STP-PT-025

EXTENDED FATIGUE EXEMPTION RULES FOR LOW CR ALLOYS INTO THE TIME-DEPENDENT RANGE FOR SECTION VIII DIV 2

ASME STANDARDS TECHNOLOGY, LLC

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EXTEND FATIGUE EXEMPTION RULES FOR LOW CR ALLOYS INTO THE TIME-DEPENDENT RANGE FOR SECTION VIII DIV 2 CONSTRUCTION

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FOREWORD

This document was developed under a research and development project which resulted from ASME Pressure Technology Codes & Standards (PTCS) committee requests to identify, prioritize and address technology gaps in current or new PTCS Codes, Standards and Guidelines. This project is one of several included for ASME fiscal year 2008 sponsorship which are intended to establish and maintain the technical relevance of ASME codes and standards products. The specific project related to this document is project 07-03 (BPVC#1), entitled "Extend Fatigue Exemption Rules for Low Cr Alloys Slightly into the Time-Dependent Range for Section VIII Div 2 Construction."

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ABSTRACT

A number of alloys have applications slightly into the creep range that are in cyclic service, such as process reactors. The 2007 edition of Section VIII, Div 2 [1] provides allowable stresses for these materials, which may be controlled by creep properties. However, the fatigue design rules and fatigue exemption rules are not applicable, precluding construction of vessels using these materials at temperatures above 370°C (700°F). This report provides a simplified approach for exemption of low chrome alloys from fatigue analysis that are slightly into the creep range.

1 BACKGROUND

A number of alloys have applications slightly into the creep range that are in cyclic service, such as process reactors. The 2007 edition of Section VIII, Div 2 [1] provides allowable stresses for these materials, which may be controlled by creep properties. However, the fatigue design rules and fatigue exemption rules are not applicable. The fatigue exemption rule of Section VIII, Div 2, Part 5, paragraph 5.5.2.2, which permits exemption by prior experience, is not applicable since prior experience with vessels constructed to the new design margins provided in the 2007 edition of Div 2 are not applicable.

In the 2004 edition of Section VIII, Div 2 [2], the maximum temperature for which allowable stresses were provided was limited to temperatures where time independent properties governed the allowable stress, as discussed below. However, this does not mean that creep is not significant. For example, hold time fatigue data in Figure 1 from reference 3, clearly show a reduction in fatigue life from creep damage associated with hold times, for 2-1/4 Cr – 1 Mo at 482°C (900°F). Perhaps as a result of this, fatigue curves have not been provided for temperatures greater than 370°C (700°F). Fatigue curves based on continuous cycling tests without hold time would be non-conservative for general design. These higher temperature vessels can only be designed per the present rules if they satisfy an exemption from fatigue analysis.

Reducing the margin on tensile strength in the 2007 edition of Section VIII, Div 2, drops the temperature at which creep properties govern to a lower temperature. A change was made to specifically consider the effect of creep properties on allowable stress. However, the same issue remains, the Div 2 rules can only be used if the component satisfies an exemption from fatigue analysis as there are no fatigue curves in the Code for temperatures greater than 370°C (700°F).

For the materials in question, the basis for the allowable stresses in the 2004 edition of Section VIII, Div 2 construction was the least of the following (per ASME Section II, Part D, and Appendix 2 [4]).

$S_T/3$

$1.1\ S_T R_T/3$

$2/3\ S_y$

$2/3\ S_Y R_Y$

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

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

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

S_T specified minimum tensile strength at room temperature.

S_Y specified minimum yield strength at room temperature.

In Section VIII, Division 1 [5], the following additional considerations in setting the allowable stress are required when the material is in the creep regime.

$F_{avg}\ S_{R\ avg}$

$0.8\ S_{R\ min}$

S_c

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

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

S_c average stress to produce a creep rate of 0.01%/1000 hr.

$S_{R\ avg}$ average stress to cause rupture at the end 100,000 hr.

$S_{R\ min}$ minimum stress to cause rupture at the end of 100,000 hr.

S_T specified minimum tensile strength at room temperature, ksi.

S_Y specified minimum yield strength at room temperature, ksi.

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

In the 2004 edition maximum, use temperatures were set in Division 2 such that these creep criteria from Division 1 would not govern in setting the allowable stress, if they were considered.

In the 2007 edition, the margin on tensile strength was reduced from 3 to 2.4. This had the effect of increasing the allowable stress, at some temperatures, to the point where the criteria based on creep properties that are considered in setting the allowable stress would result in a lower allowable stress than the new Div 2 allowable stress based on tensile properties. The creep criteria were added to the Div 2 allowable stress basis, and these govern the allowable stress at higher temperatures that are permitted for some materials.

From the standpoint of design for primary stresses, given that the new Div 2 rules consider creep properties in establishing the allowable stress, the rules provide the same margins as Section VIII, Div 1. As such, in design for primary stresses, no specific further consideration within the scope of this project is required. There are, of course, other issues worth considering with respect to the margins on primary stress, such as the effect of weldments.

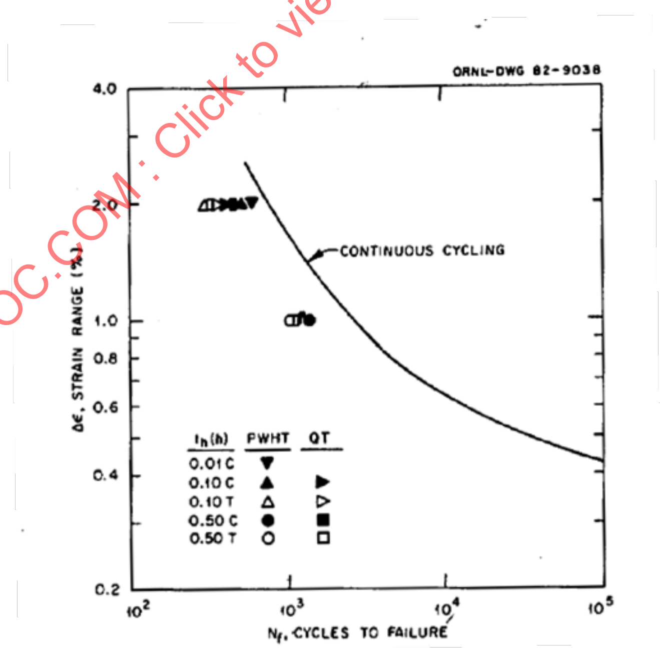

Figure 1 – Strain Range vs. Cycles to Failure

To design for cyclic stresses, additional considerations are required. Fatigue tests with hold times each cycle have demonstrated that hold times and the associated creep does have a significant effect at the temperatures of interest, as illustrated in Figure 1 [15]. Development of rules for creep-fatigue design is not within the scope of this project. Rather, the task is to develop rules that provide for exemption from fatigue analysis. Such exemption rules will permit pressure vessels in cyclic service into the temperature ranges where creep becomes significant.

The specific alloys within the scope of this study include 1-1/4 Cr-1/2 Mo, 2-1/4 Cr-1 Mo, 2-1/4 Cr-1 Mo-V, 9Cr-1 Mo-V and 12 Cr. We were not able to obtain any creep fatigue data for 12 Cr and 1-1/4 Cr-1/2 Mo and as a result coverage of these alloys is limited in this report.

2 SHAKEDOWN CONCEPTS

In this report, when discussing conditions, it is operating conditions that are being considered. This is consistent with other code life assessment approaches, including the following.

1. In piping design for thermal expansion, expected metal temperatures are used; the design temperature is for pressure design.
2. In fatigue design per Section VIII, Div 2, operating conditions, not design conditions, are considered.
3. In primary plus secondary stress range limits in Section VIII, Div 2, operating conditions, not design conditions, are considered.

While design conditions are used in pressure design, expected operating conditions should be used for shakedown and fatigue assessments.

In considering rules for exemption from fatigue analysis, two regimes of behavior are considered. These are when the component shakes down to elastic action, and when plasticity occurs each cycle. The behavior in each of these regimes is illustrated in the stress-strain and stress-time histories illustrated in Figures 2 through 5.

As an introduction to the concept of shakedown, consider elastic plastic behavior without creep. This behavior is illustrated in Figure 2, which is based on the assumption of elastic, perfectly plastic material behavior. Consider, for example, a case where the elastically calculated displacement controlled (secondary) stress range is two times the yield strength of the material. Because it is a deformation-controlled condition, one must actually move along the strain axis to a value of stress divided by elastic modulus. In material, assuming elastic, perfectly plastic behavior, the initial start-up cycle goes from point A to B (yield) to C (strain value of twice yield). When the system returns to its initial condition (shut down) temperature, the system returns to zero strain and the system will unload elastically until it reaches yield stress in the reverse direction. If the stress range is less than twice yield, there is no yielding on the return to the initial condition. On returning to the operating condition, the system returns from point D and C, which is elastic. The system has essentially self-sprung and is under stress due to displacement conditions in both the ambient and the operating conditions.

If twice the yield strength is exceeded, shakedown to elastic cycling does not occur. An example is if the elastically calculated stress range is three times the yield strength of the material. In this case, again referring to Figure 2, the startup goes from point A to point B (yield) to point E. Shutdown results in yielding in the reverse direction, from point E to F to D. The subsequent startup then is from point D to C, where yielding again is initiated, to E. Thus, each operating cycle results in plastic deformation and the system has not shaken down to elastic behavior.

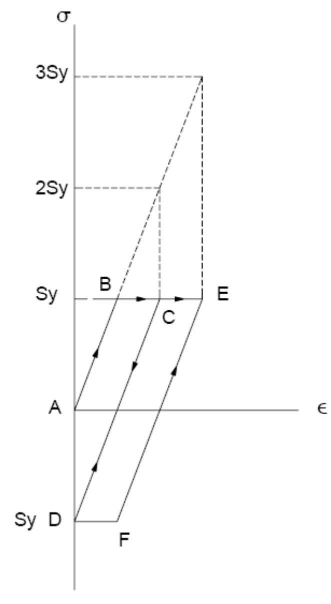

Figure 2 – Stress-Strain Behavior Illustrating Shakedown

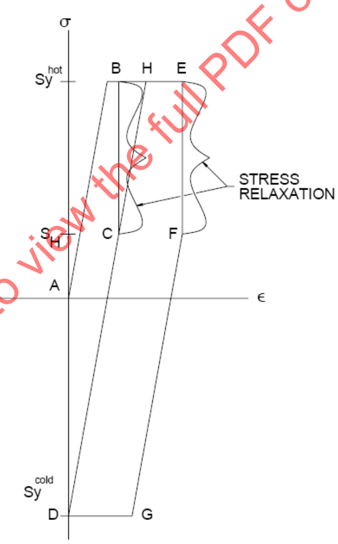

Figure 3 – Stress-Strain Behavior Illustrating Elevated Temperature Shakedown

The condition for shakedown at elevated temperatures is shakedown to elastic cycling. There will continue to be creep deformation. Deformation controlled stresses relax to a stress value sufficiently low that no further creep occurs. This stress value is the hot relaxation strength, S_H. Stress-strain behavior under the condition of creep is illustrated in Figure 3. The initial start-up cycle, which can include some yielding, goes from point A to point B. During operation, the stresses relax to the hot relaxation strength, S_H, at which point no further relaxation occurs, point C. When the system returns to the initial condition, the system returns to zero strain (for displacement controlled conditions) and the system will unload elastically until it reaches yield stress in the reverse direction. If the stress range is less than S_H plus to cold yield strength, there is no yielding on the return to the shut down condition. This is illustrated by going from point C to point D. On returning to the operating condition, the system returns from point D to point C elastically. Thus, if the stress range is less than the cold yield strength plus the hot relaxation strength, shakedown to elastic behavior also occurs at elevated temperature. The anticipated behavior over time, with multiple shut downs, is illustrated in Figure 4.

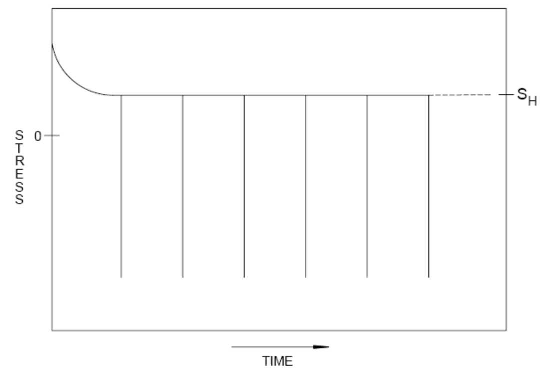

Figure 4 – Cyclic Stress History with Shakedown

Figure 3 also shows the behavior when the shakedown stress range is exceeded at elevated temperatures. In this case, the startup goes from A to E. Stresses relax to point F. When the system returns to the shut down condition, yielding in the reverse direction occurs, going from point F to G to D. Returning to operating condition again results in yielding, from point D to H to E. Since high stresses are re-established (reset), another relaxation cycle then must occur. The behavior of this system over time is illustrated in Figure 5.

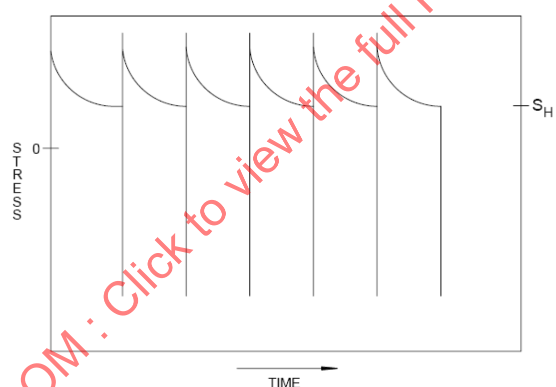

Figure 5 – Cyclic Stress History Without Shakedown

In the development of the piping codes, S_H was taken as 1.25 times the allowable stress at temperature. This has a long and successful history, although, as shown later in this report, the stress can relax to below this level of stress, given sufficient time. As a practical matter, this report recommends that the basic allowable stress be used as the hot relaxation stress. Even if the stress relaxes to less than this value, the stress reset on startup is back to the allowable stress. This behavior is illustrated in Figures 6 and 7. Initial loading is from point A to point B in Figure 6. Assuming the stress relaxes to below the basic allowable stress, S, to a lower value of S_H, point C, unloading may result in plasticity, C to D to E. Such plasticity can result in re-establishing a stress value of S on reloading, point F, which then relaxes again to point C. The rationale for accepting this is that even with some cyclic plasticity, the stress does not exceed the basic allowable while at the operating condition after the initial period of relaxation.

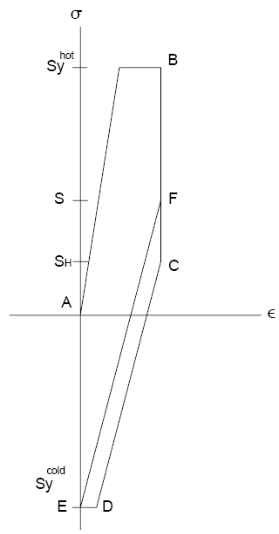

Figure 6 – Stress-Strain Behavior with Reset to Allowable Stress

Observing Figure 5, shakedown to elastic cycling, the component experiences a single relaxation cycle over its lifetime. In contrast, as exhibited in Figure 6, high stresses can be re-established each cycle if the component does not shakedown to elastic cycling. The case somewhat between, as shown in Figures 6 and 7, is proposed as the limit.

Figure 7 – Cyclic Stress History with Reset to Allowable Stress

3 STRAIN RANGE FOR SHAKEDOWN AND INITIAL STRESS

The strain range for shakedown was calculated for the alloys in this study. This is the strain range associated with an elastically calculated stress range of cold yield plus hot allowable stress. The strain range is the cold yield stress divided by the elastic modulus at ambient temperature plus the hot allowable divided by the elastic modulus at the operating temperature (the temperature for which the allowable stress was taken). This gives the strain range that will satisfy the above described shakedown criteria. These calculations are summarized in Table 1.

Table 1 - Relaxation/Damage Accumulation Data for Various Chrome Alloys

Material	T (°F)	S_a (Ksi @ T)	S_y (Ksi)	S_y (Ksi @ T)	ε_{range}	Governing	S_{start} (Ksi)	E_c	E_h	t_{relax} (hr)	D_{Sa}	Mult.	ΔD
1.25Cr-0.5Mo-Si-1	900	13.7	35	23.8	1.73E-03	Syhx1.15	27.4	29.6	24.8	1482	2.58E-03	5.7	1.20E-02
1.25Cr-0.5Mo-Si-2	900	13.7	45	30.6	2.07E-03	Syhx1.15	35.2	29.6	24.8	14252	1.66E-02	3.6	4.32E-02
2.25Cr-1Mo class 1	900	13.6	30	25.6	1.51E-03	Syhx1.15	29.4	30.6	25.6	957	1.11E-03	11.2	1.13E-02
2.25Cr-1Mo class 2	900	17	45	32.4	2.13E-03	Syhx1.15	37.3	30.6	25.6	1622	1.38E-03	12.3	1.56E-02
2.25Cr-1Mo-V	900	23.8	60	47.8	2.89E-03	Syhx1.15	55	30.6	25.6	610	1.23E-03	16.5	1.90E-02
9Cr-1Mo-V	900	30.8	60	46.1	3.11E-03	Syhx1.25	57.6	31.0	26.2	578	3.65E-03	8.7	2.81E-02
12Cr-Al	900	11.3	25		1.34E-03			29.2	23.2				

Notes

(1) Governing: refers to how the starting stress is determined. It is the greater of either materials multiplier times Yield Stress, the stress-strain curve that corresponds to the strain range

(2) S_{start}: is the starting stress from which the material relaxes

(3) E_c and E_h: refer to the cold and hot modulii of elasticity, respectively

(4) t_{relax}: refers to the required time to relax from the starting stress to the allowable stress

(5) D_{Sa}: refers to the damage that would be accumulated if the material was kept at allowable stress for t_{relax}

(6) Mult.: refers to the actual damage accumulated for t_{relax} divided by D_{Sa}

(7) ΔD: refers to the difference between actual damage accumulated and D_{sa}

For relaxation damage calculations, an initial stress is required. Two approaches to establishing this initial stress were considered, and the maximum of the two were taken.

1. Based on the stress-strain curve from Section VIII, Div 2, an initial stress was determined based on the value of strain determined from the strain range (as listed in Table 1). This, however, ended up being less than the minimum yield strength because the yield strength is the 0.2% offset yield strength, for which the strain is the sum of the elastic strain and 0.2% plastic strain.

2. The yield strength at temperature was also considered, with an upwards adjustment to conservatively adjust from minimum to average yield strength. The adjustment was taken as 15%, except for Grade 91 material, for which an adjustment of 25% was included. This approach governed in all cases.

The maximum of the above two was taken as the initial stress on the first start up, from which stresses relaxed.

4 CREEP FATIGUE WITH SHAKEDOWN TO ELASTIC ACTION

Intuitively, if the component shakes down to elastic action, creep damage due to secondary and peak stresses should be small. This was checked for the alloys in this study by evaluating lifetime damage during relaxation using the Omega method provided in ASME FFS-1 [6]. The creep damage during relaxation was calculated from an initial stress to the time when the stress relaxed to the basic allowable stress.

The initial stress was determined as described in Section 4. The time it took to relax to the basic allowable stress was determined, and the total damage during that time was calculated. All the calculations were done for a 480°C (900°F) temperature. The relaxation/damage accumulation curves are provided in Appendix A, with a sample shown in Figure 8. The difference between the damage that was calculated during that period of relaxation, and the damage that would have occurred should the material have been held at the basic allowable stress for that same time period, was determined. This difference is the additional damage caused by that single cycle of relaxation. These values are provided in Table 1.

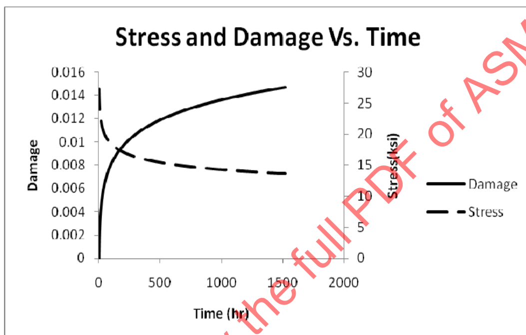

Figure 8 - Relaxation/Damage Accumulation Curves for 1.25Cr-0.5Mo-Class 1 Material

In no case was the additional creep damage caused by the single cycle of relaxation greater than 0.05 as compared to an allowable limit of 0.80 in ASME FFS-1. This is consistent with expectations.

Fatigue damage should also be low with a reasonable number of cycles. For purposes of this calculation, the strain range determined as described in Section 4 was used.

Creep-fatigue data from a variety of sources for the alloys of interest are provided in Appendix B. Data for Grades 22 and 91 are also tabulated in Appendices C and D, respectively. Note that some of the data presented are for temperatures greater than 480°C (900°F) and are consequently more conservative. The total number of major cycles was taken as 1000 and the strain range was taken as the shakedown strain range from Table 1. Looking at that point relative to the average continuous cycling data, the actual fatigue damage is less than about 1% (i.e., there are about two orders of magnitude between the shakedown point and the average continuous cycling fatigue data. As such, fatigue damage is negligible if the shakedown limit is satisfied.)

If the typical impact of a butt weld (which is not necessarily considered in the stress calculations) is considered, the margin is reduced. The effect of an as-welded butt weld on fatigue performance is about a factor of two on stress or strain. To maintain the same margin, the strain range can be decreased, or the number of cycles decreased. Considering the slope of fatigue curves for welded components, as discussed in Section 7, the allowable number of cycles for the same nominal strain range (which is combined with a factor of two for the weld) gives an allowable number of cycles of 125 to provide the same margin as for the base material without welds. The following simplified rule can be used for welds.

1. If the number of equivalent cycles is less than, or equal to, 125, it is only necessary to demonstrate shakedown by one of the means permitted.
2. If the number of cycles is greater than 125, it is necessary to demonstrate shakedown by elastic analysis, and the allowable stress range is $(S_y^c + S)(1000/N) – 1/3$, where N is the equivalent number of cycles (see Section 7).

The second rule follows the slope of the fatigue curve to reduce from one times the shakedown limit at 125 cycles to ½ of the shakedown limit at 1000 cycles.

While creep damage from secondary and peak stress is low, creep damage from primary stress can be higher. However, limiting fatigue damage limits the effect of fatigue on creep life. Consider a typical interaction diagram for creep-fatigue, as shown in Figure 9 from reference 7. If the fatigue damage fraction is low, there is little impact on the creep life. Further, for the class of alloys where plastic strain cycling reduces tensile strength and also creep strength, limiting the strain cycling to elastic cycling prevents this condition.

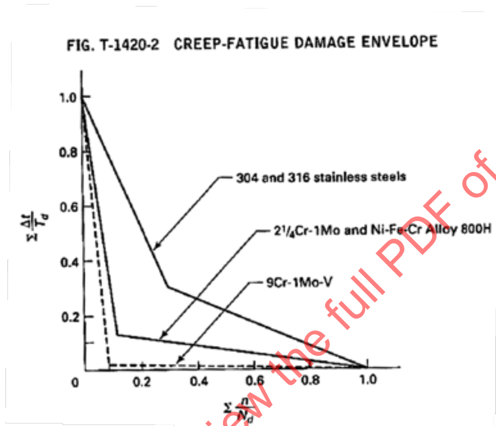

Figure 9 - Creep-Fatigue Interaction Diagram

The above illustrates that both creep (due to the relaxation of secondary and peak stresses) and fatigue damage are low for a material that shakes down to elastic action. A 1000 full cycle limit is a reasonable limit for the base material. Additional considerations at welds are discussed above. The combination of different cycles is discussed in Section 7.

Shakedown to elastic action is sufficient to provide an exemption from fatigue analysis, when combined with a reasonable cycle limit. The report proposes a 1000 cycle limit for the base material, which is far greater than that required for typical process vessel applications. It also proposes a limit for welds which is also within the cycle limits required for typical process vessel applications.

5 DEMONSTRATION OF SHAKEDOWN

Considering the major cycle, that from ambient to the highest operating temperature and to operating pressure, the component will shakedown to elastic action if the stress range is less than the yield strength at ambient temperature plus the lowest stress to which the material will relax over its life time, the hot relaxation stress. As discussed previously, this is taken as the basic allowable stress, although the stress may relax to a lower value.

The hot relaxation stress is taken herein as the allowable primary membrane stress limit. The following provide several justifications for this assumption.

1. While it is possible for stresses to relax to below this stress value, given sufficient time, if the primary stress is at the allowable limit, the stress will not relax below this stress level.
2. If the stress does relax below the primary stress limit, the reset stress due to reverse plasticity is back to the primary stress limit, as illustrated in Figure 6 and described in Section 3.
3. Significantly higher stress ranges have been in use in the B31 piping codes for up to 7000 cycles, as described below.

In ASME B31.3 [8], the limit on SE, which is a calculated stress range due to displacement stresses, when the number of equivalent cycles is less than 7000, is $1.25(S_c + S_h) - S_L$. S_L and S_h are the allowable stresses in the cold and hot condition, respectively. It is well known that the calculated stress range is ½ of the actual peak stress range, because the fatigue design basis is relative to butt welded pipe. Therefore, the actual permitted peak stress range in the pipe is $2[1.25(S_c + S_h) - S_L]$. S_L is the stress due to sustained loads such as due to weight and pressure; the code rules reduce the permitted stress range by S_L to preclude plastic ratchet due to the combination of primary and secondary stress. S_c is less than, or equal to, 2/3 the cold yield strength (S_y^c) and S_h is the basic allowable stress at temperature. Assuming S_L is equal to the maximum permitted stress, S_h, and substituting $2/3S_y^c$ for S_c results in the following stress range for when the sustained stress is at the limit: $5/3S_{yc} + 1/2S_h$. Since $2/3S_y^c$ is always greater than ½ S_h, it can be observed that the existing B31.3 code permits a stress range greater than $S_y^c + S_h$. If the stress due to internal pressure were included in the stress range, as it would be in a vessel, the allowable range is even greater (as S_L is added back in).

If the total elastically calculated stress range, including primary plus secondary, plus peak stress, is less than this limit, shakedown to elastic action is assured.

Thus, the first option for exemption from fatigue analysis is for the maximum stress range, calculated elastically, to be less than the yield strength at ambient temperature plus the allowable stress at the maximum temperature.

Peak stresses are included because cyclic plasticity may occur in local regions, even though the overall structure shakes down. The cyclic FEA analysis shown in Section 8 illustrates this condition.

A second option would be to demonstrate shakedown to elastic action by elastic-plastic-creep calculations. If the detailed calculation demonstrates that the component will shakedown to elastic action, considering the design life of the component, then again it would be exempt from creep-fatigue analysis (if it satisfies the cycle limit). As described in the basis for setting the basic allowable stress as the hot relaxation strength, plasticity in the unloading condition should also be permitted, as long as the stress in the loaded condition does not exceed the greater of the basic allowable stress and the stress that existed prior to the unloading.

6 INTERMEDIATE CYCLES

Cycles other than the major cycle need to be considered for two reasons. The simplest consideration is their impact on fatigue. An additional consideration is their impact on shakedown.

Consideration of the impact on fatigue is straightforward. Cycles of lesser strain ranges can be turned into equivalent numbers of cycles of the maximum strain range by the same process that is used in the B31 Codes. The rules from ASME B31.3 follow.

$N = N_E + S\,(r_i^5 N_i)$ for $i = 1, 2, \ldots, n$

Where:

N = equivalent number of full displacement cycles during the expected service life of the piping system

N_E = number of cycles of maximum computed displacement stress range, S_E

N_i = number of cycles associated with displacement stress range, S_i

$r_i = S_i S_E$

S_E = maximum computed stress range

S_i = any computed stress range less than S_E

For the purposes of the proposed rules, N would remain the equivalent number of cycles and be limited to 1000 (or a lesser number at welds); N_E would be the number of cycles of the greatest computed stress or strain range (this may be at a point, or, more conservatively, for a component); and S could be taken as stress range or strain range. The exponent of five is to follow the slope of the fatigue curve developed by A. R. C. Markl. This exponent has been shown to result in too flat of a fatigue curve, rather the exponent should be taken as 3 rather than 5. A slope of –3:1 for the fatigue curve has been shown to be generally appropriate for welded components. [9]

The second consideration is if the equipment is operated at two different conditions that are both in the creep regime. This is illustrated in Figures 10 and 11. In these figures, the initial loading is from A to B. A period of relaxation to C is illustrated, with unloading to a second operating condition at D. Assuming no creep due to low stress at D, the subsequent reloading is to C. A period of further relaxation to E is assumed, again with displacement controlled unloading to F. If the material relaxes at F, to G, the stress can be reset on loading to H. If a stress reversal occurs in the second, less severe condition, and if the material creeps under that condition, it can reset the stress.

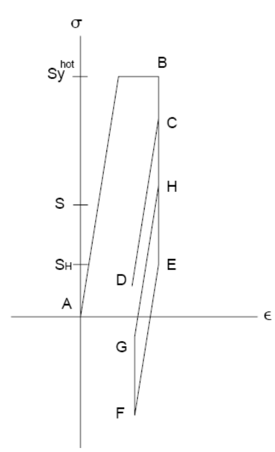

Figure 10 – Stress Strain Behavior with Stress Reset Caused by Relaxation at Second Operating Condition

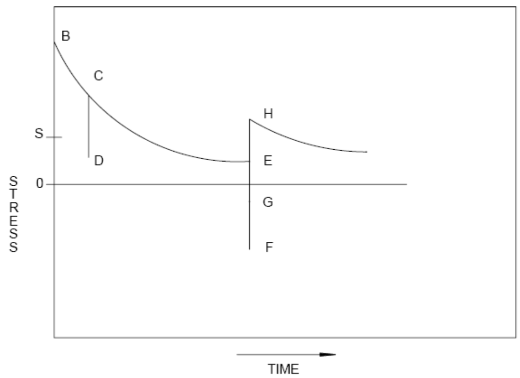

Figure 11 – Stress-Time Behavior with Stress Reset Caused by Relaxation at Second Operating Condition

In an elastic analysis, if the stress range between these conditions is less than the sum of the hot relaxation strengths for the two conditions, the component will cycle elastically. Unfortunately, the argument previously used in favor of using the basic allowable stress for the hot relaxation strength does not work under this condition, because reverse relaxation could reset the stress higher than the basic allowable stress.

If an elastic-plastic-creep analysis is performed, either of the two following conditions would be an acceptable demonstration that the intermediate cycle did not violate the shakedown requirements.

1. The stresses do not reverse with the change to the intermediate condition (this avoids reverse creep).
2. On reloading, the stress does not exceed the greater of the basic allowable stress, or the stress the component was at prior to switching to the intermediate condition (the latter, in Figure 10, would be C to D to C).

Normal fluctuations in pressure and temperature about nominal operating conditions should be excluded from consideration.

7 LOW CYCLE EXEMPTION

If the number of cycles are sufficiently low, creep-fatigue analysis should not be required even if shakedown is not satisfied. Figure 12 shows a detail which has a confined region of high peak stress in a nozzle caused by internal pressure. Figure 13 shows stress history and damage accumulation. Since the component does not shakedown to elastic cycling, high stresses are reestablished each cycle, leading to a further increment in creep damage resulting from creep relaxation each cycle.

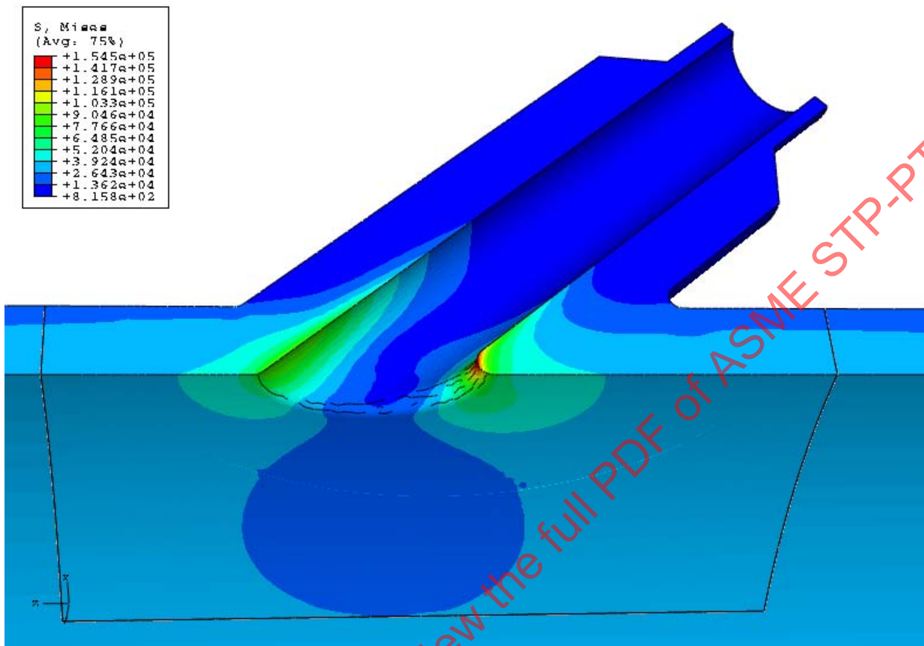

Figure 12 - Nozzle Subjected to Internal Pressure with High Peak Stress at the Acute Corner [10]

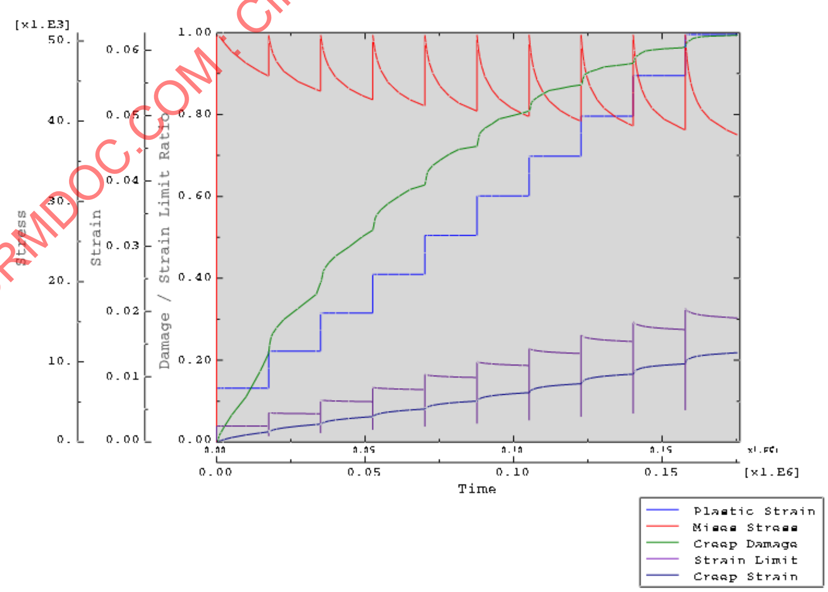

Figure 13 - Stress, Plastic and Creep Strain, Strain Limit Ratio and Damage After 10 Cycles with 2 Year Hold Time [10]

Observation of the creep-fatigue data in Appendix B indicates that perhaps a strain range of between 0.5% and 1% and a cycle limit of 100 cycles could be a conservative design basis (with it reduced perhaps in half at welds). Creep fatigue testing can be performed on the alloys of interest with 1 hour hold times, including tension hold tests, compression hold tests and tests of both base material and welds. If the cycle limit is 100 cycles, a test to 20 times that limit is a 2000 hour creep fatigue test, and thus readily manageable.

However, such evaluation of data or testing does not consider the interaction of creep-fatigue damage due to cyclic loads with the creep damage due to long term primary stresses. Further, it does not consider the impact of plastic cycling on reducing tensile and creep strength of some alloys, lowering resistance to sustained loads such as pressure, as discussed in reference [11]. Thus, testing by itself does not provide assurance of long term performance.

An option is to treat the potential for local damage and reduced life as a maintenance issue. While not desirable, cracking of high temperature process vessels has been handled on a detection and repair basis: that is, to accept the possibility of local damage but with the condition of having an inspection program designed to detect such damage. A set of requirements could be as follows.

1. Demonstrate shakedown for most components of the vessel.
2. For components where shakedown to elastic cycling cannot be demonstrated, limit primary plus secondary stresses to 3S (where S is the average of the allowable stresses at the temperature extremes of the cycle under consideration) so stress reset is limited to local peak stress conditions.
3. Identify regions where the peak stresses do not shakedown. Possibly limit that strain range to a limit determined by evaluation of existing creep-fatigue data and additional test results, as described above.
4. Have owner-user acceptance of this condition.
5. Owner-user to have a documented continuing inspection program specifically designed to detect long term creep fatigue damage in those areas.

With the above requirements, the desirability of achieving shakedown is emphasized, but if it cannot be achieved, there is a means to assess and manage the risk.

The above creates contractual issues in the design and construction of such vessels, but provides a pragmatic approach to attain safety without undue conservatism that would otherwise be required to address uncertainties. The contractual issue results from the fact that the vessel manufacturer may not know it is not possible to satisfy shakedown prior to receiving the contract to design and build the vessel. However, the issue is manageable and can be dealt with if recognized.

8 CONCLUSION

A simplified approach for exemption from fatigue analysis has been proposed. The approach limits the creep fatigue interaction by limiting fatigue damage and creep damage to essentially that permitted by primary stress limits. By significantly limiting fatigue damage, the effect of fatigue in reducing creep life is mitigated. These approaches require demonstration of shakedown to elastic cycling.

Some concepts are outlined for possible rules for the circumstance when shakedown to elastic cycling cannot be demonstrated. Development of pragmatic exemption rules for this condition requires significant additional work.

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[2] ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, American Society of Mechanical Engineers, New York, 2004.

[3] R. W. Swindeman and J. P. Strizak, Response of Bainitic 2-1/4Cr-1Mo Steel to Creep-Fatigue Loadings at 482°C, ORNL/TM-8392, Oak Ridge National Laboratory, Oak Ridge, TN, 1982.

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[5] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, American Society of Mechanical Engineers, New York, 2007.

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[16] J. P. Strizak and R. W. Swindeman, Response of Bainitic 2-1/4Cr-1Mo Steel to Creep-Fatigue Loadings at 482ºC, ORNL/TM-8392, Oak Ridge National Laboratory, Oak Ridge, TN, Nov. 1982.

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[21] T. Takehana, T. Sano, S. Terada and H. Kobayashi, Proposal of High Temperature Design Fatigue Curve for 2-1/4 Cr-1 Mo-V and 3 Cr-1 Mo-V Steels, paper presented at the 2004 ASME Pressure Vessels and Piping Conference.

[22] Data Sheets on Elevated-Temperature, Time-Dependent Low-Cycle Fatigue Properties of ASTM A 387 Grade 91 (9Cr-1Mo) Steel Plate For Pressure Vessels. NRIM Fatigue Data Sheet No. 78, 1993.

APPENDIX A - RELAXATION/DAMAGE ACCUMULATION CURVES

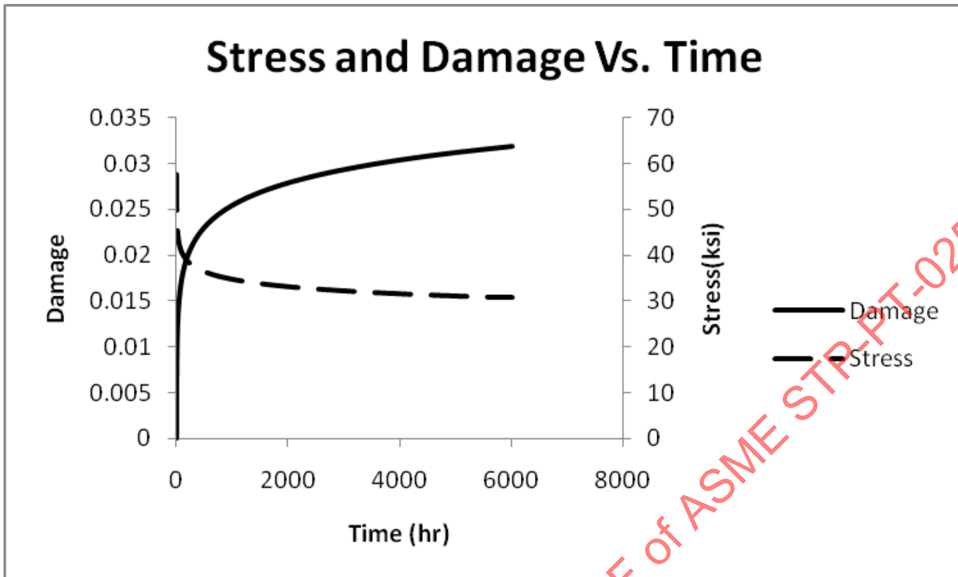


Figure 14 - 9Cr-1Mo-V 900°F

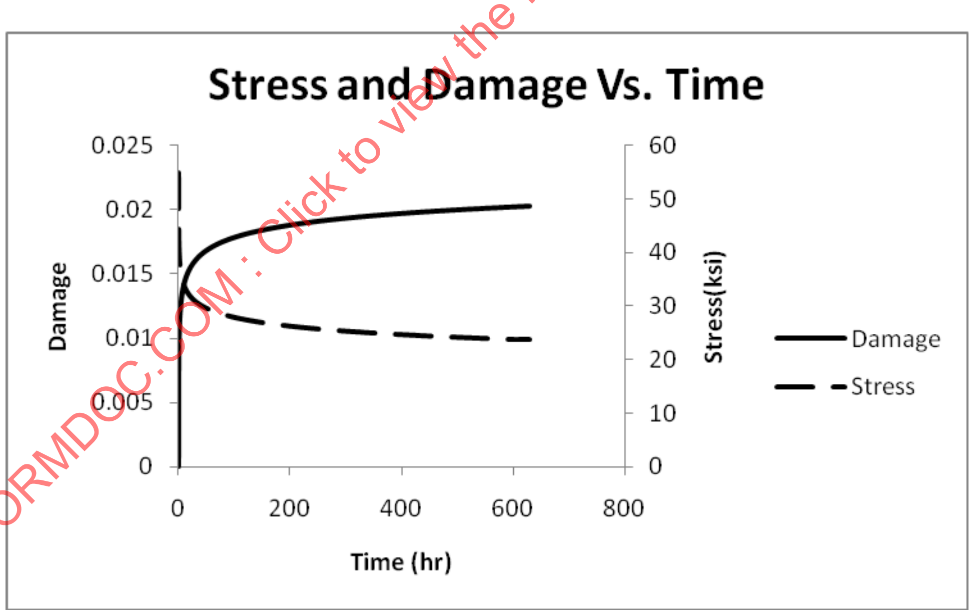


Figure 15 - 2.25Cr-1Mo-V 900°F

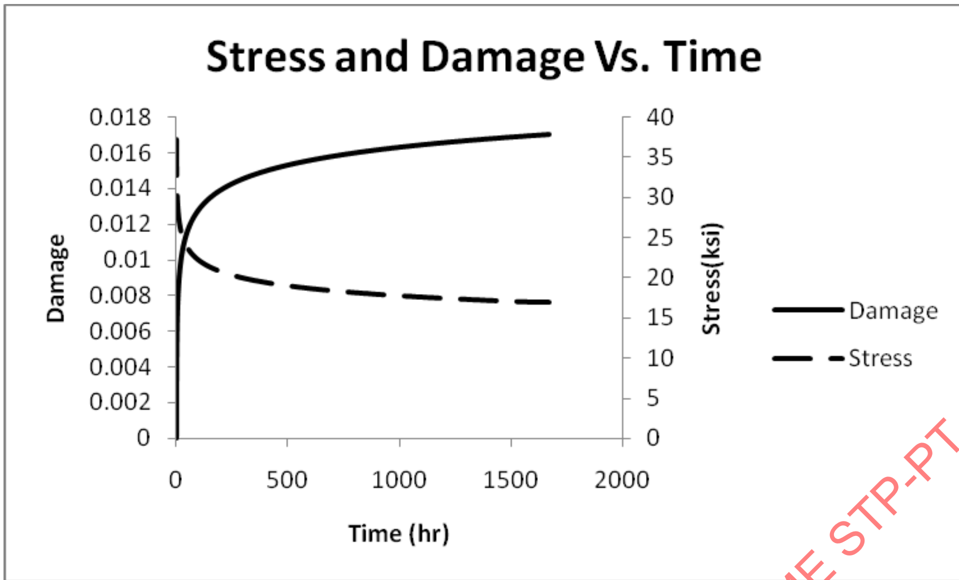


Figure 16 - 2.25Cr-1Mo Class 2 900°F

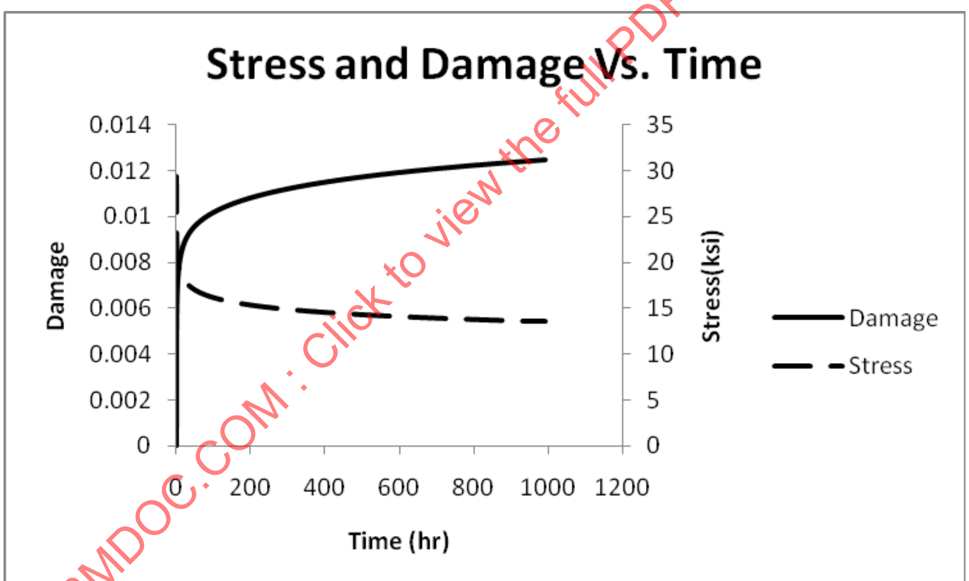


Figure 17 - 2.25Cr-1Mo Class 1 900°F

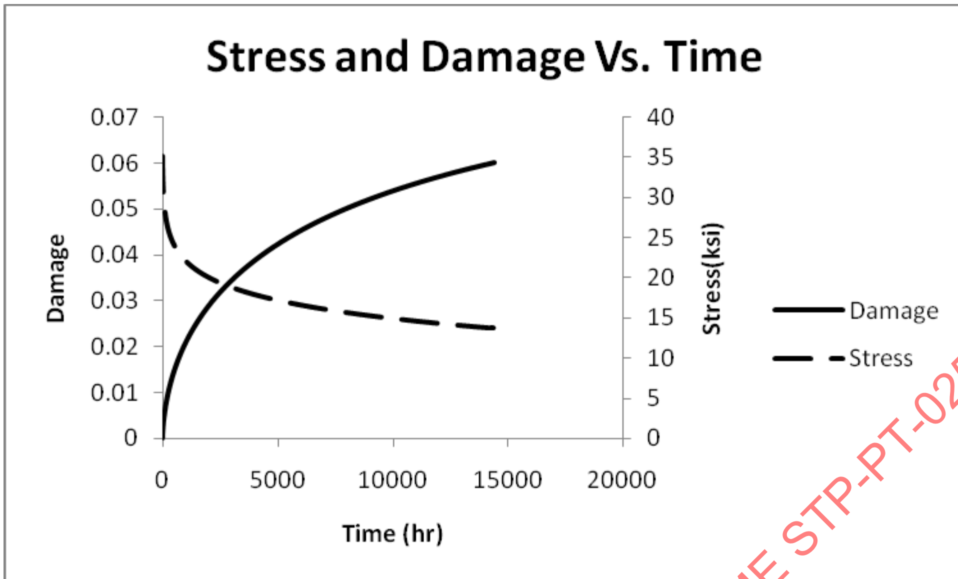


Figure 18 - 1.25Cr-0.5Mo-Si Class 2 900°F

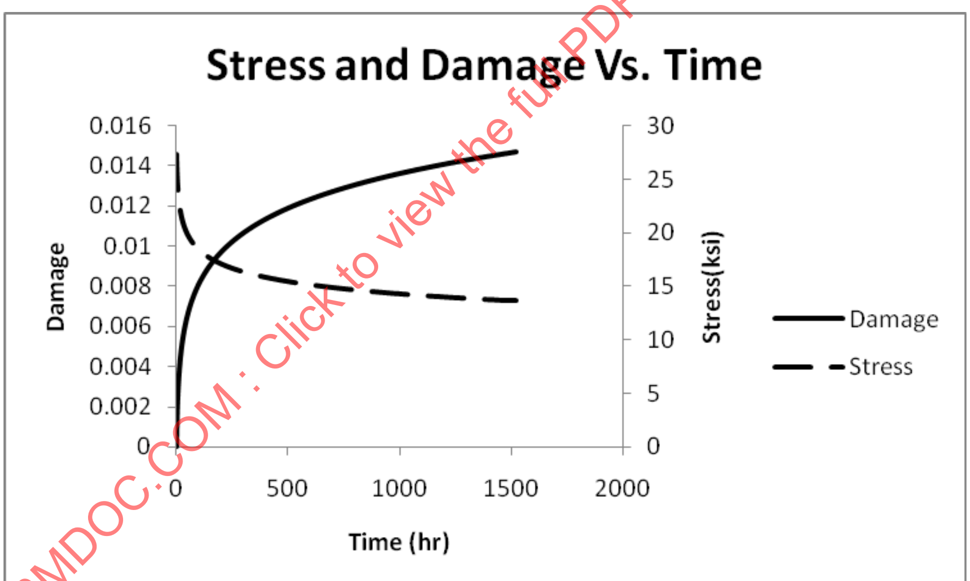


Figure 19 - 1.25Cr-0.5Mo-Si Class 1 900°F

APPENDIX B - CYCLIC FATIGUE DATA AND CHARTS

Appendix B contains a compilation of creep-fatigue data for the alloys of interest that were gathered via a literature search. The shakedown strain range calculated by the report for the listed alloys is marked on the charts at 1000 cycles, with the following symbol:

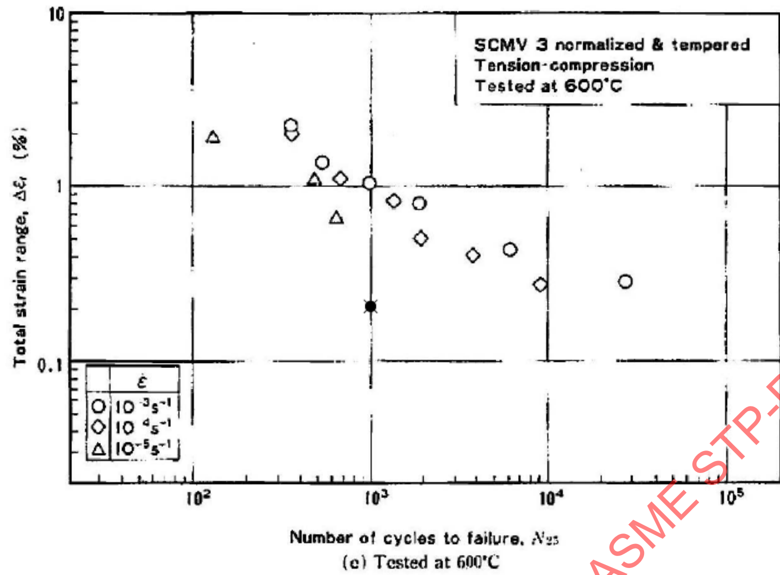
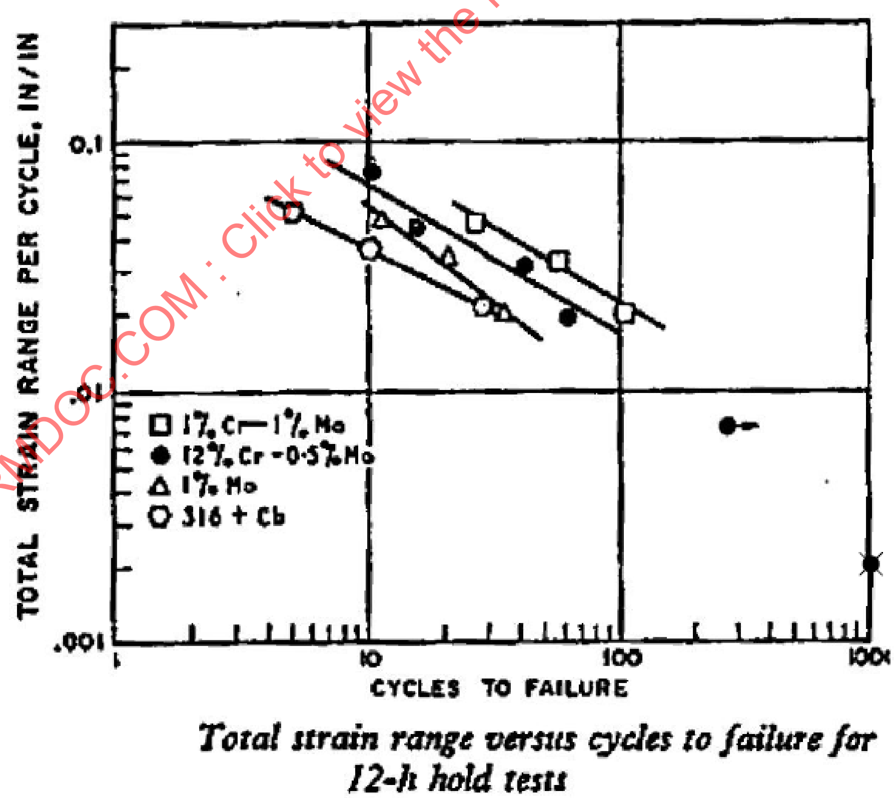


Figure 20 - 1.25Cr-0.5Mo-Si-Class 2 Data Point Plotted Versus SCMV 3 Material (45/75 grade [bainitic]) which has Exhibited Similar Behavior to 1.25Cr Alloys.[12]



Total strain range versus cycles to failure for 12-h hold tests

Figure 21 - 1.25Cr-0.5Mo-Si-Class 2 Data Point Plotted Versus Various Alloys with Similar Behavior to 1.25Cr Alloys.[13]

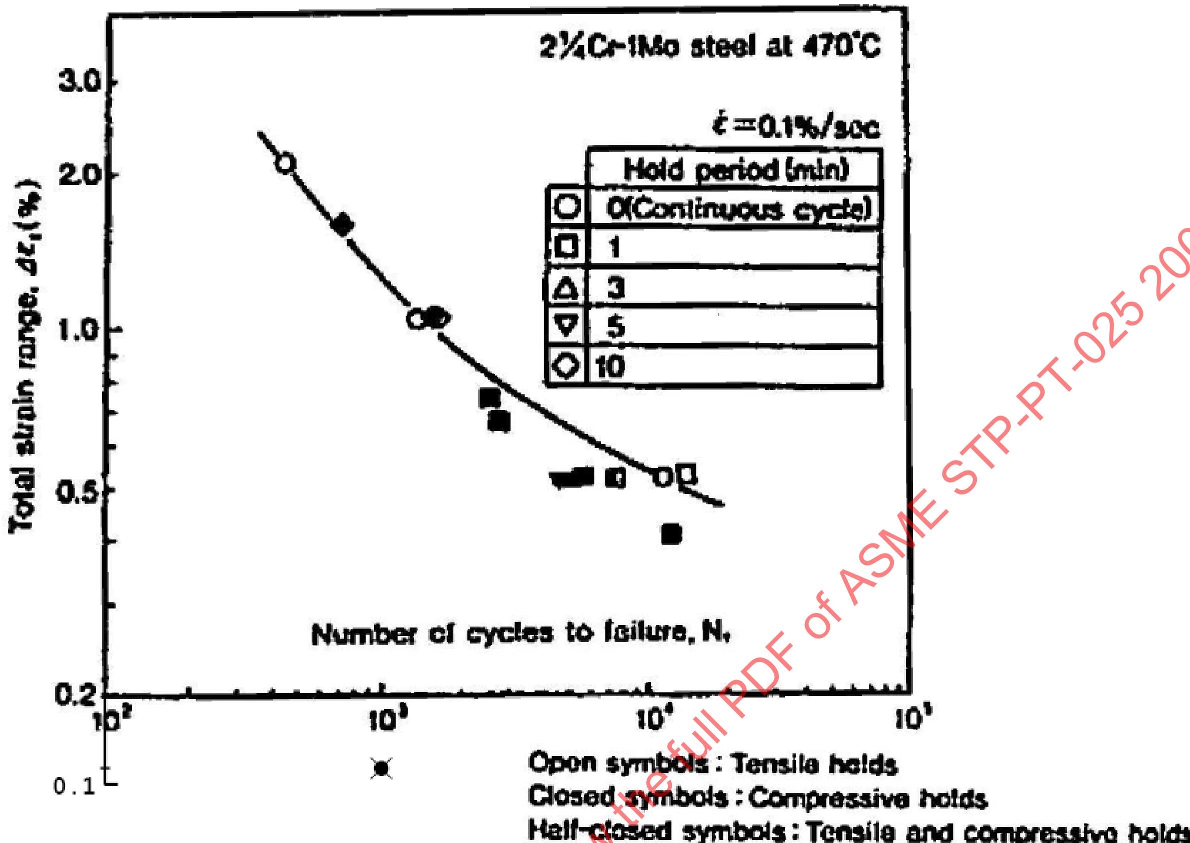


Figure 22 - 2.25Cr-1Mo Class 1 Data Point Plotted Versus 2.25Cr-1Mo Steel Whose Heat Treatment was Normalization and Tempering Followed by Stress Relief Annealing.[14]

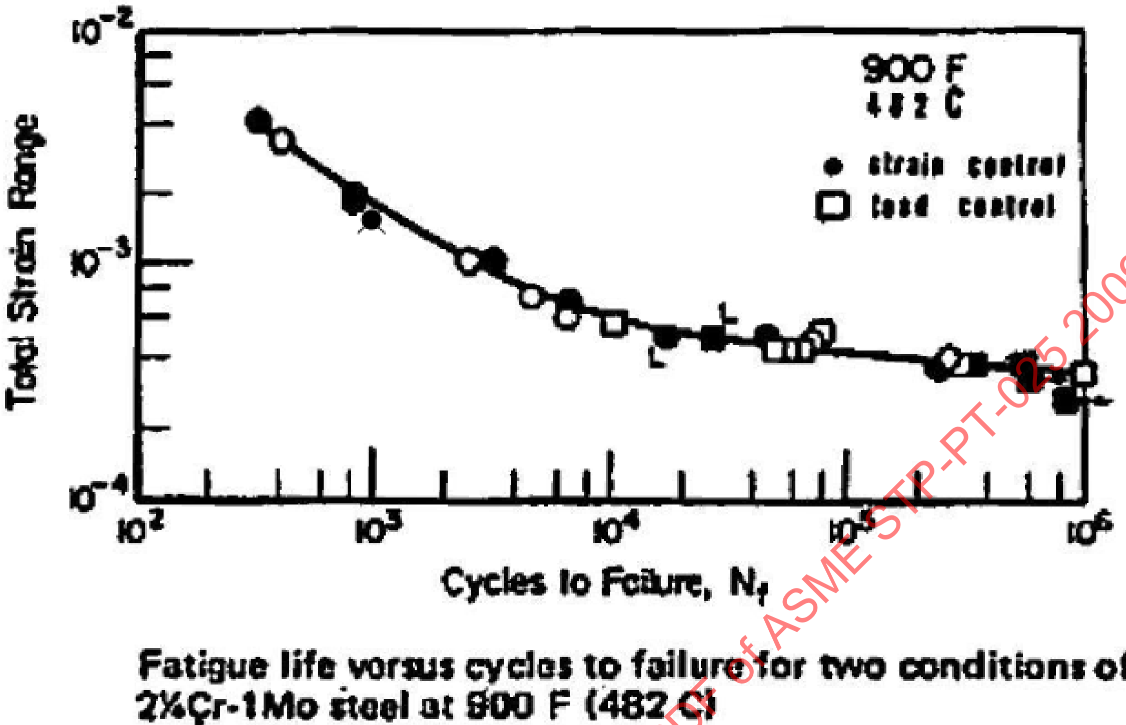


Figure 23 - 2.25Cr-1Mo Class 1 Data Point Plotted Versus Fatigue Data for Annealed 2.25Cr-1Mo Steel. Note that this data does not appear to match any of the other data compiled during this investigation.[15]

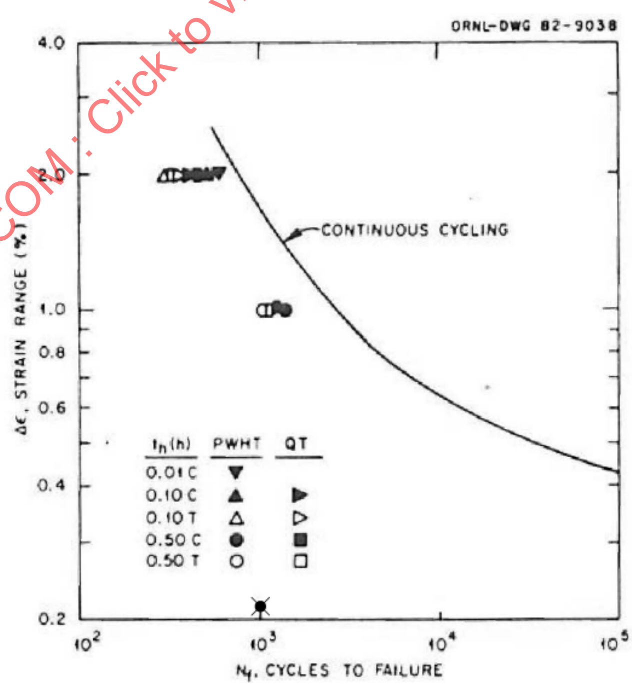
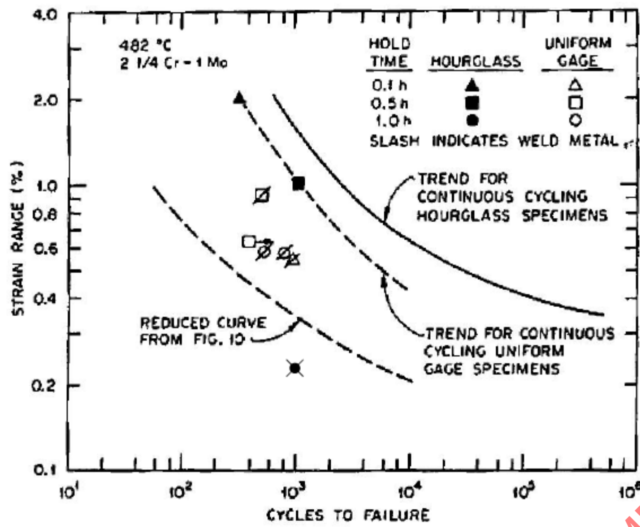
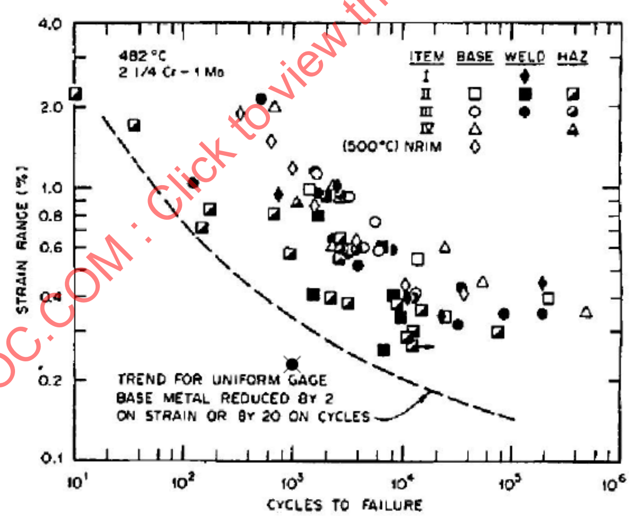


Figure 24 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for PWHT and QT (both bainitic) 2.25Cr-1Mo Steel.[15]



Combined tensile hold-time fatigue data produced on 2 1/4 Cr-1 Mo steel base metal and weldments.

Figure 25 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for 2.25Cr-1Mo Steel Class 2.[16]



Combined low-cycle fatigue data for 2 1/4 Cr-1 Mo steel base metal and weldments. Also included are data produced by the National Research Institute for Metals.

Figure 26 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for 2.25Cr-1Mo Steel Class 2, Note HAZ stands for heat affected zone.[16]

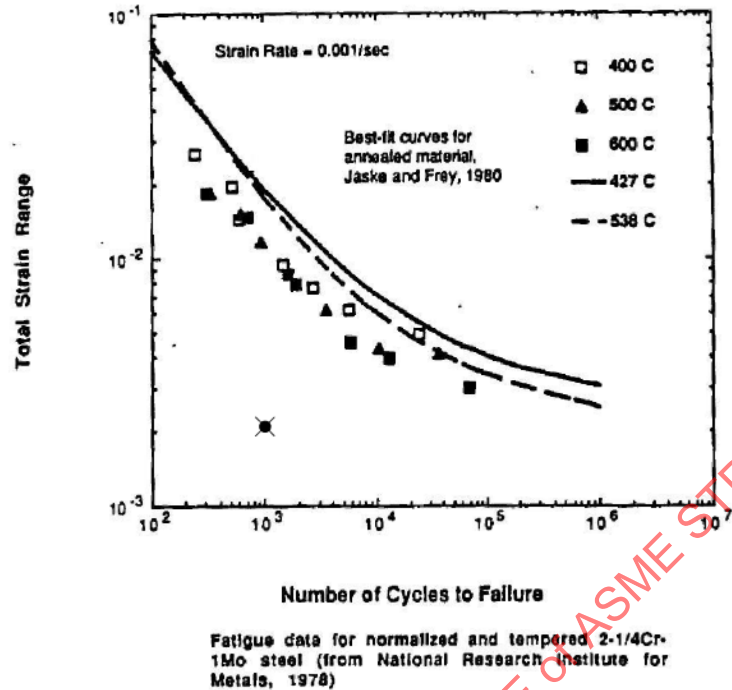


Figure 27 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for Normalized and Tempered 2.25Cr-1Mo Steel.[17]

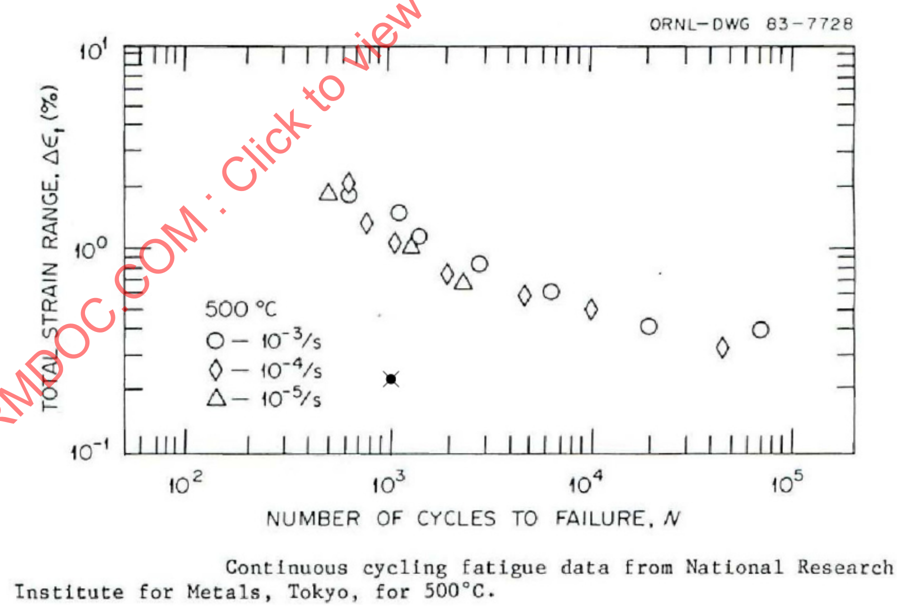


Figure 28 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for Normalized and Tempered 2.25Cr-1Mo Steel.[18]

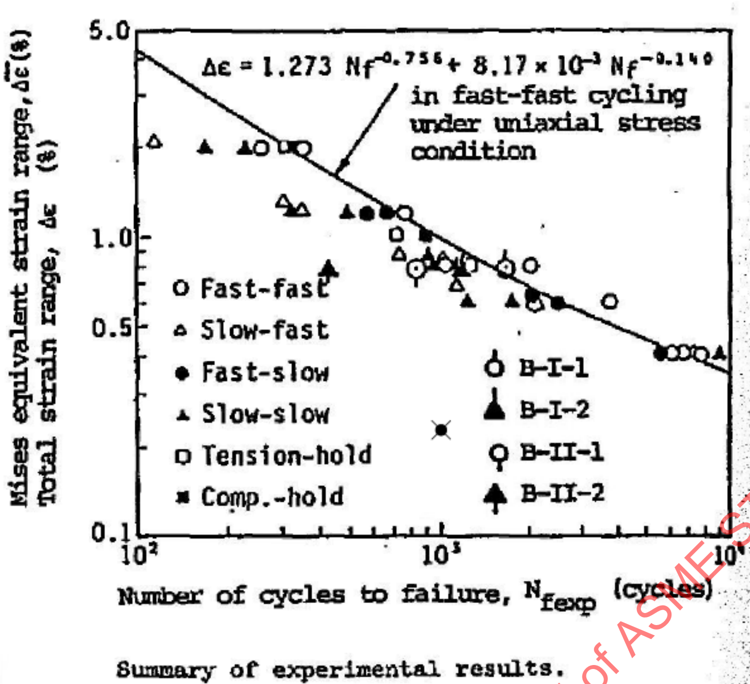


Figure 29 - 2.25Cr-1Mo Class 2 Data Point Plotted Versus Fatigue Data for Normalized and Tempered 2.25Cr-1Mo Steel.[19]

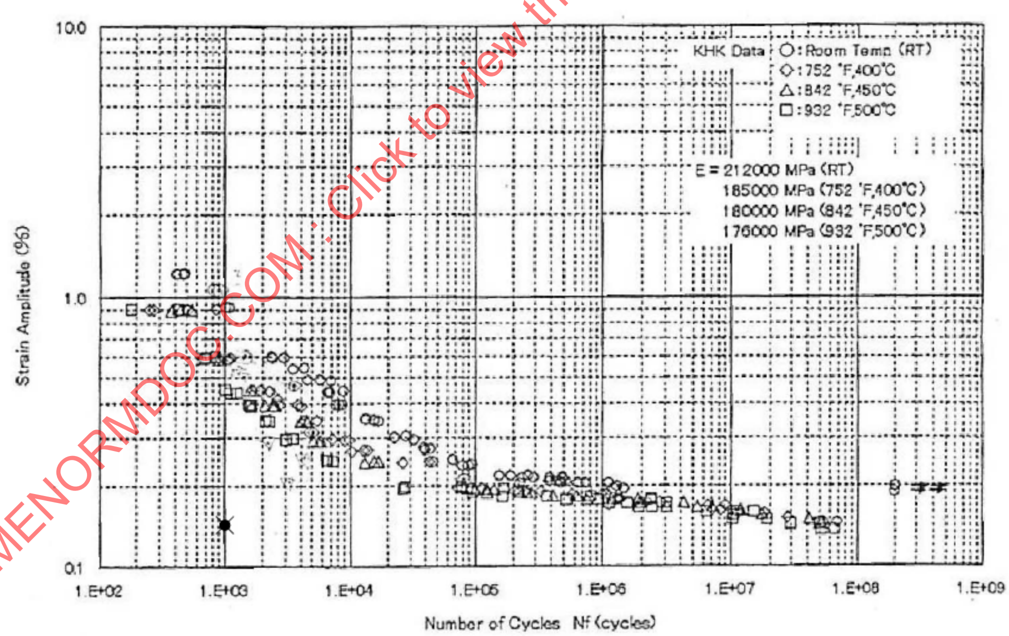
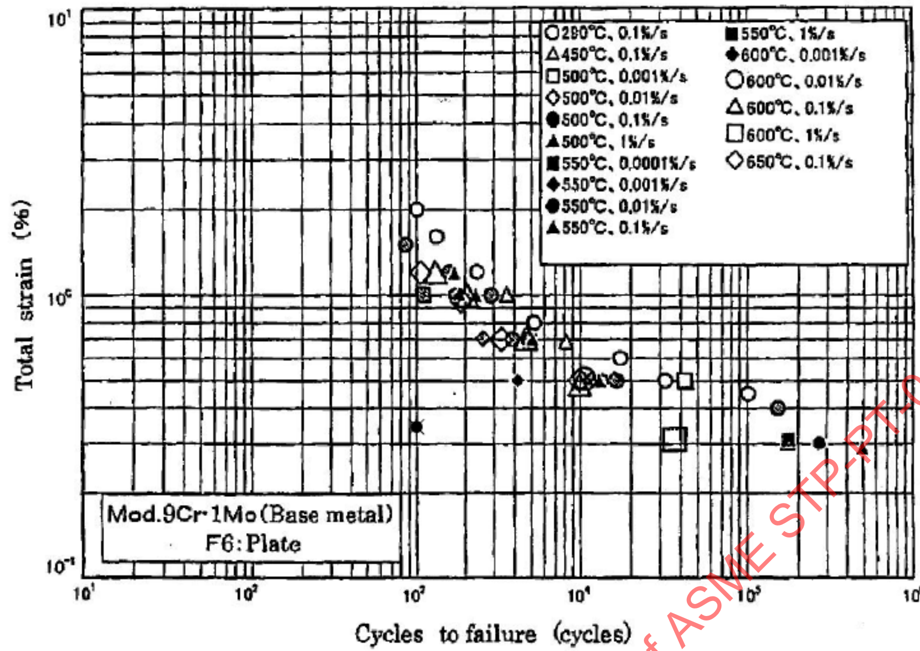
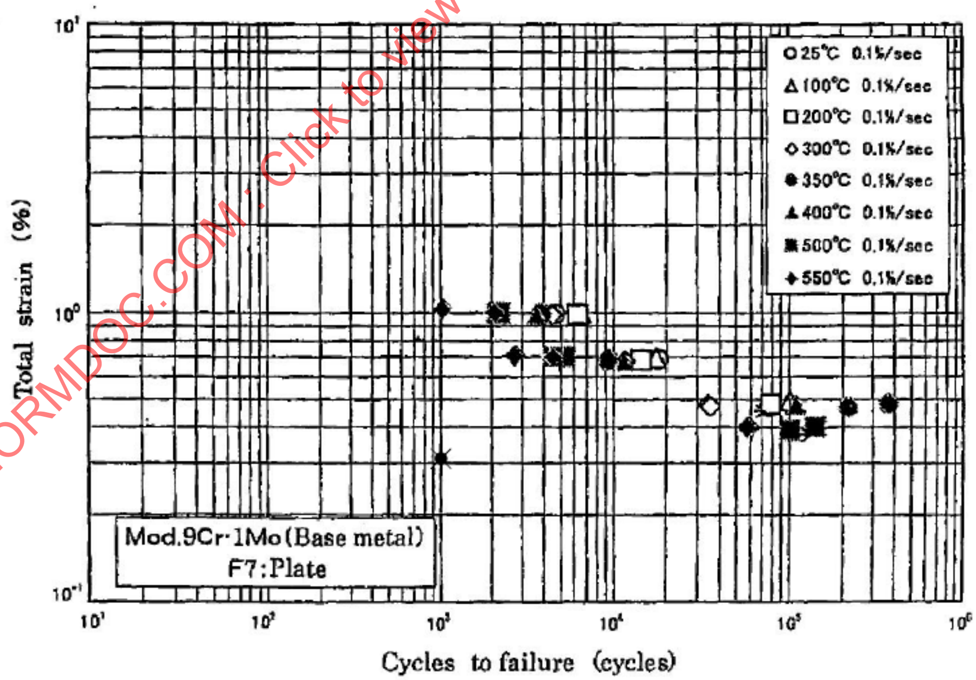


Figure 30 - 2.25Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 2.25Cr-1Mo-V Steel.[20]



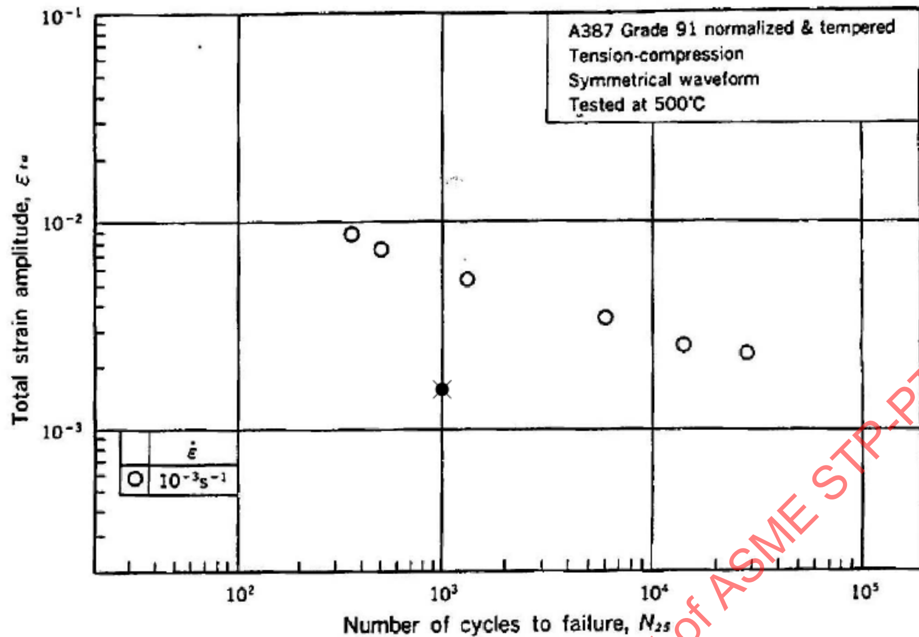
Fatigue life[F6]

Figure 31 – 9Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 9Cr-1Mo-V Steel. [See App. D]



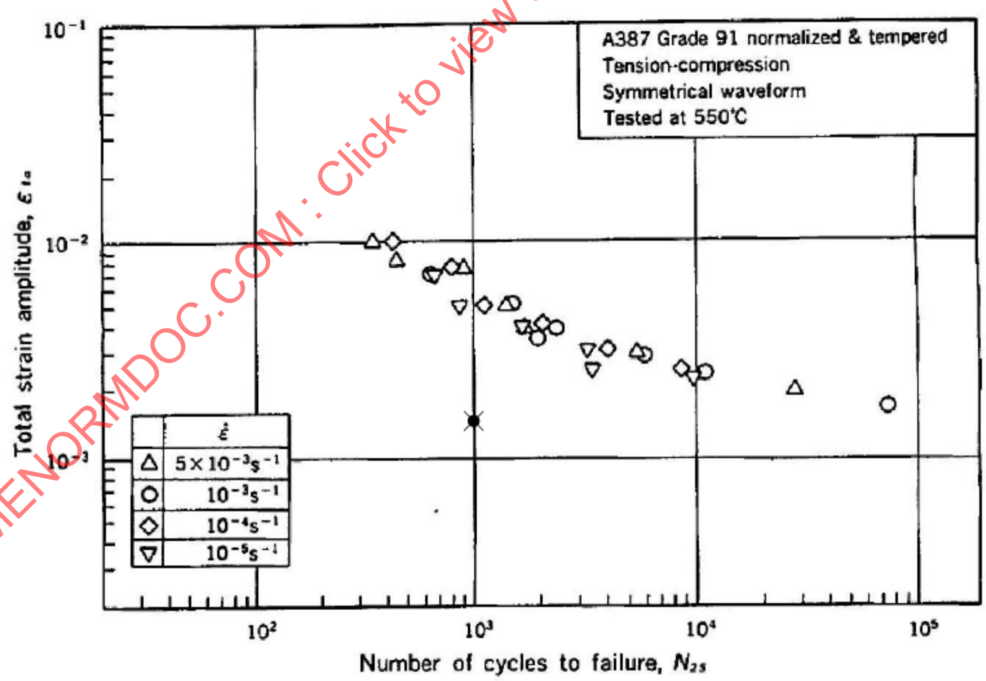
Fatigue life[F7]

Figure 32 - 9Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 9Cr-1Mo-V Steel. [See App. D]



(b) Tested at 500°C

Figure 33 - 9Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 9Cr-1Mo-V Steel.[21]



(c) Tested at 550°C

Figure 34 - 9Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 9Cr-1Mo-V Steel.[21]

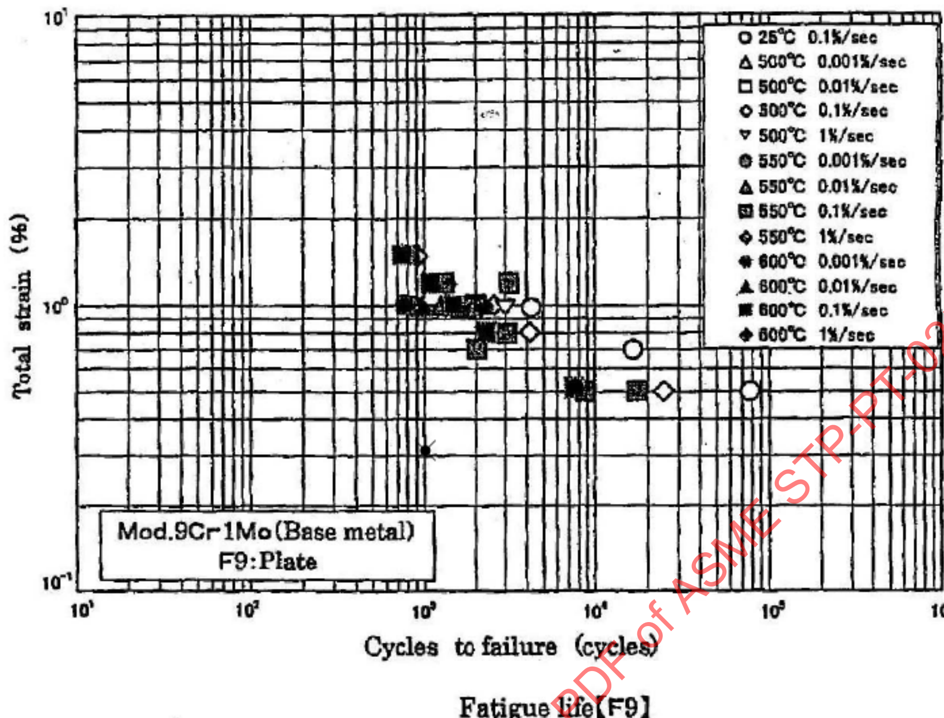


Figure 35 - 9Cr-1Mo-V Data Point Plotted Versus Fatigue Data for 9Cr-1Mo-V Steel. [See App. D]

APPENDIX C - GR 22 DATA TABLES

Appendix C contains tables of Gr 22 data that have been compiled from various sources that are referenced at the end of the appendix.

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
3P5601-IA	MIL-65	HG-B	482	0.4		6	0.50								3420	
3P5601-IA	IIT-30	HG-B	482	0.4	3	3	0.48								3525	
3P5601-IA	MIL-72	HG-B	482	0.4	3	3	0.35								>71000	
3P5601-IA	MIL-54	HG-B	482	0.4		3	0.35			206	188		179		34995	
3P5601-IA	MIL-61	HG-B	482	0.4		0.6	0.30								>600000	
3P5601-IA	MIL-60	HG-B	482	0.4		6	0.35								31694	
3P5601-IA	MIL-63	HG-B	482	0.4		15	0.40								14936	
3P5601-IA	ITL-214	HG-B	482	0.4		15	0.35								20523	
3P5601-IA	ITL-217	HG-B	482	0.4		60	0.40								>4249	
3P5601-IA	MIL-69	HG-B	538	0.4		3	0.30								24732	
3P5601-IA	MIL-71	HG-B	538	0.4	6		0.50								14023	
3P5601-IA	MIT-3	HG-B	538	0.4		6	0.30								19438	
3P5601-IA	BIL-35	HG-B	538	0.4		6	0.50								5680	
3P5601-IA	BIL-26	HG-B	538	0.4		3	0.10								>161359	
3P5601-IA	MIL-44	HG-B	482	0.4			0.5	0.263	0.237	220	224				51656	ornl-5625
3P5601-IA	MIL-36	HG-B	482	0.4	6		0.5	0.221	0.279	202	215	158			20147	ornl-5625
3P5601-IA	MIL-27	HG-B	482	0.4		6	0.5	0.228	0.274	211	213		175		6111	ornl-5625
3P5601-IA	MIL-65	HG-B	482	0.4	6	6	0.5	0.204	0.296	204	214	165	179		3420	ornl-5625
3P5601-IA	MIL-21	HG-B	538	0.4			0.52	0.334	1.666	246	272				881	ornl-5625
3P5601-IA	MIL-15	HG-B	538	0.4	30		2.0	0.237	1.763	233	261	107			640	ornl-5625
3P5601-IA	MIL-14	HG-B	538	0.4		30	2.0	0.256	1.744	268	261		130		359	ornl-5625
3P5601-IA	MIL-17	HG-B	538	0.4	30	30	2.0	0.144	1.856	234	245	110	114		533	ornl-5625
3P5601-IA	ITL-134	HG-B	538	0.4			1.0	0.329	0.671	259	252				2377	ornl-5625
3P5601-IA	MIL-10	HG-B	538	0.4			0.5	0.242	0.248	192	199				16036	ornl-5625
3P5601-IA	ITL-106	HG-B	538	0.4	6		0.5	0.254	0.246	200	236	157			15450	ornl-5625

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
3P5601-IA	MIL-12	HG-B	538	0.4		6	0.5	0.202	0.298	191	177		122		4496	ornl-5625
3P5601-IA	ITL-127	HG-B	538	0.4	6	6	0.5	0.184	0.316	208	198	165	121		1954	ornl-5625
3P5601-IA	ITT-7	HG-B	538	0.4			0.38	0.227	0.144	209	205				63907	ornl-5625
3P5601-IA	ITL-31	HG-B	593	0.4			0.50	0.244	0.255	182	196				17252	ornl-5625
3P5601-IA	ITL-44	HG-B	593	0.4	0.06		0.50	0.25	0.25	195	230	152			17780	ornl-5625
3P5601-IA	ITL-39	HG-B	593	0.4		0.06	0.50	0.198	0.301	178	170		133		8420	ornl-5625
3P5601-IA	ITL31A	HG-B	593	0.04			0.50	0.211	0.291	161	178				8432	ornl-5625
3P5601-IA	ITL-34	HG-B	593	0.004			0.50	0.19	0.31	158	166				4200	ornl-5625
3P5601-IA	FL14	UG-Thd	316	0.4			0.4	0.31	0.09	303	303				28400	esg-doe-13243 S control after stablization
3P5601-IA	FL6	UG-Thd	316	0.4			0.31	0.29	0.02	274.5	274.5				236800	esg-doe-13243 S control after stablization
3P5601-IA	FL15	UG-Thd	316	0.4			0.3	0.28	0.02	278.5	278.5				170600	esg-doe-13243 S control after stablization
3P5601-IA	FL18	UG-Thd	316	0.4			0.29	0.29		276.5	276.5				1441600	esg-doe-13243 S control after stablization
3P5601-IA	FL16	UG-Thd	316	0.4			0.27	0.27		251	251				17437600	esg-doe-13243 S control after stablization
3P5601-IA	FL19	UG-Thd	427	0.4			0.33	0.32	0.01	278.5	278.5				138000	esg-doe-13243 S control after stablization
3P5601-IA	FL9	UG-Thd	427	0.4			0.29	0.29		282	282				829600	esg-doe-13243 S control after stablization
3P5601-IA	FL23	UG-Thd	427	0.4			0.29	0.29		270	270				1011500	esg-doe-13243 S control after stablization
3P5601-IA	FL10	UG-Thd	427	0.4			0.29	0.29		255	255				31919400	esg-doe-13243 S control after stablization
3P5601-IA	FT1	UG-Thd	538	0.4			0.3	0.22	0.08	192.5	192.5				108500	esg-doe-13243 S control after stablization
3P5601-IA	FL20	UG-Thd	538	0.4			0.29	0.21	0.08	197	197				76490	esg-doe-13243 S control after stablization
3P5601-IA	FT3	UG-Thd	538	0.4			0.26	0.23	0.03	188	188				1279700	esg-doe-13243 S control after stablization
3P5601-IA	FT4	UG-Thd	538	0.4			0.24	0.22	0.02	183.5	183.5				2225200	esg-doe-13243 S control after stablization
3P5601-IA	FT5	UG-Thd	538	0.4			0.21	0.21		175.5	175.5				5993400	esg-doe-13243 S control after stablization
3P5601-IA	FT6	UG-Thd	538	0.4			0.19	0.19		148.5	148.5				10736400	esg-doe-13243 S control after stablization
3P5601-IA	ITL-76	HG-B	25	0.4			1.017	0.318	0.698						4042	
3P5601-IA	ITT-5	HG-B	25	0.4			2	0.368	1.733						958	

Heat No.	Spec. No.	Type	Temp	Ramp Rate	Ten. Hold	Comp. Hold	Strain Range	Elastic Strain	Plastic Strain	Ten Stress Amplitude	Comp Stress Amplitude	Ten. Rlx Stress	Comp Rlx Stress	Stress Range	Cycles to Failure	Comment
			(deg C)	(%/s)	(min)	(min)	(%)	(%)	(%)	(MPa)	(MPa)	(Mpa)	(MPa)	(MPa)		
3P5601-IA	ITL-75	HG-B	25	0.4			2.007	0.382	1.656						724	
3P5601-IA	ITL-77	HG-B	25	0.4			2.12	0.374	1.75						712	
3P5601-IA	ITT-6	HG-B	25	0.4			0.35	0.23	0.12						140235	
3P5601-IA	I-4	HG-B	371	0.4			1	0.332	0.668						4303	
3P5601-IA	I17	HG-B	371	0.4			1	0.324	0.676						3310	
3P5601-IA	I20	HG-B	371	0.4			1.25	0.336	0.914						2711	
3P5601-IA	I11	HG-B	371	0.4			1.5	0.409	1.091						2028	
3P5601-IA	I7	HG-B	371	0.4			1.75	0.365	1.395						1470	
3P5601-IA	I10	HG-B	371	0.4			0.6	0.293	0.307						18568	
3P5601-IA	ITL-38	HG-B	371	0.4			0.503	0.289	0.214						30566	
3P5601-IA	ITL-32	HG-B	371	0.4			0.502	0.281	0.221						29363	
3P5601-IA	I3	HG-B	371	0.4			0.35	0.25	0.1						417225	
3P5601-IA	I2	HG-B	371	0.4			0.4	0.29	0.101						157252	
3P5601-IA	ITL-18	HG-B	482	0.4			0.5	0.251	0.249						36295	
3P5601-IA	ITT-7	HG-B	538	0.4			0.381	0.227	0.144						639069	
3P5601-IA	ITL-31	HG-B	593	0.4			0.5	0.244	0.255						16254	
3P5601-IA	ITL-40	HG-B	538	0.4			0.503	0.263	0.24						15765	
3P5601-IA	ITL-22	HG-B	538	0.4			0.5	0.229	0.271						22353	
3P5601-IA	6MTL	HG-B	538	0.4			0.5	0.27	0.23						18292	
3P5601-IA	ITT-19	HG-B	538	0.4			0.72	0.26	0.46						4376	
3P5601-IA	ITT-12	HG-B	538	0.4			0.71	0.27	0.44						2758	
3P5601-IA	ITL-68	HG-B	538	0.4			0.7	0.24	0.46						2974	
3P5601-IA	ITT-17	HG-B	538	0.4			0.56	0.24	0.32						2593	
3P5601-IA	ITT-18	HG-B	538	0.4			1	0.28	0.72						1386	
3P5601-IA	ITL-79	HG-B	538	0.4			1.01	0.27	0.74						1527	

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
3P5601-IA	ITL-100	HG-B	538	0.4			1.02	0.29	0.73						1480	
3P5601-IA	ITL-61	HG-B	538	0.4			2	0.31	1.69						532	
3P5601-IA	ITL-11	HG-B	538	0.4			2	0.31	1.69						496	
3P5601-IA	ITL-22	HG-B	538	0.4			2.96	0.28	2.68						315	
3P5601-IA	ITL-20	HG-B	538	0.4			2.98	0.35	2.63						147	
3P5601-IA	ITL-62	HG-B	538	0.4			2.98	0.32	2.66						293	
3P5601-IA	IUL-14	UG-Thd	25	0.4			1.98	0.357	1.626						1042	
3P5601-IA	IUL-18	UG-Thd	25	0.4			1.004	0.3	0.7						4079	
3P5601-IA	IUL-19	UG-Thd	25	0.4			0.35	0.237	0.113						115122	
3P5601-IA	IUL-16	UG-Thd	25	0.4			0.51	0.256	0.256						32403	
3P5601-IA	IUL-8	UG-Thd	538	0.4			0.97	0.274	0.699						2000	
3P5601-IA	IUL-10	UG-Thd	538	0.4			1.996	0.32	1.676						679	
3P5601-IA	IUL-7	UG-Thd	538	0.4			0.35	0.225	0.125						73256	
3P5601-IA	IUL-6	UG-Thd	538	0.4			0.5	0.236	0.264						10764	
3P5601-IA	MIL-30	HG-B	316	0.4			2	0.35	1.65						1806	Mar-Test Data
3P5601-IA	MIL-38	HG-B	371	0.4			2	0.36	1.64						1314	Mar-Test Data
3P5601-IA	MIL-8	HG-B	427	0.4			0.7	0.28	0.42						9975	Mar-Test Data
3P5601-IA	MIL-2	HG-B	427	0.4			1	0.3	0.7						4307	Mar-Test Data
3P5601-IA	MIL-49	HG-B	427	0.4			2	0.36	1.64						1360	Mar-Test Data
3P5601-IA	MIL-37	HG-B	427	0.4			2	0.35	1.65						1200	Mar-Test Data
3P5601-IA	MIL-11	HG-B	427	0.4			0.6	0.27	0.33						25048	Mar-Test Data
3P5601-IA	MIL-7	HG-B	427	0.4			0.55	0.26	0.29						91457	Mar-Test Data
3P5601-IA	MIL-3	HG-B	427	0.4			0.5	0.26	0.24						111471	Mar-Test Data
3P5601-IA	MIL-40	HG-B	427	0.4			0.4	0.24	0.16						605190	Mar-Test Data
3P5601-IA	MIL-67	HG-B	482	0.4			0.35	0.23	0.12						883895	Mar-Test Data

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
3P5601-IA	MIL-57	HG-B	482	0.4			0.35	0.24	0.11						766573	Mar-Test Data
3P5601-IA	MIL-42	HG-B	482	0.4			0.4	0.24	0.16						297300	Mar-Test Data
3P5601-IA	MIL-48	HG-B	538	0.4			0.25	0.2	0.05						2144472	Mar-Test Data
3P5601-IA	MIL-10	HG-B	538	0.4			0.5	0.22	0.28						16036	Mar-Test Data
3P5601-IA	MIL-18	HG-B	482	0.4			1.1	0.38	0.72						3721	Mar-Test Data
3P5601-IA	MIT-1	HG-B	482	0.4			2	0.31	1.69						910	Mar-Test Data
3P5601-IA	MIL-31	UB-B	538	0.4			0.5	0.22	0.28						9353	Mar-Test Data
3P5601-IA	BIL-15		538	0.4			1.03	0.27	0.76						2477	BCL Data
3P5601-IA	BIL-16		538	0.4			2.09	0.36	1.73						846	BCL Data
3P5601-IA	BIL-11		538	0.4			0.5	0.27	0.23						16185	BCL Data
3P5601-IA	BIL-13		482	0.4			0.5	0.22	0.28						24035	BCL Data
3P5601-IA	BIT-1		427	0.4			0.5	0.28	0.22						38770	BCL Data
3P5601-IA	BIL-2		317	0.4			0.5	0.26	0.24						32514	BCL Data
3P5601-IA	FCM6	UG-Thd	540	0.006	1500		0.382									
3P5601-IA	ITL-123	HG-B	482	0.4			0.5	0.286	0.214	235	248				69742	HTGR He
3P5601-IA	ITL-125	HG-B	482	0.4	6		0.5	0.236	0.274	204	246	153			18154	HTGR He
3P5601-IA	ITL-126	HG-B	482	0.4		6	0.5	0.253	0.247	229	229				13740	HTGR He
3P5601-IA	ITL-124	HG-B	482	0.4	6	6	0.5	0.223	0.277	225	245	181	196		5481	HTGR He
3P5601-IA	ITL-132	HG-B	538	0.4			2	0.4	1.6	300	321				1059	HTGR He
3P5601-IA	ITL-131	HG-B	538	0.4	30		2	0.305	1.695	308	330	143			546	HTGR He
3P5601-IA	ITL-130	HG-B	538	0.4		30	2	0.287	1.713	297	318		148		715	HTGR He
3P5601-IA	ITL-136	HG-B	538	0.4			1	0.351	0.649	192	286				5913	HTGR He
3P5601-IA	ITL-111	HG-B	538	0.4			0.5	0.329	0.177	248	261				21643	HTGR He
3P5601-IA	ITL-101	HG-B	538	0.4	6		0.5	0.243	0.257	195	241	136			5860	HTGR He
3P5601-IA	ITL-109	HG-B	538	0.4		6	0.5	0.202	0.298	211	206		137		11220	HTGR He

Heat No.	Spec. No.	Type	Temp	Ramp Rate	Ten. Hold	Comp. Hold	Strain Range	Elastic Strain	Plastic Strain	Ten Stress Amplitude	Comp Stress Amplitude	Ten. Rlx Stress	Comp Rlx Stress	Stress Range	Cycles to Failure	Comment
			(deg C)	(%/s)	(min)	(min)	(%)	(%)	(%)	(MPa)	(MPa)	(Mpa)	(MPa)	(MPa)		
3P5601-IA	ITT-27	HG-B	538	0.4	6	6	0.5	0.208	0.292	195	217	149	174		2950	HTGR He
3P5601-IA	ITL-202	HG-B	538	.004/.4			0.5	0.218	0.282	184	215				7192	HTGR He
3P5601-IA	ITL-138	HG-B	538	.4/.004			0.5	0.212	0.288	219	209				10466	HTGR He
3P5601-IA	ITL-102	HG-B	538	0.4			0.4	0.276	0.124	205	223				89137	HTGR He
3P5601-IA	ITL-220	HG-B	538	0.4			0.4	0.283	0.117	203	236				73772	HTGR He
3P5601-IA	ITL-104	HG-B	538	0.4			0.35	0.274	0.076	206	219				180925	HTGR He
3P5601-IA	ITL-118	HG-B	538	0.4			0.3	0.265	0.035	196	215				243851	HTGR He
3P5601-IA	ITL-203	HG-B	538	0.4			0.31	0.251	0.057	188	234				682834	HTGR He
3P5601-IA	ITL-205	HG-B	593	0.4			2	0.41	1.59	276	281				1645	HTGR He
3P5601-IA	ITL-209	HG-B	593	0.4			0.96	0.332	0.628	222	229				6220	HTGR He
3P5601-IA	ITL-208	HG-B	593	0.4			0.52	0.233	0.287	190	202				44064	HTGR He
3P5601-IA	ITL-210	HG-B	593	0.4			0.5	0.233	0.77	186	207				44000	HTGR He
3P5601-IA	ITL-206	HG-B	593	0.4	6		0.5	0.189	0.32	172	207	86			4855	HTGR He
3P5601-IA	ITL-212	HG-B	593	0.4		6	0.5	0.206	0.294	193	160		86		12000	HTGR He
3P5601-IA	ITL-211	HG-B	593	0.4			0.4	0.258	0.142	172	178				67905	HTGR He
3P5601-IA	ITL-207	HG-B	593	0.4			0.3	0.244	0.056	160	171				283032	HTGR He
3P5601-IA	ITT26	HG-B	538	0.4	6	6	0.5									HTGR He
3P5601-IA	ITL-216	HG-B	538	0.4			2	0.416	1.584	289	334				1188	HTGR He
3P5601-IA	ITL-219	HG-B	538	0.4			0.5	0.256	0.244	212	234				41015	HTGR He
C7409-IA	FB2-29	HG-THD	593	0.4	60		2.02	0.2	1.82						465	
C7409-IA	F1-4	HG-THD	593	0.4	30		0.76	0.16	0.6						1200	
C7409-IA	FB2-22	HG-THD	593	0.4	30		2.08	0.29	1.79						389	
C7409-IA	FB2-41	HG-THD	593	0.4	10		2.13	0.29	1.84						282	
C7409-IA	FB2-18	HG-THD	593	0.4	10		2.09	0.29	1.8						343	
C7409-IA	FB2-20	HG-THD	593	0.4		10	2.09	0.3	1.79						392	

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
C7409-IA	FB-21	HG-THD	593	0.4	10	10	2	0.2	1.8						334	
C7409-IA	FB-28	HG-THD	593	0.4	10		0.82	0.22	0.6						1457	
C7409-IA	FB-27	HG-THD	593	0.4	5		0.55	0.23	0.32						4504	
C7409-IA	FB2-24	HG-THD	538	0.4	60		2.04	0.25	1.79						406	
C7409-IA	FB2-23	HG-THD	538	0.4	30		2.03	0.24	1.79						378	
C7409-IA	FB2-2	HG-THD	538	0.4	30		0.98	0.25	0.73						1213	
C7409-IA	FB2-3	HG-THD	538	0.4		30	0.97	0.27	0.7						1400	
C7409-IA	FB2-25	HG-THD	538	0.4	10		2.05	0.3	1.76						520	
C7409-IA	FB2-31	HG-THD	538	0.4		10	2.06	0.26	1.8						658	
C7409-IA	FB2-32	HG-THD	538	0.4	10	10	2.04	0.23	1.8						444	
C7409-IA	FB2-39	HG-THD	538	0.4	10		0.98	0.22	0.76						1262	
C7409-IA	FB2-30	HG-THD	538	0.4	5		0.54	0.25	0.29						11718	
C7409-IA	FB2034	HG-THD	482	0.4	10		2.04	0.36	1.68						588	
C7409-IA	FB2-33	HG-THD	482	0.4	5		2.05	0.32	1.73						607	
C7409-IA	FB2-35	HG-THD	482	0.4		5	1	0.33	0.67						1741	
C7409-A	FA-42	HG-THD	593	0.4	30		2	0.22	1.78						461	
C7409-A	FA-2	HG-THD	593	0.4	30		0.77	0.22	0.55						1340	
C7409-A	FA-63	HG-THD	593	0.4	10		2.03	0.23	1.8						516	
C7409-A	FA-121	HG-THD	593	0.4	10		0.81	0.16	0.65						1679	
C7409-A	FA-118	HG-THD	593	0.4	5		0.5	0.17	0.33						5478	
C7409-A	FA-51	HG-THD	538	0.4	30		2	0.3	1.7						490	
C7409-A	FA-3	HG-THD	538	0.4	30		0.98	0.21	0.77						1222	
C7409-A	FA-51	HG-THD	538	0.4		30	1	0.24	0.76						1573	
C7409-A	FA-106	HG-THD	538	0.4	10		2.11	0.23	1.88						562	
C7409-A	FA-102	HG-THD	538	0.4	10		1.04	0.23	0.81						2191	

Heat No.	Spec. No.	Type	Temp (deg C)	Ramp Rate (%/s)	Ten. Hold (min)	Comp. Hold (min)	Strain Range (%)	Elastic Strain (%)	Plastic Strain (%)	Ten Stress Amplitude (MPa)	Comp Stress Amplitude (MPa)	Ten. Rlx Stress (Mpa)	Comp Rlx Stress (MPa)	Stress Range (MPa)	Cycles to Failure	Comment
C7409-A	FA-87	HG-THD	538	0.4	5		0.53	0.21	0.22						14446	
C7409-A	FA-67	HG-THD	482	0.4	5		2.06	0.29	1.77						658	
C7409-A	FA-36	HG-THD	482	0.4	5		0.98	0.26	0.72						2180	

References for Annealed 2 ¼ Cr- 1 Mo Steel

[1] E. Krempl and C. D. Walker, Effect of Creep-Rupture Ductility and Hold Time on the 1000 F Strain-Fatigue Behavior of a 1Cr-1Mo-0.25V Steel, Fatigue at High Temperature, pp. 75-99, American Society for Testing and Materials, Philadelphia, 1969.

(Comparison of hold time effect to Gr 22)

[2] C. E. Jaske and H. Mindlin, Elevated-Temperature Low-Cycle Fatigue Behavior of 2-1/4Cr-1Mo and 1 Cr-1Mo-1/4V Steels, 2 ¼ Chrome 1 Molybdenum Steel in Pressure Vessels and Piping, pp. 137-210, American Society of Mechanical Engineers, New York, 1970.

(Control data for tests run by GA with hold time.)

[3] R. M. Curran and B. M. Wundt, A Study of Low-Cycle Fatigue and Creep Interactions in Steels at Elevated Temperatures, Current Work on Behavior of Materials at Elevated Temperatures, pp. 1-104, American Society of Mechanical Engineers, New York, 1974.

(Some loops and eventual analysis by strain range partitioning.)

[4] E. P. Esztergar and J. R. Ellis, Cumulative Damage Concepts in Creep-Fatigue Life Prediction, Thermal Stresses and Thermal Fatigue, pp. 128-155, Butterworths, London, 1974.

[5] C. E. Jaske, B. N. Leis and C. E. Pugh, Monotonic and Cyclic Stress-Strain Response of Annealed 2-1/4Cr-1Mo Steel, Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation, MPC-1, pp. 191-212, American Society of Mechanical Engineers, New York, 1975.

(Provides some cyclic hardening data, hysteresis loops and relaxation data.)

[6] J. R. Ellis, M. T. Jakub, C. E. Jaske and D. A. Utah, Elevated Temperature Fatigue and Creep-Fatigue Properties of Annealed 2 1/r Cr-1 Mo Steel, Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation, MPC-1, pp. 213-246, American Society of Mechanical Engineers, New York, 1975.

(Important paper on hold time effects and introduces the Gittus equation.)

[7] C. R. Brinkman, W. R. Corwin, M. K. Booker, T. L. Hebble and R. L. Klueh, Time Dependent Mechanical Properties of 2-1/4Cr-1Mo Steel for Use in Steam Generator Design, ORNL-5125, Oak Ridge National Laboratory, Oak Ridge, TN, March 1976.

[8] R. Eisenstadt and H. Popat, Effect of Welding on the Low-Cycle Flexural Fatigue Performance of 2-1/4Cr-1Mo Seamless Pipe Material at 1000F (538C), Effects of Melting and Processing Variables on the Mechanical Properties of Steel, MPC-6, pp. 107-111, American Society of Mechanical Engineers, New York, 1977.

(No hold times but some crack initiation data.)

[9] M. K. Booker, Construction of Creep-Fatigue Elastic-Analysis Curves and Interim Analysis of Long-Term Creep-Fatigue Data for 2-1/4Cr-1Mo Steel, ORNL/TM-6324, Oak Ridge National Laboratory, Oak Ridge, TN, July 1978.

(Includes some cyclic relaxation to 100 hr. at 538°C.)

[10] M. K. Booker, Analysis of the Long-Term Creep-Fatigue Behavior of 2-1/4Cr-1Mo Steel, ORNL/TM-7068, Oak Ridge National Laboratory, Oak Ridge, TN, Dec. 1979.

[11] C. R. Brinkman, J. P. Strizak and M. K. Booker, The Influence of Environment, Metallurgical Variables, and Prolonged Test Times on the Fatigue and Creep-Fatigue Behavior of Annealed

2-1/4Cr-1Mo Steel, ORNL-5625, Oak Ridge National Laboratory, Oak Ridge, TN, April 1980.

(Includes some relaxation to 100 hr.)

[12] C. R. Brinkman, J. P. Strizak, M. K. Booker and V. K. Sikka, A Status Report on Exploratory Time-Dependent Fatigue Behavior of 2-1/4Cr-1Mo and Modified 9 Cr-1 Mo Steel, ORNL/TM-7699, Oak Ridge National Laboratory, Oak Ridge, TN, June 1981.

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[14] R. W. Swindeman, Mechanical Relaxation Response of 2-1/4Cr-1Mo Steel, Residual Stress and Relaxation, pp. 157-178, Plenum, 1982.

(Relaxation for both annealed and normalized and tempered conditions.)

APPENDIX D - GR 91 DATA POINTS

Appendix D contains tables of Gr 91 data that have been compiled from various sources that are referenced at the end of the appendix.

MATERIAL ID	TESTPIECE ID	TESTPIECE ORIENTATION / POSITION	TEMP	de/dt	t_{ht}	t_{hc}	$2.e_a$									N_f	COMMENTS
							De_t	e_e	e_p	s_{max}	s_{min}	Ds	s_m	s_{h1end}	s_{h2end}		
			˚C	%/s	min	min	%	%	%	MPa	MPa			MPa	MPa	cycles	
30176	32	UG-B	593	0.4			0.65	0.344	0.298			447	0			4165	
30176	33	UG-B	593	0.4			0.63	0.4	0.23			415	0			6470	
30176	34	UG-B	593	0.4			0.37	0.288	0.082			298	4.9			695530	
30176	35	UG-B	593	0.4			0.5	0.264	0.236			451	0.7			9225	
30176	62	UG-B	593	0.4			0.41	0.29	0.12			458	-10.5			47000	
30176	66	UG-B	593	0.4			1	0.312	0.688			519	-2.1			1675	
30176	67	UG-B	593	0.4			0.76	0.29	0.47			486	0			2155	
30176	48T	UG-B	538	0.4	60		1	0.33	0.67							1734	
30176	279T	UG-B	23	0.4			0.46	0.4	0.06	467	435					71576	
30176	278T	UG-B	23	0.4			1.46	0.52	0.94	594	592					577	
30176	281T	UG-B	23	0.4			0.98	0.49	0.49	545	557					2808	
30176	282T	UG-B	23	0.4			0.465	0.39	0.07	458	426					47471	
30176	283T	UG-B	23	0.4			0.464	0.4	0.06	494	404					65301	
30176	285T	UG-B	23	0.4			0.466	0.4	0.06	444	461					55967	
30176	286T	UG-B	23	0.4			0.468	0.41	0.05	510	432					28958	
30176	294T	UG-B	23	0.4			1.072	0.54	0.53	602	620					1814	
30176	297T	UG-B	23	0.4			0.574	0.38	0.19	433	525					28395	
30176	302T	UG-B	23	0.4			0.38	0.34	0.04	412	351					202656	
30176	300T	UG-B	23	0.4			0.32	0.32	0	384	346					>1484683	
30176	12	UG-B	371	0.4			1	0.38	0.62	374	377					1975	
30176	14	UG-B	371	0.4			0.71	0.41	0.3	364	351					4528	
30176	15	UG-B	371	0.4			0.52	0.35	0.17	362	343					18984	
30176	17	UG-B	371	0.4			0.36	0.32	0.04	333	302					66834	
30176	13	UG-B	371	0.4			0.33	0.29	0.04	302	327					163100	

MATERIAL ID	TESTPIECE ID	TESTPIECE ORIENTATION / POSITION	TEMP	de/dt	t_{ht}	t_{hc}	$2.e_a$								N_f	COMMENTS
							De_t	e_e	e_p	s_{max}	s_{min}	Ds	s_m	s_{h1end}	s_{h2end}		
			˚C	%/s	min	min	%	%	%	MPa	MPa			MPa	MPa	cycles	
30176	10	UG-B	371	0.4			0.32	0.27	0.05	331	318					61130	
30176	16	UG-B	371	0.4			0.26	0.24	0.02	269	322					784843	
30176	22	UG-B	482	0.4			1	0.33	0.67	318	317					1481	
30176	18	UG-B	482	0.4			1	0.37	0.63	322	326					1388	
30176	24	UG-B	482	0.4			0.68	0.31	0.37	308	326					4147	
30176	20	UG-B	482	0.4			0.5	0.34	0.16	302	293					13001	
30176	19	UG-B	482	0.4			0.42	0.31	0.11	285	276					47114	
30176	21	UG-B	482	0.4			0.37	0.3	0.07	287	259					78300	
30176	23	UG-B	482	0.4			0.31	0.25	0.06	255	242					1223675	
30176	25	UG-B	482	0.4			0.25	0.24	0.01	242	250					>668200	
30176	9	UG-B	538	0.4			1.5	0.43	1.07	329	332					1035	
30176	6	UG-B	538	0.4			1	0.37	0.63	285	285					1408	
30176	4	UG-B	538	0.4			0.7	0.36	0.34	280	277					3032	
30176	3	UG-B	538	0.4			0.6	0.31	0.29	265	261					4895	
30176	2	UG-B	538	0.4			0.5	0.34	0.16	260	257					10840	
30176	1	UG-B	538	0.4			0.4	0.31	0.09	236	238					12965	
30176	7	UG-B	538	0.4			0.4	0.3	0.1	238	238					42532	
30176	5	UG-B	538	0.4			0.36	0.3	0.06	236	229					40284	
30176	11	UG-B	538	0.4			0.36	0.32	0.04	261	244					30857	
30176	8	UG-B	538	0.4			0.3	0.29	0.01	225	225					190733	
30176	52T	HG-B	538	0.4			0.4	0.32	0.07	232	265					52129	
30176	53T	HG-B	538	0.4			0.3	0.25	0.05	183	283					4456920	
30176	46T	HG-B	538	0.4		60	1	0.33	0.67	312	281				190	1176	
30176	47T	HG-B	538	0.4	60	60	1	0.22	0.78	262	285			159	174	>1208	
30176	48T	HG-B	538	0.4	60		1	0.33	0.67	291	348			162		1734	