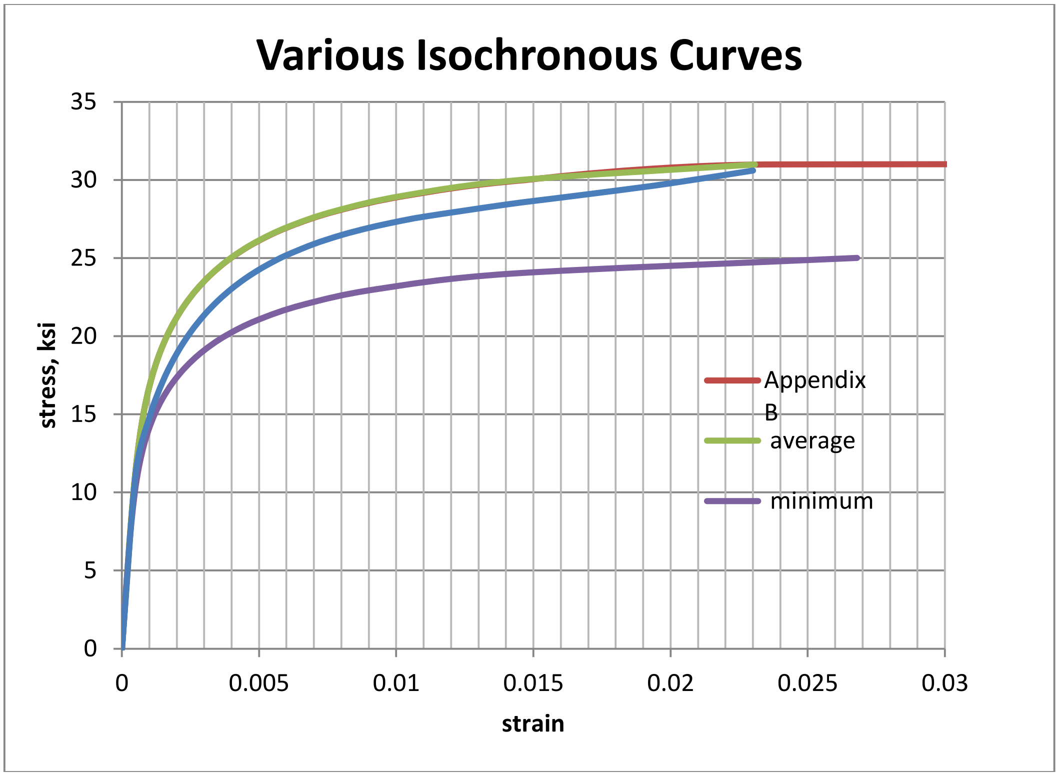

Figure 3.1. Isochronous curves

3.3 Derivation of the Tangent Modulus Equations, E_t

The elastic buckling equations for shells and heads are a function of the modulus of elasticity E while the buckling equations in the non-linear regime are normally expressed as a function of the tangent modulus E_t. In this section the tangent modulus is obtained in equation form rather than numerically. This will permit the construction of an external pressure curve for any given temperature and time, within the limits set in this project.

The tangent modulus is defined as

$$E_t = \partial S/\partial \varepsilon. \tag{3.10}$$

or,

$$E_t = \frac{1}{\partial \varepsilon/\partial S} \qquad 3.11)$$

The strain, ε, has three components. They are elastic, plastic, and creep strain as given by Eq. (3.1). Accordingly, the values of $\partial\varepsilon/\partial S$ are obtained by taking the partial derivative of this equation as

$$\partial \varepsilon/\partial S = \partial \varepsilon_e/\partial S + \partial \varepsilon_p/\partial S + \partial \varepsilon_c/\partial S. \tag{3.12}$$

Hence, Eq. (3.11) becomes

$$E_t = \frac{1}{(\partial \varepsilon_e/\partial S + \partial \varepsilon_p/\partial S + \partial \varepsilon_c/\partial S)} \tag{3.13}$$

The elastic strain, ε_e, is given by Eq. (3.2). Its derivative is

$$\partial\varepsilon_e/\partial S = 1/E \tag{3.14}$$

The minimum plastic strain, ε_{pa}, is given by Eq. (3.9). Its derivative is

$$\partial\varepsilon_{pa}/\partial S = -\frac{2\ K_{17}\ \ln(K_{18}/(\ S - K_{19}))}{S - K_{19}} \tag{3.15}$$

The creep strain, ε_c, is given by Eq. (3.4) as

$$\varepsilon_c = (-1/\alpha_3)\ln[(1 + \alpha_1\ \dot{\varepsilon}_{01}\ K_{20})^{-\alpha 3/\alpha 1} - \alpha_3\ \dot{\varepsilon}_0\ \ K_{20}\ ] \tag{3.16}$$

where K_{20} = t and α_1 , α_3 , $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$, are a function of stress, S, as given by Eqs. (3.5) through (3.8), respectively.

The derivative of Eq. (3.16) is complicated. It can best be obtained from any commercial Symbolic Math program. The derivative can be expressed as

$$\partial\varepsilon_c/\partial S = (\gamma_1/\gamma_2) - [(\gamma_{31}/\gamma_{32})/\gamma_4] \tag{3.17}$$

Where,

$$\gamma_1 = (K_2*\ln(1/((S^\wedge(K_{16}*K_2) + K_{20}*S^\wedge(K_2*K_8)*\exp(K_{14} + K_6 - K_{15}*K_2 + K_2*K_7))/S^\wedge(K_{16}*K_2))^\wedge(S^\wedge(K_2*(K_4 - K_8))*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 - K_6 + K_2*K_3 - K_2*K_7)) - (K_{20}*\exp(K_1 + K_9 - K_{10}*K_2 + K_2*K_3 - K_{12}*K_2*(\ln S)^\wedge 2 - K_{13}*K_2*(\ln S)^\wedge 3 + K_2*K_5*(\ln S)^\wedge 2))/S^\wedge(K_2*(K_{11} - K_4)))*(K_4 + 2*K_5*(\ln S))) \tag{3.18}$$

$$\gamma_2 = (S^\wedge(K_2*K_4 + 1)*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 + K_2*K_3)) \tag{3.19}$$

$$\gamma_{31} = (K_2*K_{20}*S^\wedge(K_2*K_4 - K_{11}*K_2 - 1)*\exp(K_1 + K_9 - K_{10}*K_2 + K_2*K_3 - K_{12}*K_2*(\ln S)^\wedge 2 - K_{13}*K_2*(\ln S)^\wedge 3 + K_2*K_5*(\ln S)^\wedge 2)*(3*K_{13}*(\ln S)^\wedge 2 + 2*K_{12}*(\ln S) + K_{11}) - K_2*K_{20}*S^\wedge(K_2*K_4 - K_{11}*K_2 - 1)*\exp(K_1 + K_9 - K_{10}*K_2 + K_2*K_3 - K_{12}*K_2*(\ln S)^\wedge 2 - K_{13}*K_2*(\ln S)^\wedge 3 + K_2*K_5*(\ln S)^\wedge 2)*(K_4 + 2*K_5*(\ln S)) - (K_2*S^\wedge(K_2*K_4 - K_2*K_8 - 1)*\ln((S^\wedge(K_{16}*K_2) + K_{20}*S^\wedge(K_2*K_8)*\exp(K_{14} + K_6 - K_{15}*K_2 + K_2*K_7))/S^\wedge(K_{16}*K_2))*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 - K_6 + K_2*K_3 - K_2*K_7)*(K_4 - K_8 + 2*K_5*(\ln S))) \tag{3.20}$$

$$\gamma_{32} = ((S^\wedge(K_{16}*K_2) + K_{20}*S^\wedge(K_2*K_8)*\exp(K_{14} + K_6 - K_{15}*K_2 + K_2*K_7))/S^\wedge(K_{16}*K_2))^\wedge(S^\wedge(K_2*(K_4 - K_8))*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 - K_6 + K_2*K_3 - K_2*K_7)) + (K_2*K_{20}*S^\wedge(K_2*K_4 - K_{16}*K_2 - 1)*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 + K_{14} - K_{15}*K_2 + K_2*K_3)*(K_{16} - K_8))/((S^\wedge(K_{16}*K_2) + K_{20}*S^\wedge(K_2*K_8)*\exp(K_{14} + K_6 - K_{15}*K_2 + K_2*K_7))/S^\wedge(K_{16}*K_2))^\wedge(S^\wedge(K_2*(K_4 - K_8))*\exp(K_2*K_5*(\ln S)^\wedge 2 + K_1 - K_6 + K_2*K_3 - K_2*K_7) + 1)) \tag{3.21}$$

γ_4 = (S^(K_2*K_4)*exp(K_2*K_5*(lnS)^2 + K_1 + K_2*K_3)*(1/((S^(K_{16}*K_2) + K_{20}*S^(K_2*K_8)*exp(K_{14} + K_6 - K_{15}*K_2 + K_2*K_7))/S^(K_{16}*K_2))^(S^(K_2*(K_4 - K_8))*exp(K_2*K_5*(lnS)^2 + K_1 - K_6 + K_2*K_3 - K_2*K_7)) - (K_{20}*exp(K_1 + K_9 - K_{10}*K_2 + K_2*K_3 - K_{12}*K_2*(lnS)^2 - K_{13}*K_2*(lnS)^3 + K_2*K_5*(lnS)^2))/S^(K_2*(K_{11} - K_4)))). (3.22)

The value of E_t is obtained by substituting Eqs. (3.14), (3.15), and (3.17) into Eq. (3.13).

3.4 Equations for External Pressure Charts

The procedure for constructing external pressure charts is detailed in ASME BPVC Section II-D. In the elastic region the stress and strain are directly related by the equation $S = E\varepsilon$. In the non-linear region the tangent modulus, E_t, at a given stress and strain is obtained from Eq. (3.13). Once E_t is obtained at a given stress, a factor A is then calculated from the relationship

$$A = S/E_t = S(d\varepsilon/dS) \quad (3.23)$$

The external pressure chart in ASME BPVC Section II-D is constructed by plotting Eq. (3.23) versus the value of S/2. This reduction factor takes into account the reduction of buckling stress in an actual cylinder due to imperfections compared to the values obtained from theoretical buckling equations which are based on perfectly round cylinders. In the ASME BPVC Section VIII-2 code the reduction factor is embedded in the design equation for buckling since VIII-2 does not use external pressure charts.

Example 3.2
Plot the external pressure curve for Grade 91 at 37,000 hours and 1065°F using
Actual stress, S
One-half the stress, S/2. This is the curve adopted by VIII-1 for external pressure calculations.

Solution
The following parameters are obtained first

Temp, °F	1065		Time, hrs	37000	
E , ksi	24762	S_{pm}	18.59	S_u /1.1	45.17
1/b	0.00196408	S_y	35.52		
K_1	-12.4338	K_2	1.180327869	K3	14.6558
K4	1.4278	K5	-0.5056	K6	-25.3281
K7	41.0177	K8	-4.2777	K9	81.7404
K10	120.0467	K11	-27.9095	K12	9.0461
K13	-1.303	K14	21.8743	K15	34.6401
K16	-3.3972				

The values of $\partial\varepsilon_e/\partial S$, $\partial\varepsilon_{pm}/\partial S$, and $\partial\varepsilon_c/\partial S$ are calculated from Eqs. (3.14), (3.15), and (3.16). The results are shown in Table 3.2.

Table 3.2. Strain derivatives

S	$\partial\varepsilon_e/\partial S$	$\partial\varepsilon_{pm}/\partial S$	$\partial\varepsilon_c/\partial S$
0.1	4.03845E-05	-4.58816E-05	1.35424E-12
1	4.03845E-05	-4.50225E-05	6.93617E-09

S	$\partial \varepsilon_e/\partial S$	$\partial \varepsilon_{pm}/\partial S$	$\partial \varepsilon_c/\partial S$
2	4.03845E-05	-4.39816E-05	1.09152E-07
4	4.03845E-05	-4.15919E-05	1.71822E-06
6	4.03845E-05	-3.87212E-05	8.7716E-06
8	4.03845E-05	-3.52657E-05	2.86392E-05
10	4.03845E-05	-3.10933E-05	7.419E-05
12	4.03845E-05	-2.6034E-05	0.000170255
14	4.03845E-05	-1.98665E-05	0.00037444
16	4.03845E-05	-1.22975E-05	0.000852712
18	4.03845E-05	-2.93272E-06	0.002278347
18.5	4.03845E-05	-2.51671E-07	0.003094507
19	4.03845E-05	2.5846E-06	0.004425904
19.5	4.03845E-05	5.58725E-06	0.006948751
20	4.03845E-05	8.76843E-06	0.013558541

The total values of $\partial\varepsilon/\partial S$ and calculated corresponding A values are shown in Table 3.3.

Table 3.3. Total strain derivative and calculated value of "A"

S	Total $\partial\varepsilon/\partial S$	ε_p excluded	$A = S(\partial\varepsilon/\partial S)$
0.1	4.03845E-05	yes	4.03845E-06
1	4.03915E-05	yes	4.03915E-05
2	4.04937E-05	yes	8.09874E-05
4	4.21028E-05	yes	0.000168411
6	4.91561E-05	yes	0.000294937
8	6.90237E-05	yes	0.00055219
10	0.000114575	yes	0.001145745
12	0.00021064	yes	0.00252768
14	0.000414824	yes	0.005807541
16	0.000893097	yes	0.014289551
18	0.002318731	yes	0.041737162
18.5	0.003134892	yes	0.057995494
19	0.004466289	no	0.084859491
19.5	0.006989135	no	0.136288139
20	0.013598925	no	0.271978505

The required external pressure curve is plotted using the first and fourth columns in Table 3.3. This is shown as the top curve in Figure 3.2. The bottom curve in Figure 3.2 is the value of A versus S/2 (designated as B in Section II-D) which is the conventional external pressure curve plotted by ASME for the external pressure charts in ASME BPVC Section II-D.

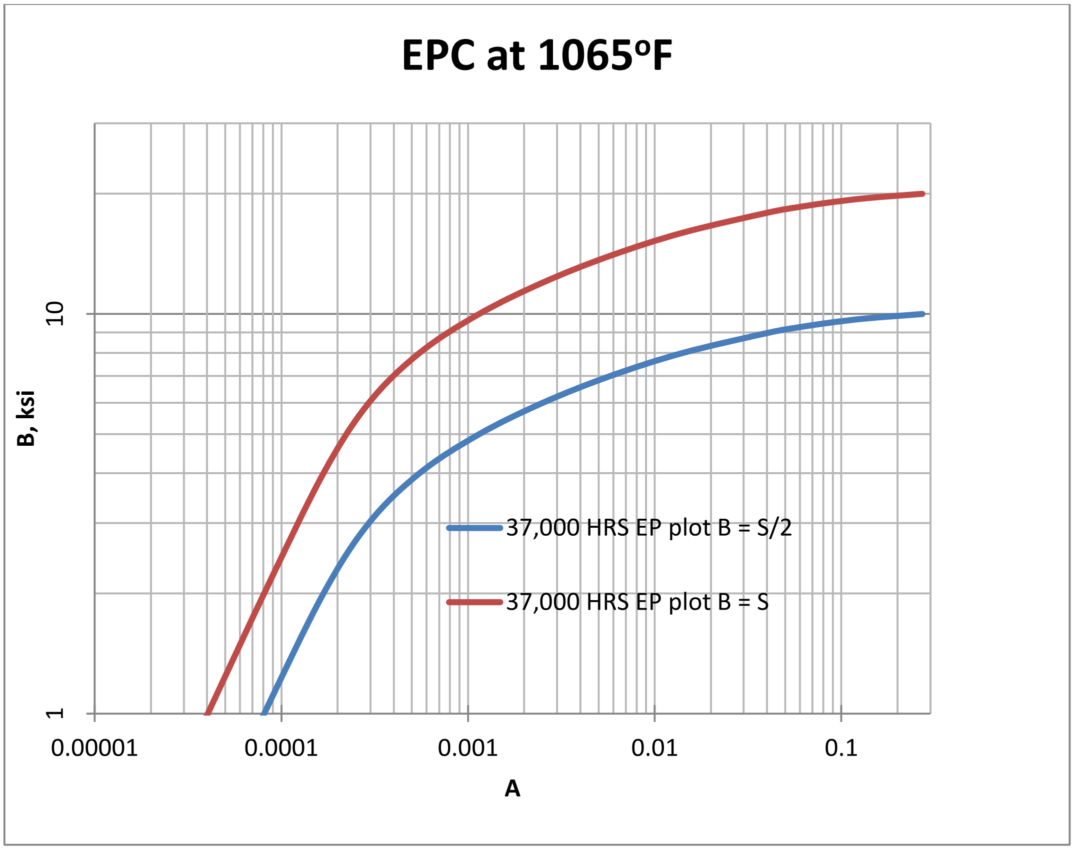

Figure 3.2. External pressure chart at 1065°F and 37,000 hours

3.5 Verification of the Equations Developed for Constructing External Pressure Charts

A number of External Pressure Charts (EPC) were plotted directly from Eqs. (3.13), (3.14), (3.15), and (3.17). These charts were then compared to those obtained from the following two methods

1. Values of the tangent modulus, E_t, were graphically determined from a plot of the minimum isochronous stress-strain curves obtained from Eqs. (3.1), (3.2), (3.9), and (3.10). Factor A was calculated for various S and corresponding E_t values. An external pressure chart was then plotted using the A versus S/2 values (factor B) in accordance with the criterion described in Section II-D.

2. Values of the tangent modulus, E_t, were obtained by using a finite difference method at various selected points on a plot of the minimum isochronous stress-strain curves obtained from Eqs. (3.1), (3.2), (3.9), and (3.10). Factor A was then calculated for various S and corresponding E_t values. An EPC was plotted using the A versus B values in accordance with the criterion described in Section II-D.

A comparison of the above three methods for various EPCs indicated that in all cases the three methods resulted in virtually identical answers. Accordingly, it was determined that EPCs obtained from Eqs. (3.13), (3.14), (3.15), and (3.17) for Grade 91 steel are adequate to construct for any temperature between 800°F and 1200°F and time range between Hot Tensile and 300,000 hours.

3.6 Adjustment of E_t Equations for Modified Isochronous Curves

In Section 2.2 of Part 2, a method was introduced to adjust the basic isochronous curves upwards or downwards in order to take care of some special design conditions. A modification factor "f" was inserted in the equations to accomplish such increase or decrease. The "f" factor was defined as follows

$$f = 1/(\text{increase or decrease in stress value}) \quad \text{for } S \geq S_{pl} \tag{3.24a}$$
$$f = 1.0 \quad \text{for } S < S_{pl} \tag{3.24b}$$

The values of E_t can be adjusted as follows to take care of the "f" factors.

The elastic strain, ε_e, given by Eq. (2.16) is

$$\varepsilon_e = S/E$$

Its derivative is

$$\partial\varepsilon_e/\partial S = 1/E \tag{3.25}$$

The minimum plastic strain, ε_{pm}, is given by Eqs. (2.17) and (3.9) as

$$\varepsilon_{pm} = K_{17}\{\ln[K_{18}/(fS - K_{19})]\}^2 \quad S > S_{pm} \tag{3.26a}$$
$$\varepsilon_{pm} = 0 \quad S \leq S_{pm} \tag{3.26b}$$

Its derivative is expressed as

$$\partial\varepsilon_{pm}/\partial S = -\frac{2\, f\, K_{17} \ln(K_{18}/(f\, S - K_{19}))}{f\, S - K_{19}} \tag{3.27}$$

The expression for creep strain is given by Eqs. (3.4) through (3.8). Modification factor f is introduced as shown in Eqs. (2.19) through (2.22) of Part 2.

$$\varepsilon_c = (-1/\alpha_3)\ln[(1 + \alpha_1\, \dot{\varepsilon}_{01}\, t)^{-\alpha_3/\alpha_1} - \alpha_3\, \dot{\varepsilon}_0\, t)] \tag{3.28}$$

$$\alpha_1 = \text{EXP}\{ K_6 + (K_2)[K_7 + K_8 \ln(f\, S)]\}$$

$$\alpha_3 = \text{EXP}\{ K_1 + (K_2)[K_3 + K_4 \ln(f\, S) + K_5(\ln (f\, S))^2]\}$$

$$\dot{\varepsilon}_0 = \text{EXP}\{ K_9 - (K_2)[K_{10} + K_{11} \ln (f\, S) + K_{12}(\ln (f\, S))^2 + K_{13}(\ln (f\, S))^3]\}$$

$$\dot{\varepsilon}_{01} = \text{EXP}\{ K_{14} - (K_2)[K_{15} + K_{16} \ln (f\, S)]\}$$

The derivative of Eq. (3.28) is exactly the same as the derivative of Eq. (3.17) if some modifications are made to account for the f factor in the above equations for α_1 , α_3, $\dot{\varepsilon}_0$, and $\dot{\varepsilon}_{01}$. This can be accomplished by combining the f factor with other constants. The above four expressions can then be redefined as

$$\alpha_1 = \text{EXP}\{ K_6 + (K_2)[D_1 + K_8 \ln(S)]\} \quad (3.29)$$

$$\alpha_3 = \text{EXP}\{ K_1 + (K_2)[D_2 + D_3 \ln(S) + K_5(\ln (S))^2]\} \quad (3.30)$$

$$\dot{\varepsilon}_0 = \text{EXP}\{ K_9 - (K_2)[D_4 + D_5 \ln (S) + D_6(\ln (S))^2 + K_{13}(\ln (S))^3]\} \quad (3.31)$$

$$\dot{\varepsilon}_{01} = \text{EXP}\{ K_{14} - (K_2)[D_7 + K_{16} \ln (S)]\} \quad (3.32)$$

Where,

$D_1 = K_7 + K_8 \ln(f)$

$D_2 = K_3 + K_4 \ln(f) + K_5 (\ln(f))^2$

$D_3 = K_4 + 2K_5 \ln(f)$

$D_4 = K_{10} + K_{11} \ln(f) + K_{12} (\ln(f))^2 + K_{13} (\ln(f))^3$

$D_5 = K_{11} + 2K_{12} \ln(f) +3K_{13} (\ln(f))^2$

$D_6 = K_{12} + 3K_{13} \ln(f)$

$D_7 = K_{15} + K_{16} \ln(f)$

3.7 Construction of External Pressure Charts

The following external pressure charts are listed in Appendix C and are based on the minimum isochronous stress-strain curves discussed above.

- Figure C.1. External Pressure Chart (EPC) at 800°F
- Table C.1. Tabular values for EPC at 800°F
- Figure C.2. EPC at 900°F
- Table C.2. Tabular values for EPC at 900°F
- Figure C.3. EPC at 1000°F
- Table C.3. Tabular values for EPC at 1000°F
- Figure C.4. EPC at 1100°F
- Table C.4. Tabular values for EPC at 1100°F
- Figure C.5. EPC at 1200°F
- Table C.5. Tabular values for EPC at 1200°F

APPENDIX C EXTERNAL PRESSURE CHARTS

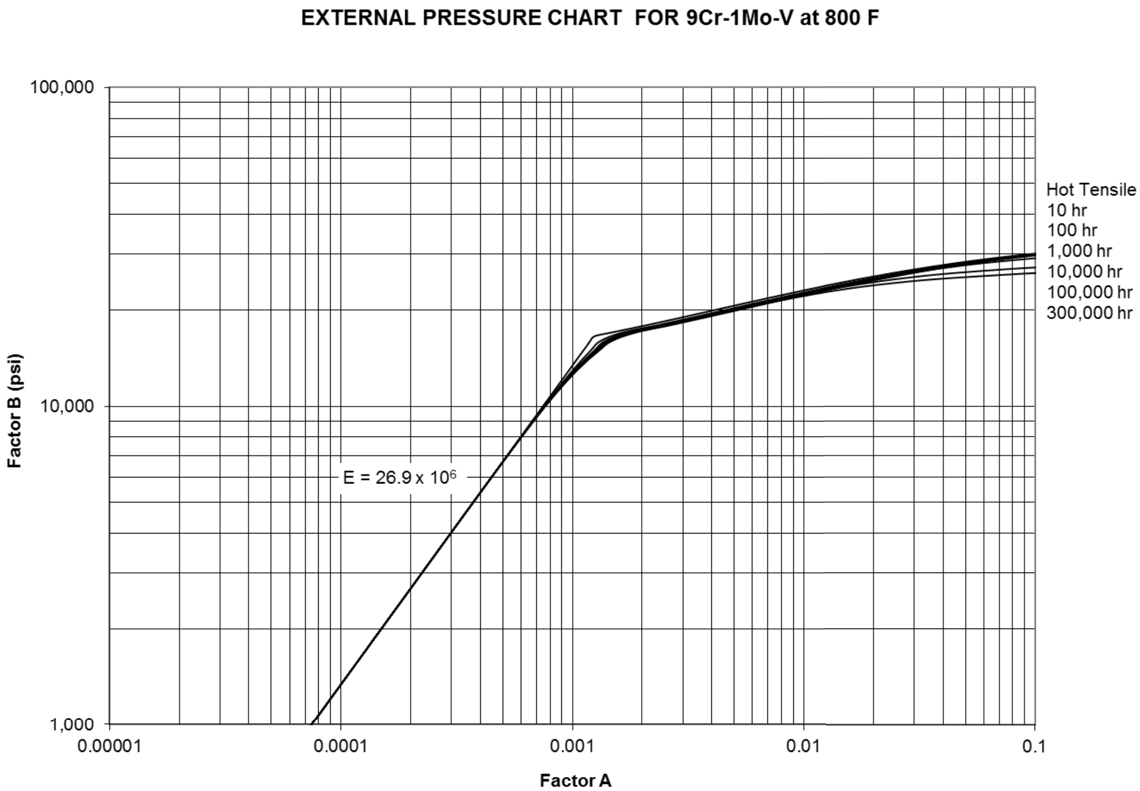

Figure C.1*. External Pressure Chart at 800°F.

*This shows that for practical applications the effects of creep need not be considered for temperatures up to and including 800 F. This is consistent with the Section III, Division 1 -NH Time-Temperature Limits for Application of Section II External Pressure Charts.

Table C.1. Tabular values of A versus B at 800°F.													
Hot Tensile		10 hr		100 hr		1000 hr		10,000 hr		100,000 hr		300,000 hr	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
3.72E-05	500	3.72E-05	500	3.72E-05	500	3.72E-05	500	3.72E-05	500	3.72E-05	500	3.72E-05	500
7.44E-05	1,000	7.44E-05	1,000	7.44E-05	1,000	7.44E-05	1,000	7.44E-05	1,000	7.44E-05	1,000	7.44E-05	1000
1.49E-04	2,000	1.49E-04	2,000	1.49E-04	2,000	1.49E-04	2,000	1.49E-04	2,000	1.49E-04	2,000	1.49E-04	2000
2.23E-04	3,000	2.23E-04	3,000	2.23E-04	3,000	2.23E-04	3,000	2.23E-04	3,000	2.23E-04	3,000	2.23E-04	3000
2.98E-04	4,000	2.98E-04	4,000	2.98E-04	4,000	2.98E-04	4,000	2.98E-04	4,000	2.98E-04	4,000	2.98E-04	4000
3.72E-04	5,000	3.72E-04	5,000	3.72E-04	5,000	3.72E-04	5,000	3.72E-04	5,000	3.73E-04	5,000	3.73E-04	5000
4.47E-04	6,000	4.47E-04	6,000	4.47E-04	6,000	4.47E-04	6,000	4.47E-04	6,000	4.48E-04	6,000	4.48E-04	6000
5.21E-04	7,000	5.22E-04	7,000	5.23E-04	7,000	5.23E-04	7,000	5.23E-04	7,000	5.23E-04	7,000	5.23E-04	7000
5.96E-04	8,000	5.98E-04	8,000	5.99E-04	8,000	6.00E-04	8,000	5.99E-04	8,000	6.00E-04	8,000	6.00E-04	8000
6.70E-04	9,000	6.74E-04	9,000	6.77E-04	9,000	6.79E-04	9,000	6.77E-04	9,000	6.79E-04	9,000	6.80E-04	9000
7.44E-04	10,000	7.53E-04	10,000	7.57E-04	10,000	7.61E-04	10,000	7.58E-04	10,000	7.61E-04	10,000	7.62E-04	10000
8.19E-04	11,000	8.33E-04	11,000	8.41E-04	11,000	8.49E-04	11,000	8.42E-04	11,000	8.47E-04	11,000	8.05E-04	10500
8.93E-04	12,000	9.17E-04	12,000	9.30E-04	12,000	9.44E-04	12,000	9.31E-04	12,000	9.39E-04	12,000	8.49E-04	11000
9.68E-04	13,000	1.01E-03	13,000	1.03E-03	13,000	1.05E-03	13,000	1.03E-03	13,000	1.04E-03	13,000	9.42E-04	12000
1.04E-03	14,000	1.10E-03	14,000	1.13E-03	14,000	1.17E-03	14,000	1.13E-03	14,000	1.15E-03	14,000	1.04E-03	13000
1.12E-03	15,000	1.20E-03	15,000	1.26E-03	15,000	1.31E-03	15,000	1.25E-03	15,000	1.27E-03	15,000	1.16E-03	14000
1.19E-03	16,000	1.32E-03	16,000	1.39E-03	16,000	1.47E-03	16,000	1.38E-03	16,000	1.42E-03	16,000	1.29E-03	15000
1.23E-03	16,500	1.62E-03	17,000	1.74E-03	17,000	1.85E-03	17,000	1.71E-03	17,000	1.77E-03	17,000	1.44E-03	16000
1.31E-03	16,750	2.36E-03	18,000	2.52E-03	18,000	2.68E-03	18,000	2.47E-03	18,000	2.55E-03	18,000	1.80E-03	17000
1.45E-03	17,000	3.30E-03	19,000	3.53E-03	19,000	3.75E-03	19,000	3.45E-03	19,000	3.56E-03	19,000	2.60E-03	18000
2.11E-03	18,000	4.52E-03	20,000	4.82E-03	20,000	5.13E-03	20,000	4.70E-03	20,000	4.87E-03	20,000	3.63E-03	19000
2.97E-03	19,000	6.07E-03	21,000	6.49E-03	21,000	6.90E-03	21,000	6.31E-03	21,000	6.57E-03	21,000	4.99E-03	20000
4.07E-03	20,000	8.09E-03	22,000	8.63E-03	22,000	9.19E-03	22,000	8.40E-03	22,000	8.84E-03	22,000	6.81E-03	21000
5.48E-03	21,000	1.07E-02	23,000	1.14E-02	23,000	1.22E-02	23,000	1.11E-02	23,000	1.20E-02	23,000	9.40E-03	22000
7.31E-03	22,000	1.42E-02	24,000	1.51E-02	24,000	1.60E-02	24,000	1.48E-02	24,000	1.67E-02	24,000	1.34E-02	23000
9.70E-03	23,000	1.88E-02	25,000	2.00E-02	25,000	2.12E-02	25,000	1.97E-02	25,000	2.46E-02	25,000	2.06E-02	24000
1.29E-02	24,000	2.51E-02	26,000	2.66E-02	26,000	2.82E-02	26,000	2.69E-02	26,000	4.04E-02	26,000	3.64E-02	25000
1.72E-02	25,000	3.39E-02	27,000	3.58E-02	27,000	3.81E-02	27,000	3.80E-02	27,000	8.09E-02	27,000	8.50E-02	26000

Table C.1. Tabular values of A versus B at 800°F. (cont'd)													
Hot Tensile		**10 hr**		**100 hr**		**1000 hr**		**10,000 hr**		**100,000 hr**		**300,000 hr**	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
2.30E-02	26,000	4.68E-02	28,000	4.93E-02	28,000	5.25E-02	28,000	5.69E-02	28,000	1.33E-01	27,500	1.15E-01	26250
3.14E-02	27,000	6.67E-02	29,000	6.98E-02	29,000	7.49E-02	29,000	7.20E-02	28,500			1.69E-01	26500
4.37E-02	28,000	9.97E-02	30,000	1.04E-01	30,000	1.13E-01	30,000	9.37E-02	29,000				
6.29E-02	29,000	1.61E-01	31,000	1.67E-01	31,000			1.08E-01	29,250				
9.50E-02	30,000												
1.56E-01	31,000												

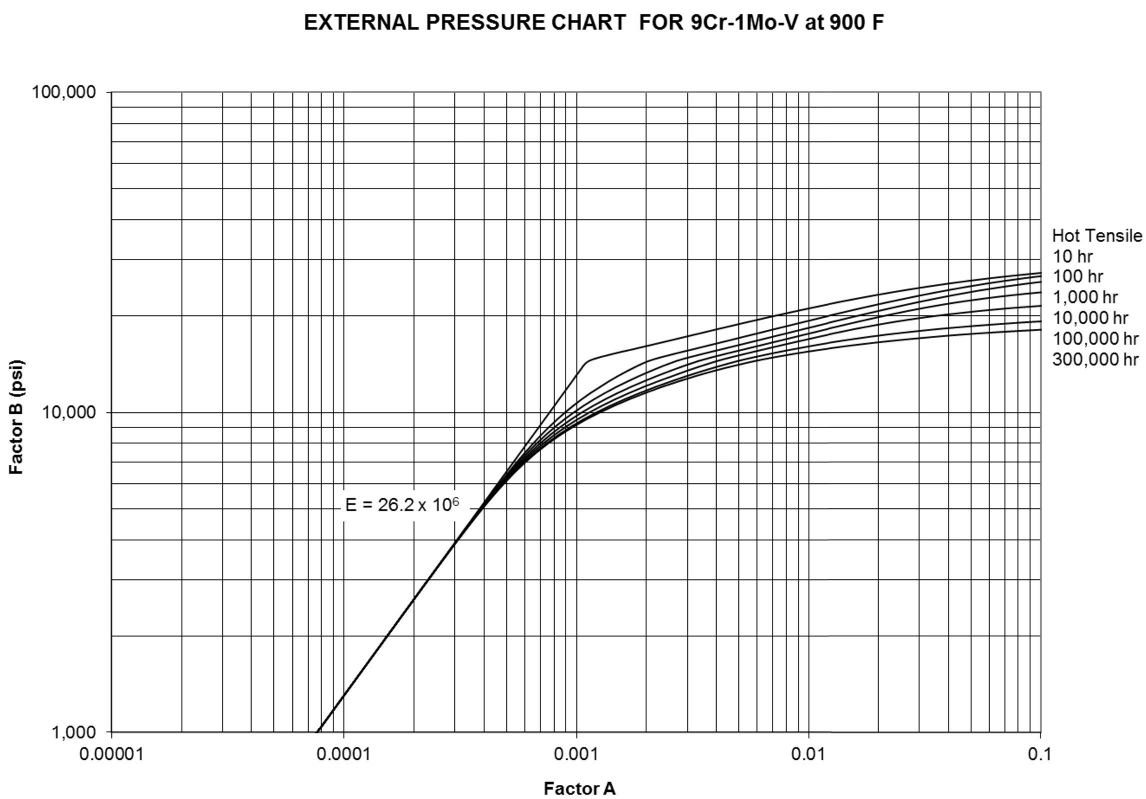

Figure C.2. External Pressure Chart at 900°F.

Table C.2. Tabular values of A versus B at 900°F.

Hot Tensile		10 hr		100 hr		1000 hr		10,000 hr		100,000 hr		300,000 hr	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
3.82E-05	500	3.82E-05	500	3.82E-05	500	3.82E-05	500	3.82E-05	500	3.82E-05	500	3.82E-05	500
0.000115	1500	0.000115	1500	0.000115	1500	0.000115	1500	0.000115	1500	0.000115	1500	0.000115	1500
0.000191	2500	0.000191	2500	0.000191	2500	0.000191	2500	0.000191	2500	0.000191	2500	0.000191	2500
0.000268	3500	0.000268	3500	0.000268	3500	0.000268	3500	0.000269	3500	0.000269	3500	0.000269	3500
0.000344	4500	0.000346	4500	0.000347	4500	0.000348	4500	0.000348	4500	0.000349	4500	0.00035	4500
0.00042	5500	0.000426	5500	0.000428	5500	0.000431	5500	0.000434	5500	0.000437	5500	0.000438	5500
0.000497	6500	0.00051	6500	0.000517	6500	0.000524	6500	0.000531	6500	0.000538	6500	0.000541	6500
0.000573	7500	0.000601	7500	0.000616	7500	0.000632	7500	0.000648	7500	0.000664	7500	0.000672	7500
0.00065	8500	0.000703	8500	0.000735	8500	0.000767	8500	0.0008	8500	0.000832	8500	0.000848	8500
0.000726	9500	0.000823	9500	0.000883	9500	0.000943	9500	0.001004	9500	0.001065	9500	0.001095	9500
0.000803	10500	0.000967	10500	0.001073	10500	0.001179	10500	0.001286	10500	0.001395	10500	0.001451	10500
0.000879	11500	0.001147	11500	0.001322	11500	0.0015	11500	0.001679	11500	0.001865	11500	0.001969	11500
0.000956	12500	0.001372	12500	0.001654	12500	0.001939	12500	0.002227	12500	0.002539	12500	0.002735	12500
0.001032	13500	0.00166	13500	0.002094	13500	0.002535	13500	0.002984	13500	0.003509	13500	0.003912	13500
0.001133	14500	0.002051	14500	0.002701	14500	0.003362	14500	0.004048	14500	0.004972	14500	0.005901	14500
0.001435	15250	0.002632	15250	0.003493	15250	0.004373	15250	0.005306	15250	0.006778	15250	0.008603	15250
0.001741	15750	0.00316	15750	0.004194	15750	0.005253	15750	0.006402	15750	0.0085	15750	0.011523	15750
0.00209	16250	0.003766	16250	0.005	16250	0.006268	16250	0.007692	16250	0.010782	16250	0.015946	16250
0.002491	16750	0.004458	16750	0.005923	16750	0.007437	16750	0.009218	16750	0.013933	16750	0.023076	16750
0.00295	17250	0.005249	17250	0.006979	17250	0.008782	17250	0.011042	17250	0.018501	17250	0.035498	17250
0.003477	17750	0.006151	17750	0.008186	17750	0.01033	17750	0.013256	17750	0.025509	17750	0.059723	17750
0.004083	18250	0.00718	18250	0.009563	18250	0.012113	18250	0.016003	18250	0.037004	18250	0.117979	18250
0.004779	18750	0.008352	18750	0.011135	18750	0.014176	18750	0.019512	18750	0.057586	18750	0.39681	18750
0.005583	19250	0.00969	19250	0.012928	19250	0.016576	19250	0.024159	19250	0.099825	19250	37.78883	19250
0.006512	19750	0.011216	19750	0.014975	19750	0.019392	19750	0.030589	19750	0.215602	19750		
0.007591	20250	0.012961	20250	0.017318	20250	0.022742	20250	0.039945	20250	39.98438	20250		
0.008848	20750	0.01496	20750	0.020007	20750	0.026797	20750	0.054376	20750				
0.010319	21250	0.017256	21250	0.023108	21250	0.031824	21250	0.078254	21250				
0.01205	21750	0.019903	21750	0.026708	21750	0.038244	21750	0.121772	21750				
0.014099	22250	0.022972	22250	0.030925	22250	0.046739	22250	0.215063	22250				

Table C.2. Tabular values of A versus B at 900°F. (cont'd)													
Hot Tensile		10 hr		100 hr		1000 hr		10,000 hr		100,000 hr		300,000 hr	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
0.016542	22750	0.026549	22750	0.035922	22750	0.058456	22750						
0.019478	23250	0.030752	23250	0.041935	23250	0.075397	23250						
0.023041	23750	0.035738	23750	0.04931	23750	0.101252	23750						
0.027413	24250	0.041721	24250	0.058564	24250	0.143431	24250						
0.032847	24750	0.049005	24750	0.070495	24750								
0.03971	25250	0.058025	25250	0.086358	25250								
0.04854	25750	0.069432	25750	0.108189	25750								
0.06017	26250	0.084224	26250	0.139406	26250								
0.075938	26750	0.104001	26750	0.186044	26750								
0.09813	27250	0.131461	27250	0.259528	27250								
0.130963	27750	0.17147	27750	0.383973	27750								
0.18305	28250	0.233687	28250	0.620359	28250								
0.274843	28750	0.340268	28750										
0.468193	29250												

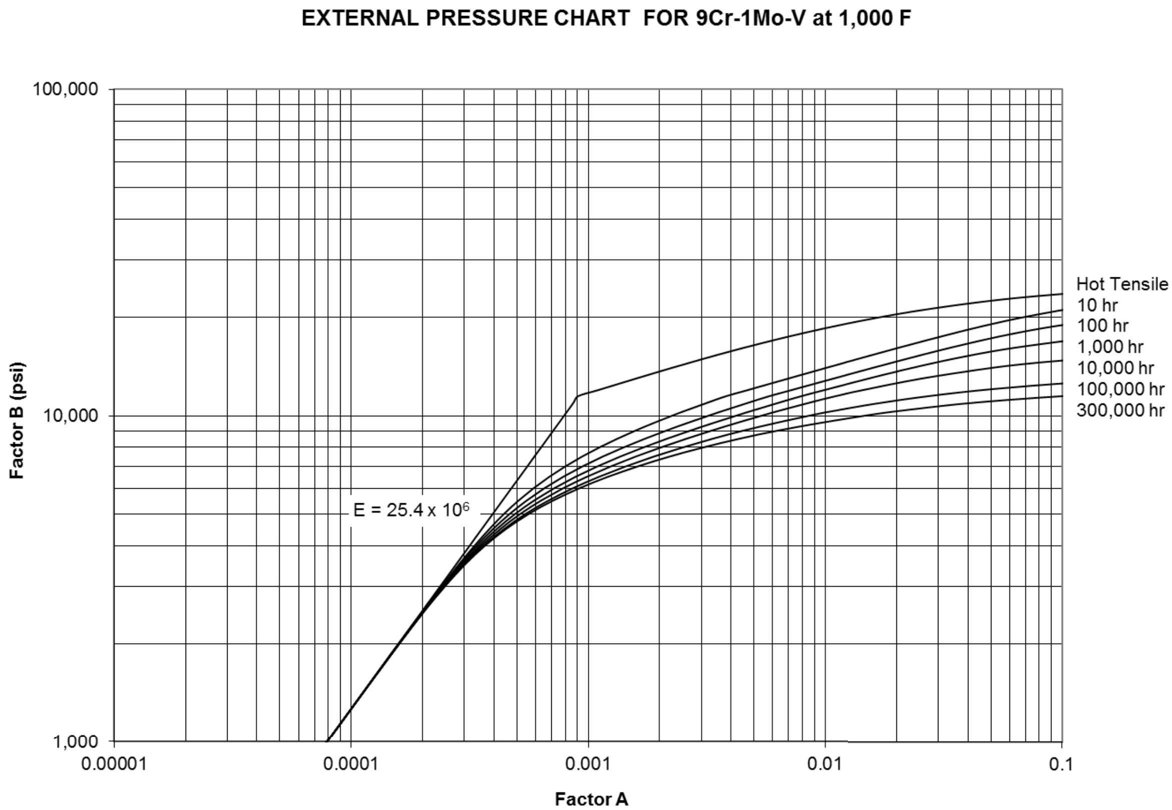

Figure C.3. External Pressure Chart at 1000°F.

Table C.3. Tabular values of A versus B at 1000°F.													
Hot Tensile		**10 hr**		**100 hr**		**1000 hr**		**10,000 hr**		**100,000 hr**		**300,000 hr**	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
3.95E-05	500	3.95E-05	500	3.95E-05	500	3.95E-05	500	3.95E-05	500	3.95E-05	500	3.95E-05	500
7.89E-05	1,000	7.89E-05	1,000	7.89E-05	1,000	7.89E-05	1,000	7.89E-05	1,000	7.89E-05	1,000	7.89E-05	1,000
1.58E-04	2,000	1.58E-04	2,000	1.58E-04	2,000	1.59E-04	2,000	1.59E-04	2,000	1.59E-04	2,000	1.59E-04	2,000
2.37E-04	3,000	2.40E-04	3,000	2.42E-04	3,000	2.44E-04	3,000	2.45E-04	3,000	2.47E-04	3,000	2.48E-04	3,000
3.16E-04	4,000	3.31E-04	4,000	3.38E-04	4,000	3.46E-04	4,000	3.54E-04	4,000	3.62E-04	4,000	3.66E-04	4,000
3.95E-04	5,000	4.40E-04	5,000	4.65E-04	5,000	4.90E-04	5,000	5.15E-04	5,000	5.42E-04	5,000	5.59E-04	5,000
4.73E-04	6,000	5.87E-04	6,000	6.52E-04	6,000	7.17E-04	6,000	7.83E-04	6,000	8.60E-04	6,000	9.16E-04	6,000
5.52E-04	7,000	7.99E-04	7,000	9.44E-04	7,000	1.09E-03	7,000	1.24E-03	7,000	1.44E-03	7,000	1.62E-03	7,000
6.31E-04	8,000	1.11E-03	8,000	1.41E-03	8,000	1.70E-03	8,000	2.02E-03	8,000	2.50E-03	8,000	3.05E-03	8,000
7.10E-04	9,000	1.57E-03	9,000	2.12E-03	9,000	2.68E-03	9,000	3.29E-03	9,000	4.48E-03	9,000	6.24E-03	9,000
7.89E-04	10,000	2.25E-03	10,000	3.20E-03	10,000	4.18E-03	10,000	5.35E-03	10,000	8.49E-03	10,000	1.46E-02	10,000
8.29E-04	10,500	2.69E-03	10,500	3.92E-03	10,500	5.20E-03	10,500	6.81E-03	10,500	1.21E-02	10,500	2.41E-02	10,500
8.68E-04	11,000	3.21E-03	11,000	4.79E-03	11,000	6.44E-03	11,000	8.68E-03	11,000	1.78E-02	11,000	4.43E-02	11,000
9.07E-04	11,500	3.83E-03	11,500	5.82E-03	11,500	7.94E-03	11,500	1.11E-02	11,500	2.75E-02	11,500	1.03E-01	11,500
1.10E-03	12,000	4.71E-03	12,000	7.21E-03	12,000	9.91E-03	12,000	1.45E-02	12,000	4.63E-02	12,000	2.01E-01	11,750
1.58E-03	13,000	6.95E-03	13,000	1.08E-02	13,000	1.52E-02	13,000	2.54E-02	13,000	9.02E-02	12,500		
1.88E-03	13,500	8.35E-03	13,500	1.31E-02	13,500	1.87E-02	13,500	4.95E-02	14,000	1.43E-01	12,750		
2.23E-03	14,000	9.98E-03	14,000	1.57E-02	14,000	2.30E-02	14,000	7.52E-02	14,500				
3.10E-03	15,000	1.40E-02	15,000	2.25E-02	15,000	3.54E-02	15,000	1.28E-01	15,000				
3.65E-03	15,500	1.65E-02	15,500	2.68E-02	15,500	5.74E-02	16,000						
4.30E-03	16,000	1.94E-02	16,000	3.18E-02	16,000	1.05E-01	17,000						
5.94E-03	17,000	2.64E-02	17,000	4.52E-02	17,000	1.57E-01	17,500						
8.27E-03	18,000	3.58E-02	18,000	6.57E-02	18,000								
1.16E-02	19,000	4.17E-02	18,500	1.01E-01	19,000								
1.67E-02	20,000	4.87E-02	19,000	1.77E-01	20,000								
2.02E-02	20,500	6.73E-02	20,000										
2.48E-02	21,000	9.66E-02	21,000										
3.86E-02	22,000	1.18E-01	21,500										
6.54E-02	23,000												

Table C.3. Tabular values of A versus B at 1000°F. (cont'd)													
Hot Tensile		**10 hr**		**100 hr**		**1000 hr**		**10,000 hr**		**100,000 hr**		**300,000 hr**	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
1.30E-01	24,000												

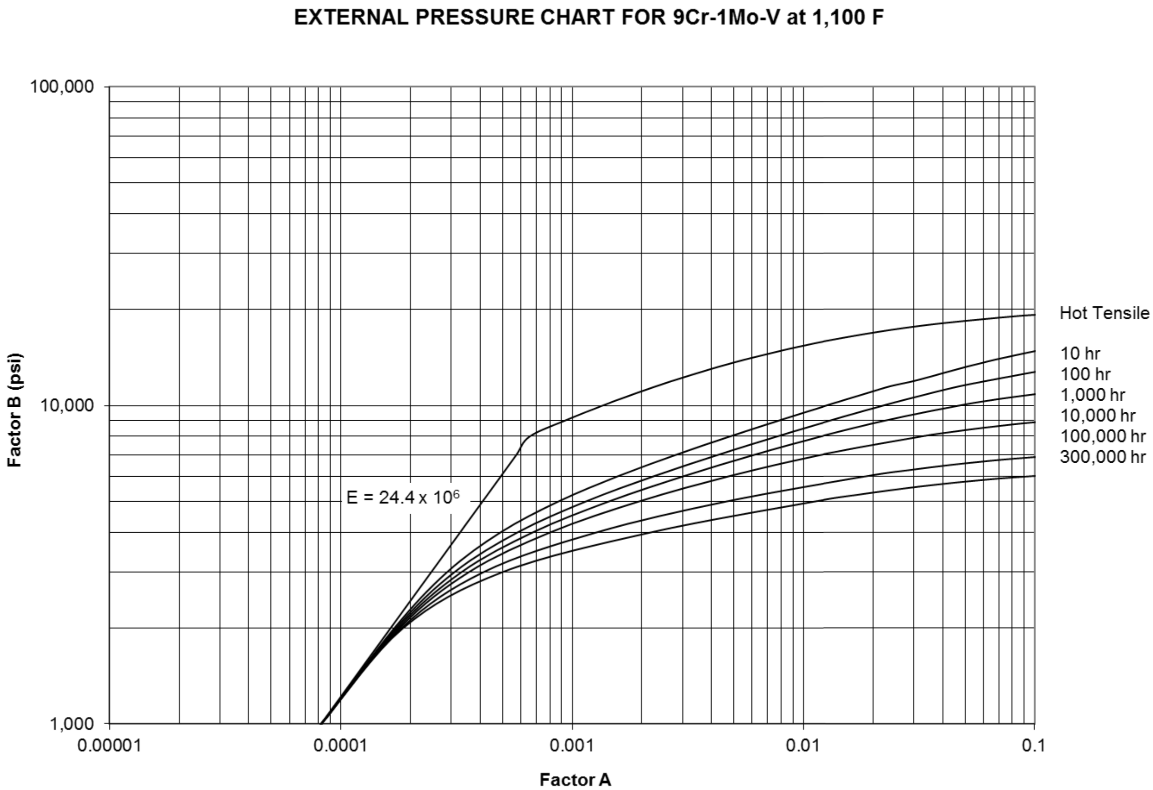

Figure C.4. External Pressure Chart at 1100°F.

Table C.4. Tabular values of A versus B at 1100°F.													
Hot Tensile		**10 hr**		**100 hr**		**1000 hr**		**10,000 hr**		**100,000 hr**		**300,000 hr**	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
4.09E-05	500	4.09E-05	500	4.10E-05	500	4.09E-06	50	4.09E-06	50	4.10E-05	500	4.10E-05	500
8.19E-05	1,000	8.21E-05	1,000	8.22E-05	1,000	4.10E-05	500	4.10E-05	500	8.25E-05	1,000	8.25E-05	1,000
1.64E-04	2,000	1.70E-04	2,000	1.73E-04	2,000	8.23E-05	1,000	8.24E-05	1,000	1.83E-04	2,000	1.85E-04	2,000
2.46E-04	3,000	2.88E-04	3,000	3.10E-04	3,000	1.76E-04	2,000	1.79E-04	2,000	4.13E-04	3,000	4.99E-04	3,000
3.28E-04	4,000	4.90E-04	4,000	5.81E-04	4,000	3.32E-04	3,000	3.57E-04	3,000	1.27E-03	4,000	2.19E-03	4,000
4.09E-04	5,000	8.71E-04	5,000	1.14E-03	5,000	6.75E-04	4,000	8.03E-04	4,000	4.64E-03	5,000	1.12E-02	5,000
4.91E-04	6,000	1.57E-03	6,000	2.25E-03	6,000	1.44E-03	5,000	1.94E-03	5,000	1.88E-02	6,000	1.74E-02	5,250
5.73E-04	7,000	2.80E-03	7,000	4.26E-03	7,000	3.02E-03	6,000	4.76E-03	6,000	2.79E-02	6,250	2.80E-02	5,500
6.55E-04	8,000	4.80E-03	8,000	7.68E-03	8,000	6.10E-03	7,000	1.19E-02	7,000	4.30E-02	6,500	3.63E-02	5,625
9.41E-04	9,000	7.93E-03	9,000	1.33E-02	9,000	1.19E-02	8,000	3.26E-02	8,000	5.20E-02	6,600	4.82E-02	5,750
1.35E-03	10,000	1.26E-02	10,000	2.22E-02	10,000	2.31E-02	9,000	4.34E-02	8,250	6.40E-02	6,700	6.64E-02	5,875
1.62E-03	10,500	1.57E-02	10,500	2.86E-02	10,500	4.75E-02	10,000	5.93E-02	8,500	8.03E-02	6,800	9.74E-02	6,000
1.93E-03	11,000	1.94E-02	11,000	3.68E-02	11,000	7.16E-02	10,500	8.43E-02	8,750	1.04E-01	6,900	1.43E-01	6,100
2.31E-03	11,500	2.39E-02	11,500	4.77E-02	11,500	1.16E-01	11,000	1.28E-01	9,000	1.40E-01	7,000		
2.76E-03	12,000	3.10E-02	12,000	6.41E-02	12,000								
3.94E-03	13,000	4.64E-02	13,000	1.17E-01	13,000								
4.74E-03	13,500	5.68E-02	13,500	1.69E-01	13,500								
5.71E-03	14,000	6.99E-02	14,000										
8.44E-03	15,000	1.09E-01	15,000										
1.04E-02	15,500	1.40E-01	15,500										
1.29E-02	16,000												
2.08E-02	17,000												
3.69E-02	18,000												
7.86E-02	19,000												
1.00E-01	19,250												
1.33E-01	19,500												

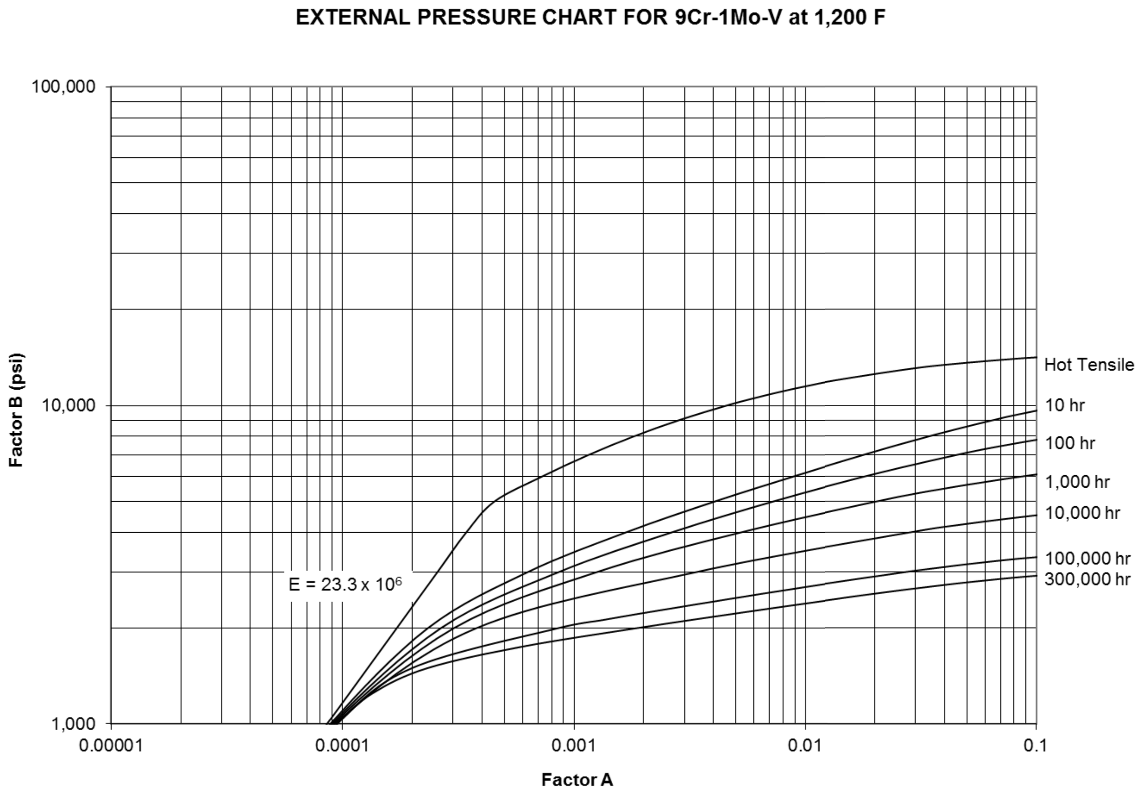

Figure C.5. External Pressure Chart at 1200ºF.

Table C.5. Tabular values of A versus B at 1200°F.													
Hot Tensile		**10 hr**		**100 hr**		**1000 hr**		**10,000 hr**		**100,000 hr**		**300,000 hr**	
A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)	A	B (psi)
4.28E-05	500	2.14E-05	250	2.14E-05	250	4.28E-06	50	4.28E-06	50	4.28E-06	50	4.28E-06	50
8.55E-05	1,000	4.29E-05	500	4.30E-05	500	2.14E-05	250	2.14E-05	250	2.14E-05	250	2.14E-05	250
0.000171	2,000	8.84E-05	1,000	8.97E-05	1,000	4.3E-05	500	4.31E-05	500	4.31E-05	500	4.31E-05	500
0.000257	3,000	0.000233	2,000	0.000265	2,000	9.1E-05	1,000	9.22E-05	1,000	9.47E-05	1,000	6.65E-05	750
0.000342	4,000	0.000629	3,000	0.000856	3,000	0.000302	2,000	0.000377	2,000	0.0002	1,500	9.42E-05	1,000
0.000453	5,000	0.001676	4,000	0.002643	4,000	0.001252	3,000	0.00336	3,000	0.000848	2,000	0.000135	1,250
0.000731	6,000	0.004056	5,000	0.007258	5,000	0.005265	4,000	0.02867	4,000	0.001342	2,125	0.000233	1,500
0.001154	7,000	0.008936	6,000	0.018375	6,000	0.020504	5,000	0.050162	4,250	0.002125	2,250	0.000594	1,750
0.001808	8,000	0.017961	7,000	0.045467	7,000	0.041061	5,500	0.094715	4,500	0.00517	2,500	0.001848	2,000
0.002844	9,000	0.03433	8,000	0.073465	7,500	0.088548	6,000	0.138586	4,625	0.011977	2,750	0.005537	2,250
0.004561	10,000	0.065231	9,000	0.125081	8,000	0.139613	6,250			0.02734	3,000	0.015403	2,500
0.00585	10,500	0.091319	9,500	0.239494	8,500					0.038524	3,100	0.023058	2,600
0.0076	11,000	0.130924	10,000							0.055426	3,200	0.03487	2,700
0.010044	11,500	0.195416	10,500							0.082848	3,300	0.054151	2,800
0.013591	12,000									0.133155	3,400	0.088999	2,900
0.027884	13,000											0.166109	3,000
0.04413	13,500												
0.079903	14,000												
0.118	14,250												
0.196612	14,500												

ABBREVIATIONS AND ACRONYMS (PART 4)

A = strain factor
a = cross sectional area
B = ASME allowable compressive stress = S/2
B' = allowable compressive stress with a given design factor = S/DF
D_o = outside diameter
E = modulus of elasticity, ksi
E_t = tangent modulus of elasticity, ksi
ε = total strain
ε_{cr} = critical strain
F = temperature, °F
DF = design factor
DF_f = design factor at 100,000 hrs
DF_i = design factor at 1 hour
DF_v = variable design factor in the creep range.
I = moment of inertia
κ = coefficient in geometric chart
KD = knock down factor
L = effective length
P = external pressure
R_o = outside radius
r = radius of gyration = $(I/a)^{0.5}$
S = stress, ksi
S_{cr} = critical stress
t = time, hours
T = thickness

4 DESIGN FORMULATIONS FOR COMPRESSIVE STRESS

4.1 Introduction

The procedure developed in this part for axial compression is intended to accomplish the following.

1. Demonstrate the applicability of Parts 1, 2, and 3 in the design of components subjected to compressive stress.

2. Demonstrate the applicability of both the External Pressure Charts and the External Pressure equations in the design of pressure vessels.

3. Refine the methodology developed in publication ASME STP-PT-029.

4. Enable the engineer to use either the conventional External Pressure Charts (with a factor of 2 imbedded in them) or the charts correlating compressive stress S versus A in the design of components under compressive stress.

4.2 Axial Compression in Long Cylinders

4.2.1 Temperature Below the Creep Range

The classical equation for the axial compression of a long cylindrical shell [Gerard 1962] is

$$\varepsilon_{cr} = S_{cr}/E = \frac{0.6}{(R_o/T)} \tag{4.1}$$

Experimental data [Gerard 1962] has shown that axial buckling could occur at a value as low as one-tenth that calculated by Eq. (4.1). Accordingly, a knock down factor, KD, is incorporated into Eq. (4.1) for design purposes.

$$A = \frac{0.6}{(KD)(R_o/T)} \tag{4.2}$$

In the elastic range,

$$S_{cr} = \varepsilon_{cr}E. \tag{4.3}$$

For design purposes a design factor, DF, is incorporated into this equation to take into account such items as inaccuracy in determining modulus of elasticity and variation in material properties. Hence the equation becomes

$$B' = S/(DF) = AE/(DF) \tag{4.4}$$

In the inelastic range the elastic modulus, E, must be replaced by the tangent modulus, E_t. This is accomplished by constructing an external pressure chart where E_t is used to correlate factor A to a stress S as shown in Fig.3.2 which is duplicated here as Fig. 4.1. Hence,

$$B' = S/(DF) \tag{4.5}$$

The ASME BPVC Section VIII-1 code uses a KD factor of 5.0 in Eq. (4.2) to account for the effect of geometric imperfections on axial compression [Miller and Griffin 1999]. Hence, Eq. (4.2) becomes

$$A \approx \frac{0.125}{(R_o/T)} \qquad \text{ASME BPVC VIII-1} \qquad (4.6)$$

Also, a design factor of 2.0 is used by VIII-1 in Eqs. (4.4) and (4.5)

$$B = 0.5AE \qquad \text{ASME BPVC VIII-1} \qquad (4.7)$$

and

$$B = 0.5S \qquad \text{ASME BPVC VIII-1} \qquad (4.8)$$

Equation (4.8) for allowable compressive stress may be obtained from either a chart expressing S versus A or from a conventional external pressure chart where allowable compressive stress is equal to B.

> The total design factor for cylindrical shells subjected to axial compression in the ASME BPV Code Section VIII-1 is 10 (the product of knock down factor of 5 and design factor of 2).

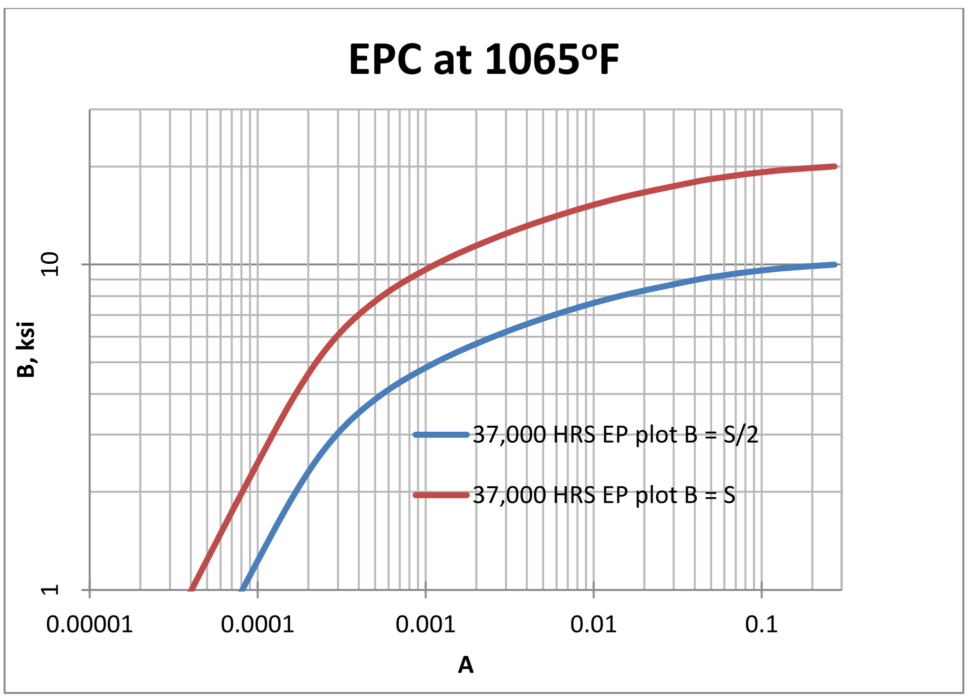

Figure 4.1 External pressure chart

4.2.2 Temperature in the Creep Range

It was shown in publication STP-PT-029 [Jawad and Griffin, 2011] that the design factor in the creep region may be decreased with an increase in the operating hours. Hence the DF in Eqs. (4.4) and (4.5) can be written as a variable as
Let DF be defined as

$$DF = \frac{1}{C_1 - C_2 \ln(t)} \tag{4.9}$$

The boundary conditions for this equation are

$DF = DF_i$ when $t = 1$ hour

$DF = DF_f$ when $t = 100{,}000$ hours

The values of C_1 and C_2 are obtained by substituting the two boundary conditions in Eq. (4.9). Equation (4.9) then becomes

$$DF = \frac{11.513\,(DF_i)(DF_f)}{(DF_f)(11.513 - \ln(t)) + (DF_i)(\ln(t))} \tag{4.10}$$

The DF of 2.0 used by ASME in Eqs. (4.7) and (4.8) at temperatures below the creep range may be assumed to be valid in the creep range up to one hour. The DF may be reduced in the creep range to 1.0 in 100,000 hours as explained in ASME publication STP- PT-029 [Jawad and Griffin, 2011]. Accordingly, Eqs. (4.4), (4.5), and (4.10) may be written as

Allowable compressive stress = $AE/(DF_v)$ in the elastic range (4.11)

or

allowable compressive stress = $S/(DF_v)$ (4.12)

or

allowable compressive stress = $2B/(DF_v)$ (4.13)

Where,

S is obtained from a chart expressing S versus A, and B is obtained from an external pressure chart expressing B versus A.

The allowable compressive stress from Eqs. (4.11) through (4.13) may not exceed the allowable compressive stress obtained from the Hot Tensile curve.

$DF_v = 2.0$ $t < 1.0$ hour

$$DF_v = \frac{2}{1 + 0.0869 \ln(t)} \qquad 1 \le t \le 100{,}000 \text{ hours} \tag{4.14}$$

$DF_v = 1.0$ $t > 100{,}000$ hours

Example 4.1
What is the ASME allowable axial compressive stress in a cylindrical shell with R_o = 25 inch and T = 0.5 inch? Let F = 1200°F and t = 100,000 hours.

Solution
From Eq. (4.6), A = 0.125/(25/0.5) = 0.0025.
The value of B is obtained from Fig.C.5.
For 100,000 hours,
B = 2200 psi
From Eq.(4.14),

$$DF_v = \frac{2}{1 + 0.0869\ \ln(100{,}000)} = 1.0$$

From Eq. (4.13)
Allowable compressive stress = 2(2200)/1.0 = 4400 psi
Check for the Hot Tensile condition
B = 8500 psi
DF_v = 2.0
Allowable compressive stress = 2(8500)/2.0 = 8500 psi > 4400 psi ok

4.3 External Pressure on Spherical Sections

4.3.1 Temperature Below the Creep Range

The classical equation for the buckling of a spherical section is given by Timoshenko [Timoshenko, 1961] as

$$\varepsilon_{cr} = S_{cr}/E = \frac{0.6}{(R_o/T)} \tag{4.15}$$

This equation is based on a perfect sphere without imperfections. However, von Karman [von-Karman 1939] showed by using energy equations, and taking into consideration imperfections, that the actual buckling coefficient for a spherical section is substantially smaller than that given by Timoshenko and is

$$\varepsilon_{cr} = S_{cr}/E = \frac{0.154}{(R_o/T)} \tag{4.16}$$

A knock down factor, KD, is usually incorporated into Eq. (4.12) for design purposes and Eq. (4.12) becomes

$$A = \frac{0.154}{(KD)(R_o/T)} \tag{4.17}$$

In the elastic range, Eq. (4.3) is applicable. For design purposes a design factor, DF, is incorporated into this equation to take into account such items as inaccuracy in determining modulus of elastic and variation in material properties. Combining Eqs. (4.3) and (4.14) gives

$$P = \frac{0.308\ E}{(DF)(KD)(R_o/T)^2} \tag{4.18}$$

In the inelastic range, the allowable external pressure, P, is calculated by determining first the factor A from Eq.(4.14). A stress is then obtained from an external pressure chart. The allowable pressure P is then calculated from the equation $S = PR_o/2T$ as

$$P = \frac{2\ S}{(DF)(R_o/T)} \tag{4.19}$$

The ASME BPVC Section VIII-1 uses a KD factor of 1.25 and a design factor of 4.0. Hence, Eqs. (4.14), (4.15), and (4.16) become

$$A \approx \frac{0.125}{(R_o/T)} \qquad \text{ASME BPVC VIII-1} \tag{4.20}$$

$$P \approx \frac{0.0625\ E}{(R_o/T)^2} \qquad \text{ASME BPVC VIII-1 in the elastic range} \tag{4.21}$$

$$P = \frac{B}{(R_o/T)} \qquad \text{ASME BPVC VIII-1 in the nonlinear range} \tag{4.22}$$

The total design factor for a spherical shell is equal to 5 (the product of knock down factor 1.25 and a design factor of 4.0) when Eq. (4.9) is used. The design factor is equal to 20 (the product of knock down factor of 5 and design factor of 4) when Eq. (4.8) is used.

4.3.2 Temperature in the Creep Range

The FS of 4.0 used by ASME in Eqs. (4.21) and (4.22) at temperatures below the creep regime may be used in the creep regime up to one hour. It can be reduced to a value of 2.0 at 100,000 hours as explained in ASME publication STP- PT-029. Hence, Eqs. (4.21) and (4.22) become

$$P = \frac{0.25\ E}{(DF_v)()(R_o/T)^2} \qquad \text{in the elastic range} \tag{4.23}$$

or,

$$P = \frac{2\ S}{(DF_v)(R_o/T)} \tag{4.24}$$

or,

$$P = \frac{4\,B}{(DF_v)(R_o/T)} \tag{4.25}$$

Where,

$$DF_v = 4.0 \qquad t< 1.0 \text{ hour}$$

$$DF_v = \frac{4}{1 + 0.0869\ \ln(t)} \qquad 1 \le t \le 100{,}000 \text{ hours} \tag{4.26}$$

$$DF_v = 2.0 \qquad t > 100{,}000 \text{ hours}$$

The allowable external pressure from Eqs. (4.23) through (4.25) may not exceed the allowable external pressure obtained from the Hot Tensile curve.

Example 4.2
What is the ASME allowable external pressure in a spherical component with R_o = 25 inch and T = 0.25 inch? Let F = 1200ºF and t = 100,000 hours.

Solution
From Eq. (4.20), $A \approx 0.125/(25/0.25) = 0.00125$
The value of B is obtained from Fig.C.5. For 100,000 hours,
B = 2100 psi
From Eq. (4.26),

$$DS_v = \frac{4}{1 + 0.0869\ \ln(100{,}000} = 2.0$$

From Eq. (4.25),

$$P = \frac{(4)(2100)}{(2.0)\ (25/0.25)} = 42.0 \text{ psi}$$

Check for hot tensile condition
B = 7000 psi
DFv = 4.0

$$P = \frac{(4)(7000)}{(4.0)\ (25/0.25)} = 70 \text{ psi} \quad > 42 \text{ psi} \qquad \text{ok}$$

4.4 External Pressure on Cylindrical Shells

4.4.1 Temperature Below the Creep Range

The classical equation for external pressure on a cylindrical shell [Sturm 1941] is

$$P = \kappa E/(D_o/T)^3 \qquad 4.27)$$

The stress equation is given by

$$S = \frac{P(D_o/T)}{2} \qquad (4.28)$$

Substituting Eq. (4.24) into Eq. (4.22) and using the quantity $\varepsilon = S/E$ gives

$$A = \kappa/(D_o/T)^2 \qquad (4.29)$$

Equation (4.29) is the geometric chart used in ASME which is a function of L/D_o, T/D_o, and A as shown in Fig.4.2. The knock-down factor in Eq. (4.29) is 1.0.

In the elastic range, $S_{cr} = \varepsilon_{cr}E$. combining this expression with $S = PR_o/T$ and applying a design factor gives

$$P = \frac{2AE}{(DF)(D_o/T)} \qquad (4.30)$$

In the inelastic range, the value of A is obtained from an external pressure chart. The allowable external pressure using A and S = PD/2T becomes

$$P = \frac{4B}{(DF)(D_o/T)} \qquad (4.31)$$

The ASME BPVC Section VIII-1 uses a design factor of 3 and Eqs. (4.30) and (4.31) become

$$P = \frac{2AE}{3(D_o/T)} \qquad \text{ASME BPVC VIII-1} \qquad (4.32)$$

$$P = \frac{4B}{3(D_o/T)} \qquad \text{ASME BPVC VIII-1} \qquad (4.33)$$

The total design factor for cylindrical shells subjected to external pressure in the ASME BPVC Section VIII-1 is equal to 3.0 (the product of knock down factor of 1.0 and design factor of 3.0).

4.4.2 Temperature in the Creep Range

The design factor of 3.0 used by ASME in Eqs. (4.32) and (4.33) at temperatures below the creep range may be used in the creep range up to one hour. The DF may be reduced to 2.0 at 100,000 hours as explained in ASME publication STP- PT-029. Equations (4.30) and (4.31) become

$$P = \frac{2AE}{(DF_v)(D_o/T)} \quad \text{in the elastic range.} \tag{4.34}$$

or,

$$P = \frac{2S}{(DF_v)(D_o/T)} \tag{4.35}$$

or,

$$P = \frac{4B}{(DF_v)(D_o/T)} \tag{4.36}$$

Where,

$$DF_v = 3.0 \qquad t < 1.0 \text{ hour}$$

$$DF_v = \frac{3}{1 + 0.0434 \ln(t)} \qquad 1 \leq t \leq 100{,}000 \text{ hours} \tag{4.37}$$

$$DF_v = 2.0 \qquad t > 100{,}000 \text{ hours}$$

The allowable external pressure from Eqs. (4.34) through (4.36) may not exceed the allowable external pressure obtained from the Hot Tensile curve.

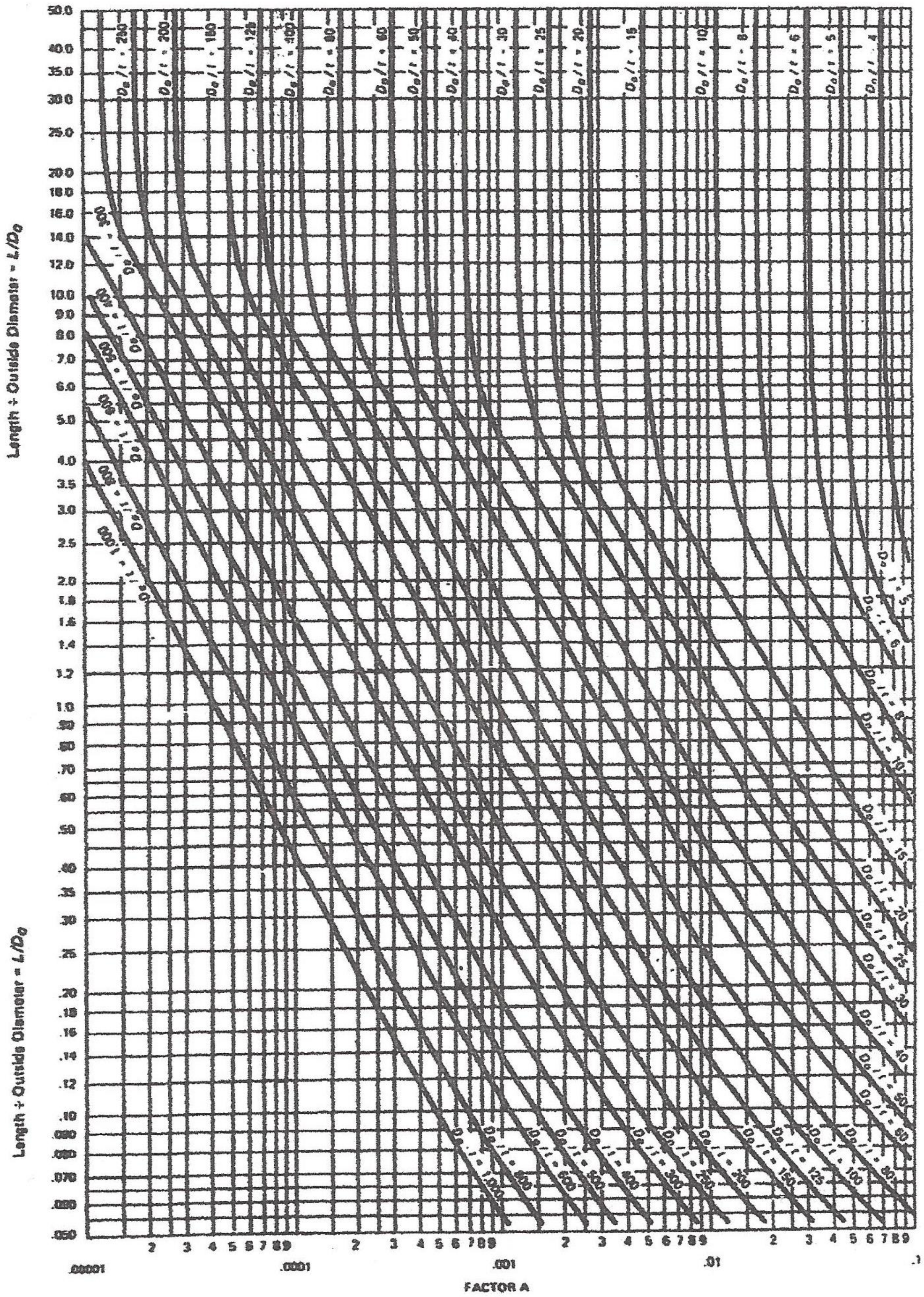

Figure 4.2. Geometric chart (ASME)

Example 4.3
What is the ASME allowable external pressure in a cylindrical shell with R_o = 25 inch, L = 150 inch, and T = 0.5 inch? Let F = 1200°F and t = 100,000 hours.

Solution
$L/D_o = 150/50 = 3.0$ $\qquad$ $D_o/T = 50/0.5 = 100$

From Fig.4.2, A = 0.0004
The value of B is obtained from Fig. C.5 of Appendix C in Part 3.
For 100,000 hours

$B = 1800$ psi

From Eq. (4.37)

$$DS_v = \frac{3}{1 + 0.0434 \ln(100{,}000)} = 2.0$$

$$P = \frac{4(1800)}{(2.0)(50/0.5)} = 36 \text{ psi}$$

Check for the hot tensile condition

$B = 4800$ psi
$DF_v = 3.0$

$$P = \frac{4(4800)}{(3.0)(50/0.5)} = 64 \text{ psi} \quad > 36 \text{ psi} \qquad \text{ok}$$

4.5 Axial Compression of Columns (Euler Buckling)

The classical elastic equation for the axial compression of a long column is

$$S_{cr} = \frac{\pi^2 E}{(L/r)^2} \tag{4.38}$$

Or in terms of allowable strain using a knock down factor,

$$A = \frac{\pi^2}{(KD)(L/r)^2} \tag{4.39}$$

In the elastic range,

$$S_{cr} = \varepsilon_{cr} E. \tag{4.40}$$

For design purposes a design factor, DF, is incorporated into this equation to take into account such items as inaccuracy in determining modulus of elastic and variation in material properties. Hence the equation becomes

$$B' = AE/(DF) \tag{4.41}$$

In the inelastic range the elastic modulus, E, must be replaced by the tangent modulus, E_t. This is accomplished by constructing an external pressure chart where E_t is used to correlate factor A to a stress S as shown in Fig.3.2 which is duplicated here as Fig. 4.1. Hence,

$$B' = S/(DF) \tag{4.42}$$

The design factor (DF) given in the SCM (Steel Construction Manual 2011) for compact members at room temperature with L/r greater than about 130 is 1.9. The ASME BPVC Section VIII-1 code uses a DF of less than 2.0 for all permitted temperatures including those in the creep regime. However, the authors of this research have not come across any data regarding the proper DF value to be used in the creep regime.

Example 4.4

What is the allowable axial compressive stress in a heat exchanger tube with $R_o = 0.25$ inch, effective length L = 24 inch, and T = 0.0625 inch? Let F = 1065°F, t = 37,000 hours, KD factor = 1.3, and DF = 1.5.

Solution

For a thin tube, $r = R_o/1.41 = 0.25/1.41 = 0.177$ in.

L/r = 24/0.177 = 136

From Eq. (4.39),

$$A = \frac{\pi^2}{1.3\,(136)^2} = 0.00041$$

From Fig. 4.1, S = 9500 psi

Hence, from Eq. (4.42) the allowable compressive stress B' = 9500/1.9 = 5,000 psi.

REFERENCES

[1] Gerard, G., “Introduction to Structural Stability Theory,” McGraw Hill, New York, 1962.

[2] Jawad, M. and Griffin, D., “External Pressure Design in Creep Range,” Publication STP-PT-029-1, ASME Press, New York, 2011.

[3] Miller, C. and Griffin, D., “Part 1: External Pressure: Effect of Initial Imperfections and Temperature Limits: The Effect of Initial Imperfections on the Buckling of Cylinders Subjected to External Pressure,” Bulletin 443, Welding Research Council. New York, 1999.

[4] “Steel Construction Manual,” 14^{th} ed., American Institute of Steel Construction, Chicago, 2011.

[5] Sturm, R., “A Study of the Collapsing Pressure of Thin-Walled Cylinders,” Engineering Experiment Station Bulletin 329, University of Illinois, Urbana, 1941.

[6] Timoshenko, S. and Gere, J., “Theory of Elastic Stability,” McGraw Hill, New York, 1961.

[7] von Karman, T. and Tsien, Hsue-Shen, “The Buckling of Spherical Shells by External Pressure,” Pressure Vessel and Piping Design Collected Papers 1927-1959, ASME, New York, 1939.

ISBN 978-0-7918-7124-9

9 780791 871249

A 2 7 3 1 Q