ELECTRIC POWER RESEARCH INSTITUTE

Guidelines and Specifications for High-Reliability Fossil Power Plants

Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components

2011 TECHNICAL REPORT

Guidelines and Specifications for High-Reliability Fossil Power Plants

Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components

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1023199
Final Report, November 2011

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Acknowledgments

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Guidelines and Specifications for High-Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components. EPRI, Palo Alto, CA: 2011. 1023199.

Abstract

The steel alloy known as Grade 91 has achieved broad acceptance within the modern power industry for use in fabricating a variety of critical pressure part components, including tubing, piping, and headers. As is true for all of the creep-strength-enhanced ferritic (CSEF) steels, designers favor Grade 91 because, within a specific temperature range and when properly processed, it provides superior elevated temperature strength at substantially lower cost than the austenitic stainless steels, while maintaining the advantageous thermal–physical properties of a ferritic alloy.

Recent service experience has confirmed that early failures can occur in components fabricated from the CSEF steels unless the required condition of the microstructure is developed and maintained during processing. The EPRI report *Service Experience with Grade 91 Components* (1018151) reviews service experience with Grade 91 steel. Fabrication irregularities can result in components entering service with substantially deficient elevated temperature properties. These issues have caused serious concern due to the obvious implications for safety of plant personnel and reliability of equipment.

The objective of the current task is to resolve issues that pertain to how the material is ordered, how it is processed, how quality control is maintained during processing, and how the material is inspected in the shop and the field to determine its condition before or soon after installation. The necessary specifications and procedural documents will be developed to enable utilities to control the quality of the material at every stage of its implementation, from purchase through manufacturing and construction. The intent is to ensure that deficient material is never installed. This report is expected to establish requirements for optimizing manufacture and construction practices for Grade 91 components based on the best available information. Additional guidelines will be developed for specific test methods, including hardness testing and other nondestructive evaluation methods to verify material properties.

This report was produced by synthesis of more than 30 years of experience with Grade 91 material in the laboratory, in the shop, and in the field. The analysis and comments provided by the project team have also been invaluable to the organization and content of this report.

Keywords

Creep-strength-enhanced ferritic (CSEF) steels
Manufacturing practices
Grade 91 component failures
Grade 91 alloy
Quality control practices

Foreward

This report has been created to address issues associated with the manufacture of components with Grade 91 steel.

Following the introduction, there is a section that provides specific details associated with the purchase of Grade 91 steel components. Every attempt has been made to ensure that the details of the specification are consistent with industry best practices. These best practices have been modified as required by research from the Electric Power Research Institute Life Assessment of Creep Strength Enhanced Ferritic Steels project. As far as possible, the appendices provide summaries of the technical background linked to specific points within the best practices section. These summaries should allow a rapid referral to key information. It should be recognized, however, that the metallurgy and performance of Grade 91 steel are complex and that a full review of references is recommended to provide a complete understanding. In addition, work is still in progress to provide additional details in key areas. Therefore, the appendices will be updated and supplemented as necessary.

The information contained in this report has been produced by synthesis of more than 30 years of experience with Grade 91 material in the laboratory, in the shop, and in the field. In addition, the analysis and comments provided by the members of the project team have proved invaluable to the organization and the content of this report.

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Section 1: Introduction

The steel alloy known as Grade 91 has achieved broad acceptance within the modern power industry for use in fabricating a variety of critical pressure part components, including tubing, piping and headers. As is true for all of the creep strength enhanced ferritic (CSEF) steels, its attractiveness to designers is based on the fact that within a specific temperature range, and when properly processed, it provides superior elevated temperature strength at substantially lower cost than the austenitic stainless steels, all the while maintaining the advantageous thermal-physical properties of a ferritic alloy.

Grade 91 was co-developed by the Oak Ridge National Laboratory (ORNL) and Combustion Engineering (CE, currently named Alstom Power Inc.) at their Metallurgical and Materials Laboratory in Chattanooga, TN. Extensive study under Department of Energy sponsorship in the 1975-1980 timeframe had demonstrated the alloy's excellent mechanical properties [1,2,3]. As a result, the alloy attracted the attention of designers of boilers and pressure vessel fabricators, and in 1983 Grade 91 gained initial acceptance in the ASME Boiler and Pressure Vessel Code as tubing for Section I construction in Code Case 1943. The ensuing years have seen broad application of the material in both the power and petrochemical industries. There has been a resurgence of research into other advanced 9-12Cr ferritic steels, leading to the introduction of a number of new alloys that claim at least modest strength advantages over Grade 91 (e.g. Grade 122 [HCM12A] in Code Case 2180. Grade 92 [NF616] in Code Case 2179 and Grade 911 [E911] in Code Case 2327).

Fundamentally, Grade 91 is a modification of the 9Cr-1 Mo alloy identified as T9 in the ASME/ASTM SA-213 tubing specification. The modification to the standard 9Crl Mo alloy that resulted in Grade 91 involved, among other things, a controlled addition of vanadium, niobium and nitrogen. These elements provide precipitation strengthening by the formation of $M_{23}C_6$ carbides and MX (Nb V) carbonitrides, which, in addition to modest solid solution strengthening effects, produced an alloy with substantially greater creep strength than traditional CrMo steels. Like Grade 9, Grade 91 is very hardenable and, with an appropriate chemical composition, will transform to 100% martensite upon air-cooling.

The primary uses of Grade 91 have been for superheater and reheater tubes, headers, and main steam or hot reheat steam line piping in fossil power plants. Grade 91 offers distinct advantages with regard to elevated temperature strength and creep performance, which makes it possible to reduce the thickness, and, therefore the weight, of certain components significantly, when compared to conventional alloys, such as Grades 2, 5, 9, 11, 12 or 22.

1.1 Summary of Experience

Recent service experience has confirmed what "theory" had predicted: failures can occur in components fabricated from the CSEF steels very early in life if the required condition of microstructure is not developed and/or maintained during processing. A recent EPRI document reviews and summarizes service experience with Grade 91 steel [4]. It is apparent that 'irregularities' during fabrication can result in components entering service with elevated temperature properties that are substantially deficient when compared to an "average" heat of material [for example 5,6,7]. These issues have caused serious concern among users because of the obvious implications for safety of plant personnel and reliability of equipment.

The current program specifies a scope of work required to address critical issues associated with the use of these CSEF steels. The issues to be addressed range from material procurement, shop fabrication, field erection and appropriate quality assurance procedures to be applied during each of these phases of implementation, to the in-service behavior of both base metal and weld metal, with a particular emphasis on the provision of a comprehensive strategy for life prediction and optimization of maintenance. During the initial phases of the project, the effort concentrated on Grade 91 material, in large part because to date much more Grade 91 material has been specified and installed than any of the other CSEF steels. It is the case that the bulk of the in-service problems encountered so far involve Grade 91 material. However, because of the fundamental similarity in metallurgy that exists between the various grades of the CSEF steels, it was anticipated that much of the information obtained from the study of Grade 91 would also apply to similar steels that are approved for use by the ASME B&PV Code, including Grades 92, 911 and 122.

1.2 Task Objective

The objective of the current task is to resolve, to the extent possible given the current state of knowledge, what might be called "front-end" issues, that is, those issues that pertain to how the material is ordered, how it is processed, how the quality control is maintained during processing, and how the material should be inspected in the shop and the field to determine its condition prior to or soon after installation. The necessary specifications and procedural documents will be developed that will enable users to control the quality of the material at every stage of its implementation, from original purchase of the material, through the manufacturing and construction phases. The intent here is to ensure that deficient material never is installed. The output from this task is a comprehensive guideline that provides information on critical aspects of the ordering,

manufacturing, and construction of components fabricated from Grade 91 material. It is intended that this guideline will establish requirements for optimizing manufacture and construction practices of Grade 91 components based on the best available information. Additional guidelines will be developed for specific test methods, including hardness testing and other NDE methods to verify material properties. Later tasks will be performed to generate additional information where deficiencies are identified.

1.3 Design Considerations

The design basis for the various ASME B&PV Codes has two broad groupings: (a) *design-by analysis,* and (b) *design-by-rule*. While details may differ between the ASME Code and codes from other countries, these two broad groupings generally describe the prevailing approaches to design [8]. Thus, the ASME Code approaches will be emphasized in this chapter. In the *design-by-analysis* approach, detailed stress analysis is typically performed to categorize the stresses by type, directionality, and operational conditions, and these multiple stresses are then checked against a series of permissible limits. In *design-by-rule*, simplified design equations are used to compute a single characteristic value for stress, usually at a single design condition, and this stress is checked against a single "allowable stress." Obviously, the level of complexity in the stress analysis for *design-by-analysis* Codes far exceeds that of the *design-by-rule* Codes.

1.3.1 Design by Analysis

In ASME, the *design-by-analysis* Codes include Section III (Nuclear Power), Section VIII, Division 2 (Pressure Vessels – Alternative Rules), Section VIII, Division 3 (Pressure Vessels – Alternative Rules for High Pressure Vessels), and implicitly, because of its connection to Section III, Section XI (Nuclear Power – In-service Inspection). These Codes require detailed stress analyses by either classical methods or numerical methods such as finite elements. They classify stresses into various categories and use the maximum shear stress strength theory, also called the Tresca theory, to equate multiaxial stress states to single-valued equivalent stresses. The three major stress categories are primary stress, secondary stress, and peak stress. Primary stress is further divided into general primary membrane stress, local primary membrane stress, and primary bending stress. Each of these stresses has an associated stress limit and/or evaluation procedure. As a consequence, there are formal evaluation procedures for fatigue life, fatigue crack growth, and flaw tolerance to safeguard against fracture during the hydrostatic test and during various stages of operation.

It is implicit that *design by analysis* gives more precise estimates of the spatial and temporal values of stresses. Thus, the margin of design (safety factor) is typically lower when this approach is used and there is a greater effort to relate the calculated stresses to phenomenological material behavior.

Since the design-by-analysis approach more closely approximates "reality," it is reasonable to ask why it is not universally applied in pressure vessel design. The answer is complex but there are two fundamental reasons. First, the evolution of pressure vessel design began with the more simple design-by-rule approach and, for the most part, that evolution has produced pressure parts having long life with a high degree of safety. Hence, there is minimal impetus for change. Second, the complexity which has evolved in design-by-analysis Codes can be formidable and it seems reasonable to restrict it to a class of construction, such as nuclear steam supply systems, which warrant such sophistication.

1.3.2 Design by Rule

The ASME *design-by-rule* Codes include Sections I (Power Boilers), IV (Heating Boilers), VIII, Division 1 (Pressure Vessels), and most recently, XII (Transport Tanks). In general, these Codes only provide formal consideration of the general primary membrane stress and they only consider the first (maximum) principal stress for design purposes [9].

The design basis for pressure parts covered by Section I is to restrict the general (average) primary membrane stress of the first (maximum) principal stress to a level that will preclude:

- Gross distortion in short term loading at temperatures below the creep range
- Substantial distortion at long times in the creep range
- Bursting at any temperature

In the case of a pressurized cylinder, the first principal stress is the hoop stress.

The safeguard against gross distortion in short term loading is to limit the average hoop stress, called the general primary membrane stress in the design-by-analysis approach, to two-thirds of the yield strength at temperature. In cases of highly ductile alloys where some modest distortion is permissible, nine-tenths of the yield strength at temperature is permitted. The safeguard against substantial distortion at long time in the creep range is to limit the allowable stress to one which will produce a secondary creep rate of 1%/100,000 hours for an average material. There are two safeguards against bursting. First, the design stress at temperature is limited to 0.314 times the expected tensile strength at temperature (1.1/3.5); the factor was formerly 0.275 (1.1/4.0). Second, at temperatures in the creep range, the design stress is limited to the lower of either: (a) the aforementioned creep rate, (b) 0.67 of the average stress to cause rupture in 100,000 hours, or (c) 0.80 of the minimum stress to cause rupture in 100,000 hours.

In effect, Section I does not call for a detailed stress analysis but merely sets the wall thickness necessary to keep the basic hoop stress below the tabulated allowable stress. It is recognized that high localized and secondary bending stresses may exist in pressure parts designed and fabricated in accordance with the Section I rules but these are not explicitly considered in the design. Thus, Section I has no explicit rules to account for secondary stresses, which by definition are displacement controlled, or for fatigue due to localized cyclic stresses created by stress

concentrations. By providing generous design margins (safety factors) on the average primary membrane stress, an adequate margin generally exists to accommodate secondary stresses and cyclic stresses as validated by the usual long component life. There are occasional exceptions in which the boiler designer has to go “beyond the rules of Section I” to assure long service life.

By steadfastly remaining in the *design-by-rule* category, Section I has opted for simplicity over complexity/exactness, and has sought to cover areas of “inexactness” through generous design margins; i.e., safety factors. This approach, while generally successful, has resulted in a notable number of failures from mechanisms which are not included in the design process, some of which were illustrated in a recent paper by Roberts [10]. In the paper examples of several problems were used to illustrate some of the deficiencies in components constructed to code rules. These deficiencies fall into several major categories: (a) real-world failure modes that are not included in the Code design process, (b) permissiveness for fabrication practices that render the material more vulnerable to service failures, (c) unfavorable metallurgical changes which occur during service exposure, (d) operational modes that are more severe than anticipated, and (e) in-service environmental degradation

It is incumbent on the designer to recognize these Code limitations. In this sense, the Code does not cover all details of design and construction. Where complete details are not given, it is intended that the manufacturer, subject to acceptance of an Authorized Inspector, shall provide details of design and construction which will be safe as otherwise provided by the rules of the Code. As is stated explicitly in the Boiler and Pressure Vessel Code documents the Code is not a handbook and cannot replace education, experience, and the use of engineering judgment.

1.4 Report Organization

This document contains specific guidance on technical issues which need to be controlled, as far as is possible, to ensure that components manufactured from Grade 91 steel meet the minimum expectations of performance when constructed to ASME codes. It is recognized that many of the factors will be open for negotiation between the utility and suppliers. Thus, in some cases the information presented should be considered an aim for target rather than a formal specification since the guidelines are in some cases more stringent than current specifications and codes.

Information of the Guidelines is provided in Section 2. Where possible further technical detail related to key issues is provided in appropriate Appendices. These technical appendices represent the most recent information available at the time of publication. This may be subject to change based on new research and in particular pending completion of the EPRI creep strength enhanced ferritic program.

In the final Appendix a typical purchasing document is outlined showing how the guidelines may be interpreted to aid component purchase. This document is provided for illustration only.

Section 2: Purchasing Instructions

2.1 Introduction

This document represents requirements for Grade 91 steel. These requirements are considered necessary to ensure the satisfactory serviceability of any component fabricated using this grade of material. In general, the component should exhibit a uniform microstructure of tempered martensite. A typical photomicrograph showing a tempered martensitic microstructure is presented in Appendix A-1.

The Foreword of all ASME Code sections states that the "objective of the rules is to afford reasonably certain protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long, safe period of usefulness" [11]. This statement is an acknowledgement of the fact that no equipment lasts forever and that boilers do have a finite life. However, Section I disavows an intent for a specific design life and contents itself with construction that gives a "reasonably long, safe period of usefulness."

Section I's method of achieving safe boiler design is a relatively simple one and rests on four foundations as follows:

- Requires all those features considered necessary for safety (e.g., water gage glass, pressure gage, check valve, drain)
- Provides detailed rules governing the construction of the various components comprising the boiler, such as tubes, piping, headers, shells, and heads
- Generally limits the materials to those contained in the specifications in Section II, Parts A and B with the design allowable stresses as tabulated in Section II, Part D
- Requires certain tests and inspections with the involvement and approval of a third-party Authorized Inspector

Another factor that has had a direct bearing on the need for this document is the fact that the purchase of materials for use in ASME Code construction are controlled by material specifications that, for the most part, are contained in Section II, Parts A and B (base metals) and C (weld metals). These specifications are developed not by ASME but by the American Society for Testing Materials (ASTM), and ASME then adopts the ASTM specifications for its own use, making any modifications considered to be essential for safe operation of the equipment. By the nature of the consensus process, in which decisions are made

by volunteers representing a number of different interests, including the end user, the fabricator and the material producer, it often is difficult to incorporate into the material specification all requirements that would reflect the primary engineering interest of the end-user, which is to optimize the performance of the material. As such, it should be understood that, while adherence to all Code requirements governing use of a particular material will in most cases assure "adequate" performance of the material relative to the Code's objective of affording "reasonably certain protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long, safe period of usefulness," it is unlikely that the requirements contained in the ASME B&PV Code ever will be sufficiently comprehensive to insure optimum engineering performance of a material for a given application.

The subsections in this Chapter provide basic information which should be considered when purchasing Grade 91 material for Code-related construction. A final summary section is provided in the form of a checklist of issues.

2.2 Chemical Composition

The chemical composition should fall with the elemental restrictions specified in Table 2-1 to the extent that commercial conditions permit. Background information outlining the effects of individual elements on microstructure and properties is provided in Appendix A with a summary of transformation behavior presented in Appendix B.

The supplier must provide the actual Mill's Certified Material Test Report (CMTR) with the results of chemical analysis for each specific heat of steel to verify that the elemental composition of the heat is within the required range.

It is recommended that all raw Grade 91 heats be validated at fabricator's site using positive material identification (PMI) testing. An excellent background summary concerned with this form of testing is provided in reference 12. The primary basis for PMI is application of portable X-ray fluorescence (XRF). These XRF instruments are not capable of quantitative measurements for elements with an atomic number less than 22 (titanium). For example, portable XRF equipment will not measure Carbon, Nitrogen or Aluminum content so they cannot be utilized to calculate or even estimate N:Al ratio. When measurement of elements with a relatively low atomic number is required, optical emission spectrometers (OES) may be applied. OES instruments produce an electrical arc between the device and the work piece so the area for examination should be selected to minimize damage to critical surfaces.

In all cases PMI should be performed by trained staff using an approved procedure. This procedure should define factors such as the method of testing, acceptance criteria, calibration requirements, sampling plan, documentation etc.

It should be recognized that although PMI testing is sensitive enough to reliably identify material type, it does not provide sufficient accuracy to determine the full chemical composition for the purpose of confirming full compliance with the specification requirements. Furthermore, it must be emphasized that PMI does not ensure that the steel has been processed correctly and provides no information on properties.

It should be noted that, due to commercial conditions at the time the material is ordered, requirements imposed that are more restrictive than those contained in the ASME/ASTM material specification may prompt the producer to impose additional charges on the base material price, or may cause the producer to decline to bid on the order. In those cases, the additional costs should be weighed against the likely impact of a failure to meet the more restrictive compositional requirement on the long-term serviceability of the material. For example, failure to meet the minimum chromium content might have no more than a minor effect on serviceability for relatively thick-walled piping, but for tubing designed to operate near the limit of Grade 91's capability, the effect could be significant. It also should be noted that in some cases producers for commercial reasons will be reluctant to accept more restrictive compositional requirements, even though in their normal practice they satisfy the requirements. For that reason it is useful to ask the producer for information regarding his "typical" production chemistries to determine whether it is necessary to commercially enforce the more restrictive requirements for that producer.

Table 2-1
Recommended chemical composition requirements for component base material (product analysis). The requirements for selected ASME specifications are tabulated in Appendix A, Table A-1.

Elements	Composition Pipe (wt%)
Carbon [D]	0.08-0.12
Manganese	0.30-0.60
Phosphorus	0.020 (max.)
Sulfur	0.010 (max.)
Silicon	0.20 - 0.50
Chromium	8.00 [C] - 9.50
Molybdenum	0.85 -1.05
Vanadium	0.18 - 0.25
Columbium	0.06-0.10
Nitrogen [D]	0.035 [B] - 0.070
Nickel	0.20 [B] (max.)
Aluminum	0.020 [B] (max.)
Titanium	0.01 (max)

Table 2-1 (continued)
Recommended chemical composition requirements for component base material (product analysis). The requirements for selected ASME specifications are tabulated in Appendix A, Table A-1.

Elements	Composition Pipe (wt%)
Zirconium	0.01 (max)
Copper [A]	0.25 (max.)
Arsenic [A]	0.012 (max.)
Tin [A]	0.010 (max.)
Antimony [A]	0.003 (max.)
N/Al ratio	4.0 minimum

Notes:

[A] These elements are not required to be controlled by current ASME/ASTM specifications, but the values above should be considered target levels. The content of these elements should be reported on the MTR supplied with each heat of material. If not on the actual MTR then the elements should be reported in an accompanying document. In addition to consideration of the levels of individual elements it is good practice [13] to ensure that the following relationship holds sum of As +Sn +Sb +Pb <0.010

[B] Different from ASME, please see Appendix A.1.2

[C] For tubing ,the minimum Cr level should be 8.5%, please see Appendix A.1.3

[D] Carbon + Nitrogen > 0.12, please see Appendix A.1.4

2.3 Heat Treatment of Grade 91 Steel at the Mill

All forms of Grade 91 product, including plate, tubing and piping, shall be normalized within the temperature range of 1920-1975°F (1049-1079°C) and shall be tempered within the temperature range of 1350-1440°F (732-782°C). Because of the link between reductions in properties and lack of control during heat treatment it is important that the upper limits specified must not be exceeded, i.e. these limits should include any measurement tolerance. Background on Heat Treatment is provided in Appendix C.

For normalizing, once the full thickness of the product has reached the target normalizing temperature, the time at temperature should be a minimum of 10 minutes. Care must be taken to insure that whole volume of product is allowed to cool uniformly. Cooling shall be continuous down to at least 200°F (93°C) or lower throughout the material thickness before tempering. The rate of cooling through the temperature range 1650-900°F (899- 482°C) shall be controlled to be no slower than 9°F/min. (5°C/min.) (See cooling rate diagrams in Appendix A). For product with a thickness greater than 3” (76 mm), forced air-cooling or oil quenching or the equivalent from the normalizing temperature to an internal work piece temperature below 200°F (93°C) may be necessary to achieve a fully martensitic structure.

For tempering, the temperature selected and the time at the tempering temperature shall be sufficient to satisfy the specified hardness requirement. The product may be cooled in still air from the tempering temperature, so long as excessive distortion or excessive thermal stress is avoided, or, as an alternative, where expedient, furnace cooling is acceptable provided the cooling rate exceeds 100°F (56°C)/hr until the internal temperature is below 1200°F (650°C).

Heat treatment equipment must be properly calibrated, and the producer must furnish evidence of the calibration for review prior to the beginning of any heat treatment on Grade 91 steel. Furnaces should be regularly surveyed for temperature uniformity throughout the work zone. The purchaser should request to see and review documentation of equipment calibration and temperature surveys prior to any heat treatment operations on Grade 91 steel.

For furnaces, including gas fired furnaces; the heat treatment supplier should demonstrate that

- The thermocouples which are used to control the temperature can be maintained within ±5°F (±3°C) of the target temperature.
- The largest variation in temperature between any two points in the work zone of the furnace (the volume holding the components) does not exceed 40°F (22°C) above the intended temperature. This shall be demonstrated by placing thermocouples on metal samples that are placed in the furnace so that the temperatures in the work zone are accurately indicated.

For resistance-type heaters, the heat treatment supplier should demonstrate that the temperature at the control thermocouple can be maintained within ±5°F (±3°C) of the target temperature. The heat treatment supplier should demonstrate that for a given component the temperature is controlled within the specified temperature range through placement of properly installed thermocouples at a sufficient number of locations along the length and around the circumference of tubular-shaped components, or along the length and across the width of flat components [14]. For piping, the pattern of thermocouple placement recommended in AWS D10.10 is a useful guide and should be followed as a minimum standard wherever possible. For other types of heating, such as induction heating, the heat treatment supplier must demonstrate the ability to maintain the temperature at all points on the component being heat treated within the required temperature range for the appropriate amount of time. The device and parameters for induction heating must be established in such way to insure that the components can be heated uniformly through the thickness of all parts and be held at the target temperature for a sufficient length of time.

If multiple components are to be processed as part of a single heat treatment cycle, all pieces must be properly separated to avoid non-uniform heating and cooling, particularly during the normalizing heat treatment. Suppliers shall provide a detailed heat treatment procedure and record for each product purchased, if required.

2.4 Hardness

It should be emphasized that although measurement of hardness does not provide a single unambiguous indication of long term creep strength hardness, measurements are an important tool in checking the quality of Grade 91 steel. In all cases care should be taken to use methods which give a meaningful result for the actual hardness of the component. Background information regarding measurement of component hardness is given in Appendix D.

It should also be appreciated that component properties may be modified following all thermal treatments. Therefore, checking hardness at each stage of fabrication and installation is considered essential good practice.

The final (that is after all fabrication and heat treatment but prior to service) hardness values of a component base metal and the weld metal should be in the range of 190 HB/200 HV (93.4 HRB) - 250HB/263HV (24.2 HRC). For components subject to multiple PWHT or tempering treatments it is typically the case that hardness will be reduced following each heat treatment. Thus, to achieve the desired minimum level of hardness after all fabrication stages have been completed, the initial component hardness will need to be higher than 190 HB (200HV).

It should further be appreciated that in most cases the hardness of Grade 91 components will decrease during service. The changes which occur will be related to the initial composition, heat treatment as well as in-service operation. Thus, the above guidelines should not be applied to a component after a period of operation.

Weldments that are normalized and tempered should meet the same hardness requirement specified above in this paragraph for the base material. For weldments that receive only a sub-critical PWHT, the weld metal hardness after heat treatment should not exceed 280HB. Local regions in the HAZ of a weldment following subcritical PWHT may show hardness values below the recommended minimum due to the positioning of the indenter or the hardness test probe within the fine-grained/inter-critical region of the HAZ. This level of hardness in the so-called Type IV region of the HAZ occurs because of the local thermal effects from welding and is unavoidable – therefore, it should not be a basis for rejection of the weldment.

It should be noted that standard hardness conversion tables are available in ASTM E 140. However, the hardness conversion tables that show the Brinell and Vickers Hardness numbers to be identical within the range of 180-250 should not be used. Conversion should be performed using the equation developed in the EPRI life management project [15].

In all cases, the hardness measuring equipment shall be properly calibrated before testing, and the test surface shall be prepared to a finish that will optimize test accuracy for the particular instrument being used. It should be recognized that even with well trained operators, properly calibrated equipment and an

established procedure there will be some scatter in the data recorded. EPRI will be publishing a report detailing issues associated with hardness measurements and data calibration [15].

2.4.1 Cold Formed Components

In cases where Grade 91 material will be cold-formed (defined as strain introduced at a temperature of below 1300°F, 705°C) to levels of strain exceeding 15%, the maximum acceptable as-supplied hardness of the T91 material should be reduced to 230 HB/242 HV (20.8 HRC/98.4HRB). This level of hardness is necessary to minimize the risk of low-ductility fracture during forming.

Background information regarding issues associated with cold bending is presented in ASME Section 1, PG-20; with a summary of the issues presented in Appendix E. Information on stress corrosion cracking is described in Appendix F.

2.5 Mechanical Properties

The room temperature mechanical properties of the as-supplied base material shall meet the following limits:

Tensile Strength: 90 - 120 ksi (620 – 830 MPa)

For materials which will be used to manufacture cold formed bends the upper strength limit should be reduced, thus the strength range for cold forming is 90 to 109 ksi (620 to 751 MPa).

All other mechanical properties shall be as indicated in the applicable material specification of Section II, Part A of ASME Boiler & Pressure Vessel Code.

2.6 Welding Practices

Background information regarding welding and associated temperature control of Grade 91 steel is given in Appendix G.

2.6.1 Preheat and Interpass Temperature

For welds made:

- Using the shielded metal arc process (SMAW), the flux-cored process (FCAW), or the submerged-arc process (SAW), in a highly restrained component, a minimum pre-heat temperature of 400°F (205°C) shall be maintained. In a tube-to-tube butt weld, the minimum pre-heat is 300°F (150°C).
- Using either the gas metal arc process (GMAW) or the gas tungsten arc process (GTAW) with a solid wire filler metal, a minimum preheat temperature of 300°F (150°C) shall be maintained until the welding is complete.

- Using either GMAW or GTAW with a filler metal other than solid wire (i.e. metal-cored or flux-cored), a minimum preheat temperature of 400˚F (205˚C) shall be maintained. An exception to this rule shall apply for welds that effectively are self-preheating, that is, welds involving a relatively small heat sink in comparison to the magnitude of the arc energy or heat input and that are continuously deposited such that the entire weld nugget and base metal Heat-Affected-Zone (HAZ) remains above the specified minimum preheat level throughout the weld cycle.

If welding is interrupted, preheat temperature must be maintained. Although not a recommended practice, if the joint temperature drops below preheat temperature, the interrupted welds must be: 1) at least one third of the final through wall thickness of the component, 2) given a hydrogen bake before slow cooling to room temperature, and 3) kept dry until the welding is re-started with the proper preheat. These precautions are necessary because in the as-welded condition the joint is vulnerable to stress-corrosion cracking (see Appendix F for additional information).

The maximum interpass temperature during welding shall be 700˚F (370˚C).

2.6.2 Hydrogen Bake

Following welding if there is a need for the temperature of the weld to be dropped to room temperature prior to the implementation of the post-weld heat treatment, then to control the amount of diffusible hydrogen present in the weldments, a hydrogen bake should be performed. The hydrogen bake involves holding in the temperature range of 500-750˚F (260-400˚C) for 1 hour minimum for thicknesses of 1 inch or less and two hours for thicknesses greater than 1 inch.

Prior to the beginning of the hydrogen bake, the temperature throughout the weld zone should be reduced to below 375˚F [190˚C] where the (Ni+Mn) content of the filler metal is less than 1.2% or where the weld was made using the GTAW process and the (Ni+Mn) content is below 1.5%. Where the (Ni+Mn) content is greater than 1.2% for all welding processes other than GTAW the temperature throughout the weld zone should be reduced to below 200˚F [95˚C] before raising the temperature for the hydrogen bake.

2.6.3 Post-Weld Heat Treatment

Following completion of welding, the temperature of the component should be reduced below 375˚F (190˚C) in cases where the Ni + Mn content of the weld filler metal is less than 1.2%. In cases where the Ni + Mn content is greater than 1.2%, the temperature of the component should be reduced below 200˚F (95˚C).

This should be the temperature at the center of the component wall to insure complete austenite transformation to martensite. The component should then be post-weld heat-treated within 8 hours of the completion of welding. If this is not possible, either

- The component should be maintained at a minimum temperature of 175°F.
- The humidity of the environment in which the weld is stored should be controlled to guarantee that no condensation can occur at any time (e.g., due to changes in temperature) on either the OD or ID surfaces of the joint until the post-weld heat treatment can be initiated.

An agreement between client and contractor should be established on the best practice to minimize the risk of stress-corrosion cracking occurring on any Grade 91 components (see Appendix F for more information).

The post-weld heat treatment should be performed within the range of 1350 - 1420°F (730 - 770°C). The maximum temperature at any point in the PWHT process should not exceed 1420°F (770°C). Information on control of the PWHT within the defined limits is provided in Appendix C. The temperature and time at temperature for the post-weld heat treatment should be selected to insure that the hardness at all locations in the area heated is within the specified range.

No additional limits on the rate of heat-up or cool-down are specified for PWHT. However, for thick-walled components, or for assemblies of complex shape, an appropriate rate of heat-up or cool-down, as determined by experienced engineering judgment, should be adopted to minimize distortion and residual stresses.

Note: Prior to the application of the PWHT to Grade 91 welds, the weld metal and portions of the heat-affected zone are vulnerable to brittle fracture if subjected to abnormally high mechanical loads during handling. Care shall be taken, therefore, in the handling of Grade 91 weldments in the as-welded condition to minimize the risk.

2.6.4 Filler Materials

2.6.4.1 Matching Filler

Matching filler materials that have similar chemistry and strength to the base metal should be used for all joints between Grade 91 materials. In so far as it is possible, the chemical composition of the matching filler metal shall conform to the following elemental restrictions specified in Table 2-2.

Table 2-2
Recommended chemical composition requirements for Grade 91 matching filler materials

Elements	ASME SFA 5.5:2008 E901X-B9	ASME SFA 5.28:2008 ER90S-B9	ASME SFA 5.23:2007 EB9	ASME SFA 5.29:2008 E9XT1-B9
(wt%)	SMAW Electrodes	GMAW/ GTAW Bare, Solid Electrodes/ Rods	SAW (Weld Deposit wire/flux combination)	FCAW Electrodes
C	0.08-0.13	0.07-0.13	0.08 - 0.13	0.08-0.13
Mn	1.20 (0.70 - 1.20)	1.20 (0.70 - 1.20)	1.20 (0.70 - 1.20)	1.20 (0.70 - 1.20)
Si	0.30	0.15 - 0.50	0.08	0.50
P	0.010	0.010	0.010	0.020 (0.10)
S	0.010	0.010	0.010	0.015
Ni	0.80	0.80	0.80	0.80
Cr	8.0 - 10.5 (8.5-9.5)	8.0 - 10.5 (8.5-9.5)	8.0 - 10.5 (8.5-9.5)	8.0 - 10.5 (8.5-9.5)
Mo	0.85 - 1.20	0.85 - 1.20	0.85 - 1.20	0.85 - 1.20
V	0.15 - 0.30	0.15 - 0.30	0.15 - 0.25	0.15 - 0.30
Cu	0.25	0.20	0.25	0.25
Al	0.04 (0.02)	0.04 (0.02)	0.04 (0.02)	0.04 (0.02)
Cb	0.02-0.10	0.02 - 0.10	0.02 - 0.10	0.02 - 0.10
N	0.02 - 0.07 (0.04 - 0.07)	0.03 - 0.07 (0.04 - 0.07)	0.02 - 0.07 (0.04 - 0.07)	0.02 - 0.07 (0.04 - 0.07) (0.04 - 0.07)
Mn + Ni	1.50 (1.00)	1.50 (1.00)	1.50 (1.00)	1.50
Ti	–	(0.01)		–
Co	–	(0.05)		–
B	–	(0.001)		–
W		(0.20)		–
As	–	(0.010)		(0.010)

Table 2-2 (continued)
Recommended chemical composition requirements for Grade 91 matching filler materials

Elements	ASME SFA 5.5:2008 E901X-B9	ASME SFA 5.28:2008 ER90S-B9	ASME SFA 5.23:2007 EB9	ASME SFA 5.29:2008 E9XT1-B9
Sn		(0.005)		(0.005)
Sb	–	(0.003)		(0.003)
O	–	(0.005)		–

Notes:

A. Elements expressed as a single value represent the maximum allowed content with no lower minimum limit.

B. Ranges or limits expressed without parenthetical ( ) references are the ranges / limits specified by the applicable ASME SFA Specification. Ranges or limits within parenthesis are recommended ranges / limits.

C. Restrictions on the following elements are recommended for the following reasons:

C1.Cr limits: Specifying a higher minimum content than the SFA Specification may be desirable in tubing products where fire-side corrosion or steam side oxidation may be a concern. Specifying a lower maximum content than called for by the SFA Specification may be desirable to help minimize the potential for formation of delta ferrite during weld metal solidification.

C2.Mn lower limit: Specifying a minimum limit will help ensure adequate strength and toughness can be achieved in the weld deposit. The Mn to S ratio should be greater than 50 to prevent crater cracking.

C3. If it is not possible to obtain filler material that meets the indicated compositional limits for a particular application, then, as a minimum, the ratio of nitrogen-to-aluminum (N/Al) should be at-least 4.

D Control of P, S and trace elements is prudent to avoid problems with low toughness [13]. It is desirable that the cumulative influence of these elements as indicated by the 'X" factor is controlled as follows:

$10P + 5Sb + 4Sn + As = X < 15$

It should be noted that these specifications represent compositions (which in certain respects are more stringent than ASME and AWS specifications). The purpose of the more restrictive requirements is to optimize the elevated temperature strength and performance of the weld metal, and these requirements should be followed where the suppliers are willing to provide them at no significant increase in cost. If it is not possible to obtain filler material that meets the indicated compositional limits for a particular application, then, as a minimum, the (Ni+Mn) content should not exceed 1.2, and the ratio of nitrogen-to-aluminum (N/Al) should be at least 4.

2.6.4.2 Under-Matching Filler

Under-matching filler materials are those that have weaker tensile and/or creep strength than Grade 91 steel. Examples include EXX18-B3 and ERXXS-B3. These fillers may be used for transition joints between Grade 91 and lower alloy steel materials when sufficient thickness of the filler metal and a proper joint design accommodate issues associated with the design allowable stresses at the joint.

2.6.4.3 Ni-Base Filler

Nickel-based filler metals may be used for welding dissimilar metal joints in Grade 91 steels. For example, when transitioning from Grade 91 steel to austenitic stainless steels. Examples of nickel-based filler materials include Weld Alloy 82 (ERNiCr-3), Weld Alloy 182 (ENiCrFe3) and EPRI P87.

These fillers are generally considered inappropriate for welding Grade 91 to Grade 91 due to increased filler metal cost and inspection difficulty.

2.6.4.4 Precautions with Usage of Electrodes

The following precautions should be implemented to minimize the risk of weld-related cracking and defects due to improper handling and/or storage of weld filer materials.

a. All SMAW electrodes to be used in the welding of Grade 91 components should be issued from a heated master storage bin to field ovens, where they will be maintained until they are removed for immediate usage. Unused electrodes left outside of the rod ovens for more than 4 hours either should be re-baked in accordance with the manufacturer's recommendations to minimize any moisture absorbed into the coating during the period of exposure or they should be discarded.

b. All SMAW electrodes should be certified to the H4 designation.

c. Welding wires, including solid wires and cored wires, should not be removed from the packing material until ready for use. If welding is interrupted for more than twenty-four (24) hours, the reel either should be stored in a container heated to a minimum temperature of 175°F, or discarded.

2.7 Forging and Forming

Grade 91 steel attains the required elevated temperature strength through control of composition and fabrication. All processes or actions that involve working or heating can potentially have an adverse affect on the properties of the material. Both hot and cold forming practices must be carefully controlled.

For all products made from a solid forging, the cross-sectional area of the solid forging shall have a reduction by forging from that of the ingot in the ratio of not less than 3:1.

2.7.1 Hot Pressing (Squeezing and Sizing) and Hot Bending

After all hot pressing or hot bending operations the entire component shall be normalized and tempered in accordance with Section: 2.3 "Heat Treatment of Grade 91 steel at the Mill."

2.7.2 Hot Adjustments to Shape

Hot drawing or hot adjustment is carried out for short periods of time at temperatures between 1300˚F (705˚C) and 1450˚F (790˚C). No heat treatment is required after these operations. If the 1450˚F (790˚C) limit is exceeded during the forming operation, then a full normalize and temper of the entire component should be performed in order to restore the full serviceability of the overheated zone. In the event that the size of the component is such that a complete renormalization is not possible, then the affected material should be removed and either should be re-normalized and tempered to restore properties or should be replaced.

Note: There have been numerous service-failures associated with the improper application of these hot adjustment techniques. It is this experience which underscores the fact that precise control of the peak temperature is necessary if these methods are to be applied successfully. Therefore, these procedures should be allowed only where an approved procedure is followed.

2.7.3 Cold Press (Swaging, Pointing, Squeezing and Sizing)

Any component subjected to cold forming, such as swaging, pointing, squeezing and sizing that is designed to operate at a metal temperature greater than 1050˚F (565˚C) should be given a full normalize and temper in accordance with Section: 2.3 "Heat Treatment of Grade 91 steel at the Mill."

2.7.4 Cold Bending

If the ratio of the radius of the bend (R) to the outer diameter of the tubing (D), R/D, is greater than or equal to 4, then no post-forming heat treatment is required. If R/D is greater than or equal to 2.5, but less than 4, the bend region may be heat treated within the temperature range of 1350-1420˚F (730-770˚C) for 30 minutes minimum to reduce the hardness of the cold-formed region and thereby minimize the risk of SCC. If R/D is less than 2.5, then the entire component should be normalized and tempered in accordance with Section: 2.3 "Heat Treatment of Grade 91 steel at the Mill."

2.7.5 Hot Forming of Fitting and Special Products

After hot forming of any fittings or special products, a normalizing and tempering treatment of the entire component should be performed in accordance with Section: 2.3 "Heat Treatment of Grade 91 steel at the Mill."

2.8 Surface Condition

During fabrication of components from Grade 91 steel, when weld repair of surface imperfections, such as grinding marks, arc strikes, etc. is conducted, as permitted in the applicable engineering code, then a post-weld heat treatment must be applied in accordance with the provisions of sub-section 2.3.2 of the "Welding Practices" section.

Note that with respect to repair welds, it is recommended that instructions be included in the purchasing requirements that specify that the weld filler metal used by the producer for repair welding conform to the requirements of Section 2.6.4.1 of this document.

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Appendix A: Background on Composition

A.1 Introduction

The different ASME and International Codes differ in some of the detail regarding specified chemical composition. These differences are illustrated with reference to ASME codes in Table A-1. This table also illustrates the fact that there can be differences in specification between the heat analysis and the actual component composition.

Table A-1
Chemical composition requirements for base material for selected ASME documents

Elements	ASME SA 335	ASME SA 336	ASME SA 387 Plate	
	Pipe (wt%)	Forging	Heat analysis	Product analysis
Carbon	0.08-0.12	0.08-0.12	0.08-0.12	0.06-0.15
Manganese	0.30-0.60	0.30-0.60	0.30-0.60	0.25-0.66
Phosphorus	0.020 (max.)	0.025 (max.)	0.020 (max.)	0.025 (max.)
Sulfur	0.010 (max.)	0.025 (max.)	0.010 (max.)	0.012 (max.)
Silicon	0.20-0.50	0.20-0.50	0.20-0.50	0.18-0.56
Chromium	8.0 -9.50	8.0 -9.50	8.0 -9.50	7.90 -9.60
Molybdenum	0.85-1.05	0.85-1.05	0.85-1.05	0.80-1.10
Vanadium	0.18-0.25	0.18-0.25	0.18-0.25	0.16-0.27
Columbium	0.06-0.10	0.06-0.10	0.06-0.10	0.05-0.11
Nitrogen	0.030 -0.070	0.030 -0.070	0.030 -0.070	0.025 -0.080
Nickel	0.40 (max.)	0.40 (max.)	0.40 (max.)	0.43 (max.)
Aluminum	0.02 (max.)	0.02 (max.)	0.02 (max.)	0.02 (max.)
Titanium	0.01(max)	0.01(max)	0.01(max)	0.01(max)
Zirconium	0.01 (max)	0.01 (max)	0.01 (max)	0.01 (max)
Copper*				

Note 1 The specification for seam welded pipe SA 691 requires that the plate used is produced to SA 387 with a maximum hardness of 241HB

Note 2 The original SA387 specification limited Al to 0.04%max in the heat but 0.05%max in the component

The composition range for the major elements within the specification is intended to give a martensitic microstructure on cooling from normalization temperature. Because martensite is relatively hard and brittle the tempering heat treatment that is essential for Grade 91 material acts to improve the ductility of the material and reduce residual stresses present prior to service. Equally important, however, is the fact that during the tempering heat treatment the temper-resistant carbides and carbo-nitrides that stabilize the alloy during high temperature service are formed. The desired microstructure for Grade 91 components, therefore, is tempered martensite with a fully developed network of $M_{23}C_6$ carbides and MX-type carbo-nitrides that precipitate on lath boundaries and other defect sites in the sub-structure [1]. Typical photomicrographs of a properly processed tempered martensitic microstructure are shown in Figure A-1; note, however, that at the magnifications shown, the precipitate network that is essential to the development of the superior creep strength of Grade 91 material cannot be seen.

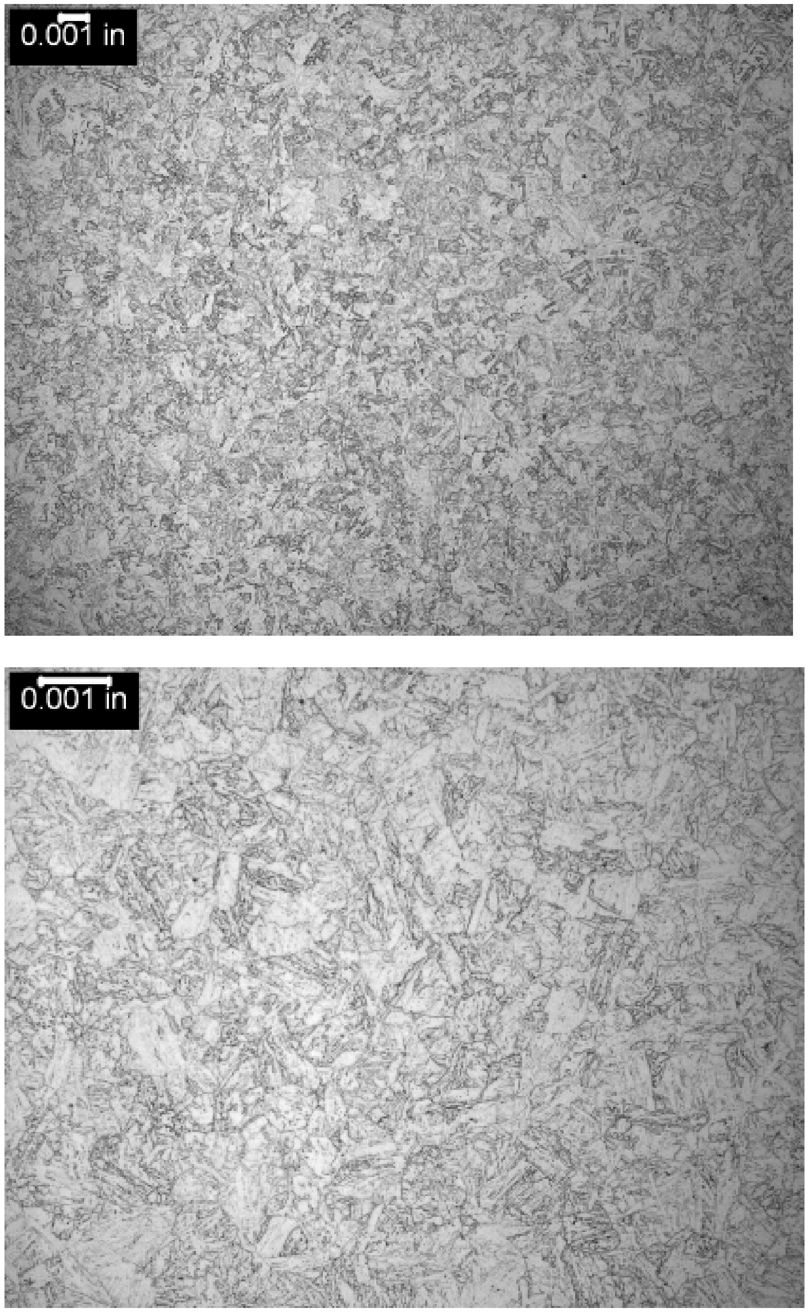

Figure A-1
Typical microstructures of tempered martensite in Grade 91 steel

Background on composition and cooling rate conditions required to produce martensite is summarized in a cooling rate diagram, a typical diagram is shown in Figure A-2.

Chemical composition (%)	C	Si	Mn	P	S	N	Al	Cr	Ni	Mo	V	Nb
	0.11	0.32	0.47	0.014	0.0030	0.038	0.018	8.50	0.13	0.85	0.22	0.076

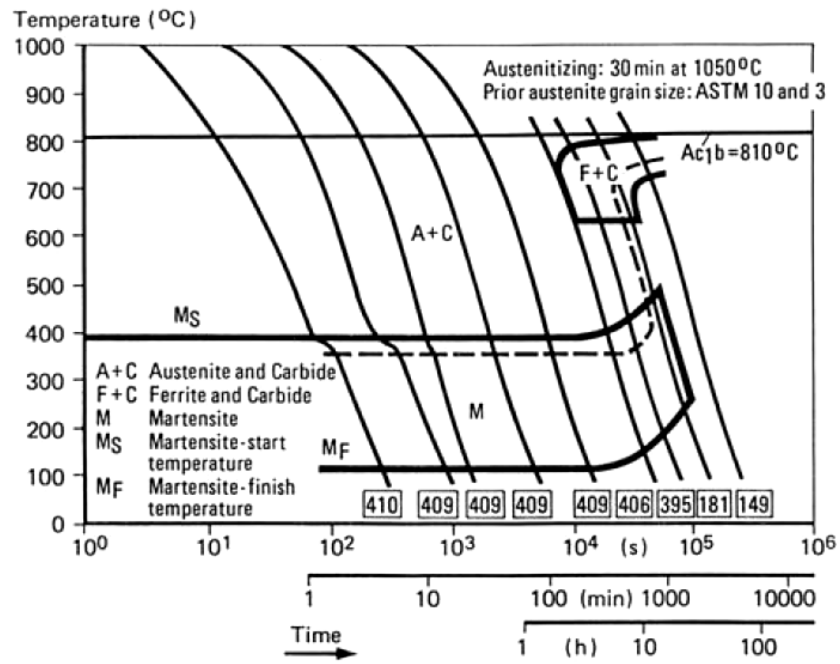

Figure A-2
Influence of cooling rate on the transformation behavior and hardness of Grade 91 steel [16]

A.2 Restriction on Aluminum Content (N/Al Ratio)

The modifications that were made to the standard 9Cr-1Mo steel to create Grade 91 included controlled additions of vanadium, columbium (niobium), and nitrogen. The mechanism of enhanced creep strength for Grade 91 is the precipitation of vanadium/columbium rich carbonitrides of type MX (where M=Cb or V and X=C or N) at defect sites and lath boundaries in the martensitic base structure. De-oxidizers, particularly aluminum, are commonly added during the melting process to remove oxygen from the melt. Since Aluminum also has a stronger tendency to combine with Nitrogen than do vanadium or columbium, high levels of Aluminum will reduce the amount of free nitrogen available to form the carbo-nitrides precipitates that support the long-term creep strength of the alloy. Since it is difficult to increase the amount of nitrogen in the molten alloy, the primary option to insure adequate free nitrogen is to limit the amount of aluminum and other de-oxidizers that can be added to melt. The target ratio for nitrogen-to-aluminum (N/Al) should be 4 or greater, and under no circumstances should a ratio of less than 2.0 be accepted.

Since the levels of Al and N are critical it is recommended that particular care is exercised in measuring these elements. For example, it is recommended that aluminum content be analyzed using Optical Emission Spectroscopy (OES) and nitrogen content be determined using a LECO Oxygen and Nitrogen Determinator. However, other analysis methodologies, such as "standard" solution method or microwave digestion method are acceptable so long as accurate calibration of the procedure is maintained and sufficient accuracy can be demonstrated. Brett, S. J. [17] studied the soluble Al content of a number heats of Grade 91 material using three analysis techniques, including a "standard" solution method (soluble), a microwave digestion method (MDM) and optical emission spectroscopy (OES), the results are shown in Figure A-3. As can be seen, the measured Al contents are in good agreement when comparing the standard soluble method and the OES method. It appears that OES, as the most convenient way of measuring Al content, gives near soluble Al levels as measured by the standard "solution" technique.

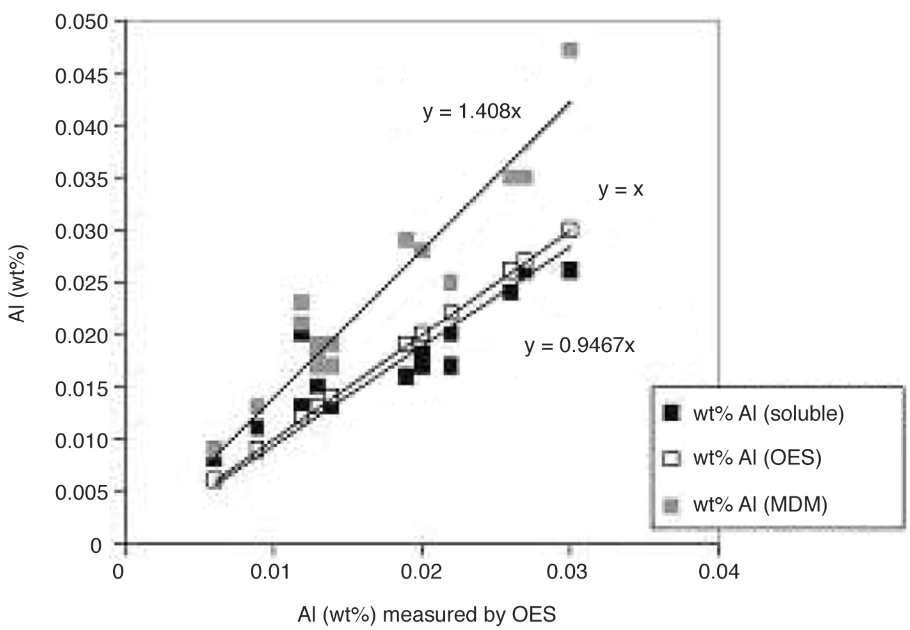

Figure A-3
Relationship between aluminum levels measured by three different analysis methods [17]

A.3 Chromium Content

The ASTM/ASME specifications for Grade 91 steel typically allow a range in chromium content of between 8.0 and 9.5%, Table A-1. Because of the cost of chromium, suppliers generally select chromium content at the lower end of the specification. Some tubing has been found in the field with chromium content below the specification limit. Although more of a concern for tubing and other thin-walled components than for thicker-walled headers and piping, the effects of both fireside corrosion and steam-side oxidation may be influenced by the chromium content within the specification range. Additionally, scale growth

during normalization may be reduced with higher levels of chromium. The lower transformation temperature is also affected by chromium content. Higher levels of chromium will raise the lower transformation temperature (A_1) and provide additional margin for PWHT without adverse microstructural changes. Until there is a better understanding of the sensitivity of the alloy's oxidation behavior to chromium content, the minimum chromium content for Grade 91 material, and particularly Grade 91 tubing, should be set at approximately 8.5%. It should be recognized that this will require some producers to modify their formulations for the alloy in order to avoid the formation of delta (δ) ferrite, which can reduce creep rupture strength. Elevated levels of chromium may have an adverse affect on delta ferrite which is covered in the next section.

A.4 Delta Ferrite

Elevated levels of chromium and other elements may increase the likelihood of the formation of delta ferrite. The presence of delta ferrite in Grade 91 may lower the material's creep-rupture strength. All Grade 91 products should therefore exhibit a fully tempered martensite microstructure that is free of delta ferrite [1].

The likelihood of delta ferrite formation can be estimated using the Chromium-Nickel Balance formula (CNB) using an equation developed by Combustion Engineering based on a modification to the work of Newhouse et al. [18] , as follows:

$$CNB = (Cr + 6Si + 4Mo + 1.5W + 11V + 5Cb + 9Ti + 12Al) - (40C + 30N + 4Ni + 2Mn + 1Cu)$$

To avoid the formation of delta ferrite, the CNB value of Grade 91 heats should be less than 10, above 12 delta ferrite is usually present and between 10 and 12 the outcome is dependent on the specific composition. Recognizing that the composition in commercial specifications does not necessarily assure a single phase martensitic microstructure, it is prudent for the alloy producer to work to a more restrictive range. One such range was suggested by ORNL [1] and a slight modification to their recommendation is contained in Table A-2 [19]. The current EPRI recommended procurement specifications for Grade 91 places restrictions similar to those suggested by ORNL to control the CNB and residual element content. The "target" composition will result in a CNB between 9.4 and 10.2.

Table A-2
Target Composition for Grade 91 steel recommended by ORNL

Element	ORNL Target	Element	ORNL Target
Carbon	0.10	Nitrogen	0.05
Manganese	0.40	Aluminium	<0.02
Silicon	0.20	Copper	<0.10
Phosphors	<0.10	Titanium	<0.005
Sulfur	<0.10	Boron	<0.001
Chromium	8.5	Tungsten	<0.01
Molybdenum	0.95	Zirconium	<0.01
Vanadium	0.21	Oxygen	<0.01
Nickel	<0.10	Antimony	<0.001
Niobium (Colubium)	0.08	Tin	<0.001

A graphical representation of the above CNB equation is shown in Figure A-4 where the elements which favor ferrite, called the chromium equivalent, are shown on the abscissa (x) and the elements which reduce the risk of ferrite, called the nickel equivalent, are shown on the ordinate (y). Several of the 9-12Cr alloys, including Grade 91, are represented by rectangular boxes. The two diagonal lines identified as "No Ferrite" and "Significant Ferrite" are for a CNB of 10 and 12, respectively.

A limitation of the modified Newhouse diagram in Figure A-4 is that the full expanse of possible phases is not encompassed; notably "austenite plus martensite" and "austenite plus martensite plus ferrite" are not represented. This limitation is overcome in the Schaeffler diagram as modified by Schneider [20, 21] and represented in Figure A-5. Again the need to control alloy composition to achieve a fully martensitic structure is emphasized. Creep testing has shown that when non Martensitic microstructure is present the creep strength is significantly reduced.

Based on review of a large numbers of heats it has been suggested that in the absence of a comprehensive analysis it appears that the steel should be free of delta ferrite when the sum of (C+N)> 0.12. Data developed by ORNL is shown in Figure A-6.

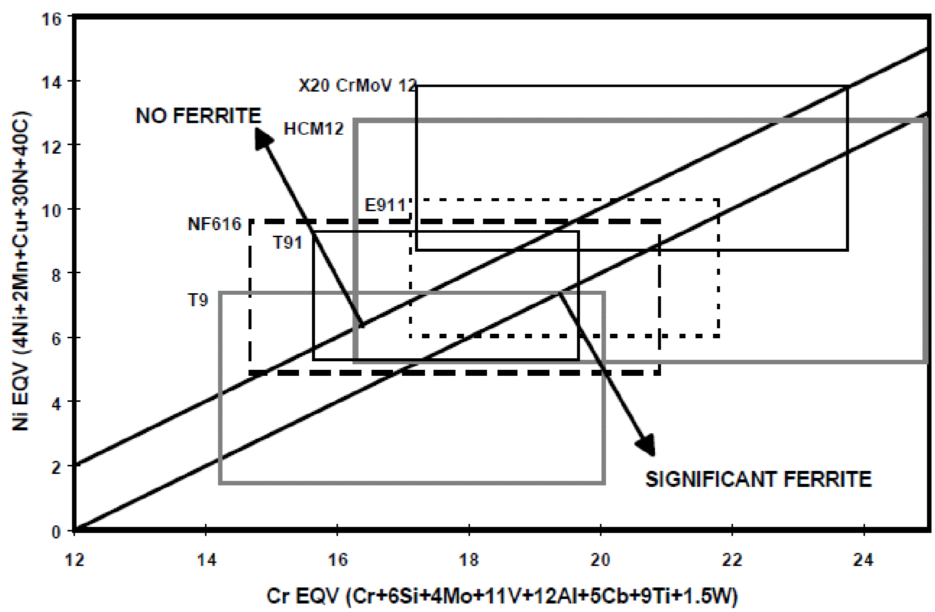

Figure A-4
Modified Newhouse diagram illustrating zones where Ni equivalent and Cr equivalent values are expected to result in the presence of ferrite in selected steels which aim to be martensitic

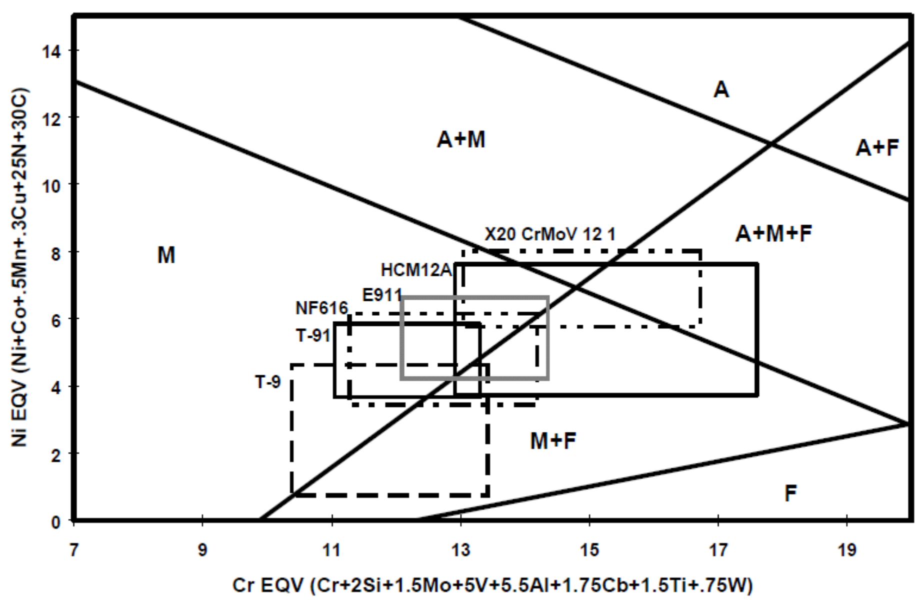

Figure A-5
Modified Shaeffler diagram showing how the expected presence of martensite, ferrite and austenite changes with Ni equivalent and Cr equivalent for selected CSEF steels

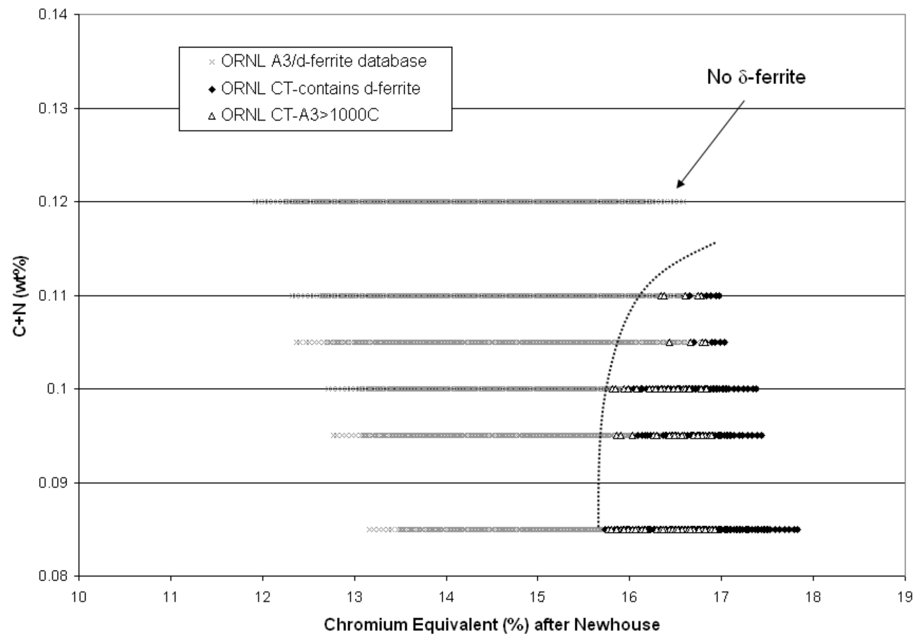

Figure A-6
Results showing that no delta ferrite was formed in Grade 91 type compositions for C + N levels of 0.12 wt % [22]

A.5 The Influence of Nickel

There is a general belief that Nickel in Grade 91 steel is required to improve the toughness of the alloy. There does not appear to be definitive evidence for this influence. Indeed, the majority of the development work which was performed examining compositional effects on the performance of 91 type steel was evaluated for steel with compositions where the Ni level was less than 0.2%. The nickel content was deliberately controlled to this low level because of concern regarding nickel's demonstrated influence on the acceleration of the coarsening of precipitates. Thus, it was recommended that the level of Ni in commercial steel should be minimized at least below the level of 0.2%.

Interestingly in a separate study it was shown that as the Ni level increased the creep strength decreased. A review distributed in 1993 [23] demonstrated this effect when considering the creep rupture strength in laboratory tests at 650°C (1202°F). Recently, this trend has been reinforced when considering the reduction in creep rupture strength at 600°C (1112°F), Figure A-7 [24].

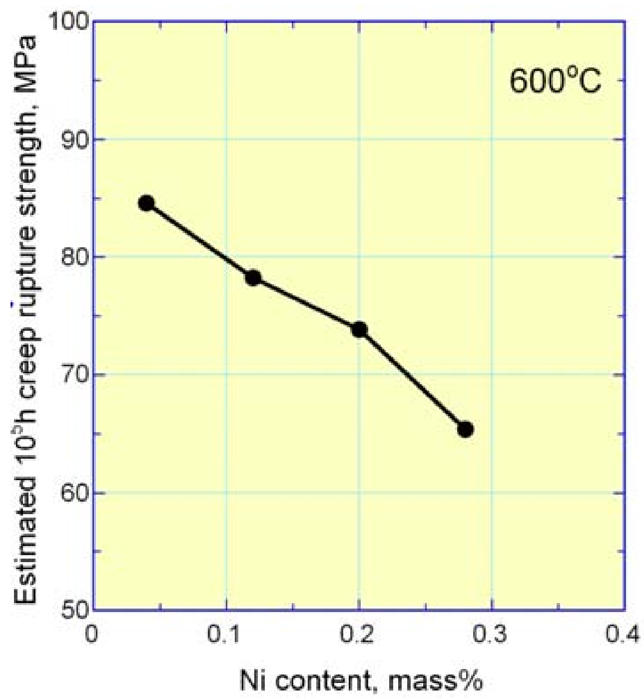

Figure A-7
The effect of nickel content on the 100,000 hour creep rupture strength at 600°C (1112°F) of Grade 91 steel [24]

In summary, there appear to be several reasons why the level of Ni in Grade 91 type steel should be below 0.2 wt%. These are due to:

- The influence of Ni on transformation behavior, as Ni increases the transformation decreases.
- The fact that as Ni increases, the resistance to tempering and the stability of the carbo – nitrides present decreases, these changes lead to a reduction in long term creep strength.

A.6 Trace Elements

The influence of trace elements has been widely studied on many of the steels used in power boiler and turbine components. Indeed, clear evidence that elements such as As, Sb, Sn, Pb and Cu can be deleterious to properties has been documented in many of the steels used today. Because of the potential problems from trace elements, the steels examined during the development of Grade 91 and other CSEF steels were almost exclusively manufactured from specialist 'pure' steel. Thus, there is presently no direct evidence linking trace elements to reductions in creep strength or toughness. Because direct evidence has not been presented many of the specifications do not require that these elements are reported. It is apparent that the lack of identifying specific values is due to the lack of direct data rather than the belief that the so – called "trace elements" do not cause problems.

As steel making typically involves the remelting of scrap there is the very real risk that steel can be produced with high levels of what are considered to be contaminants. For example, tin is used for corrosion protection on the inner surface of steel cans, if this tin is not removed prior to steel making the tin will enter the alloy and it is not removed during conventional refining. As greater amounts of steel are recycled it follows that the risk of finding trace elements in engineering alloys increases. It is recommended that, even though the specifications do not presently define safe levels of these elements, the purchase of Grade 91 is linked to the target compositional values provided in Table 2-1.

The embrittlement resulting from trace elements [25, 26] can also be linked to some of the primary alloying elements, notably Mn, Si and Ni. This influence has been studied in several low alloy piping and rotor steels and the effects can be illustrated by the following relationships [13]. Following exposure at elevated temperatures it was shown that the increase in embrittlement as measured by Charpy tests could be rationalized when the levels of Mn + Si present were plotted against an X Factor. This factor was given by the expression:

$$X = \frac{10P + 5Sb + 4Sn + As}{100} \qquad \text{Equation A.1}$$

Where the value for each element is the composition expressed as ppm. Thus, this work identified the fact that embrittlement was influenced by alloying and impurity elements. A further expression for an embrittlement factor which attempts to utilize the X parameter in combination with the influences of alloying elements has been suggested. An embrittlement factor, EF has been described as:

$$EF = \%SI + \%Mn + \%Cu + \%Ni \times X \qquad \text{Equation A.2}$$

Appendix B: Transformation Behavior

B.1 Lower Critical (A1) Temperature

One of the major issues related to improper heat treatment of Grade 91 material is an accurate determination of the lower critical transformation temperature. There has been extensive discussion of this issue in the technical literature related to Grade 91, and for the purposes of controlling heat treatment processes it is important to understand which of the transformation temperatures actually is of concern. As indicated below, in discussions of the transformation responses of steels during any type of thermal processing, a distinction is made between a theoretical transformation temperature that would apply under conditions of perfect equilibrium (i.e., an infinitely slow rate of heating or cooling) and the transformation temperatures that apply for specific rates of heating and cooling. Since the transformation on heating behavior is governed by diffusion-controlled processes, the beginning of transformation on heating will be delayed by some increment of temperature that is directly proportional to a specific rate of heating, and on cooling the beginning of transformation also will be delayed by some increment of temperature that is directly proportional to a specific rate of cooling. However, where prolonged hold times are imposed for a given heat treatment process, then in determining at what temperature transformation will begin, it is the pseudo-equilibrium temperature (i.e., a temperature close to, but not precisely equal to, the true equilibrium value, which is a theoretical number) that is of interest.

Nomenclature: Lower critical transformation temperatures are defined in Figure B-1.

A_1: Lower critical transformation temperature under equilibrium condition.

A_{C1}: On-heating lower critical transformation temperature (“Chauffage” = heating).

A_{r1}: On-cooling lower critical transformation temperature (“Refroidissement” = cooling).

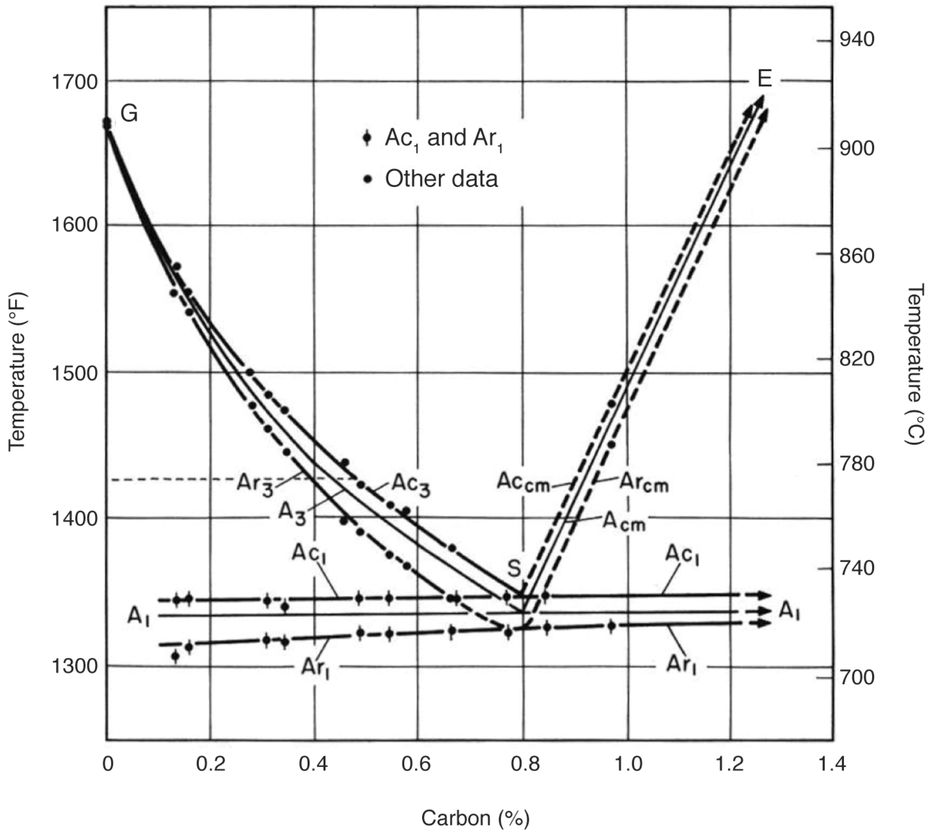

Figure B-1
Definition of lower critical transformation temperatures for conventional carbon steel [27]

It has been well-established that A_{C1} is a function of heating rate, and that the A_{C1} temperature approaches A_1 as the heating rate decreases. A typical example for the effect of heating rate on A_{C1} temperature is presented in Figure B-2 for a CSEF steel which is similar to Grade 91[28].

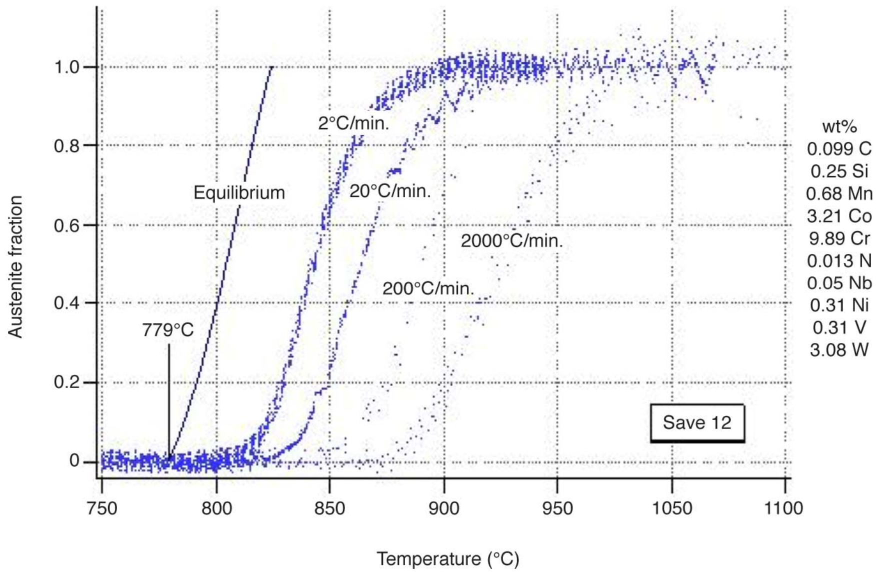

Figure B-2
AC_1 temperature approaches A_1 as heating rate decreases [28]

The measured A_1 temperature determined from experiments on different Grade 91 steels with compositions within the specification range has been seen to vary from1488°F (809°C)-1516°F(824°C).

The A_1 temperature of Grade 91 material has been evaluated [12] by ORNL through development of a computational program, which predicts the A_1 temperature based on the chemical composition of the Grade 91 material. This model was developed following review of approximately 2000 compositions meeting the specification for Grade 91 material (base metals and weld deposits) involving 93 product heats from 9 different suppliers. The results of the study revealed that A_1 temperature of Grade 91 material is a strong function of (Ni + Mn) content, as shown in Figure B-3.

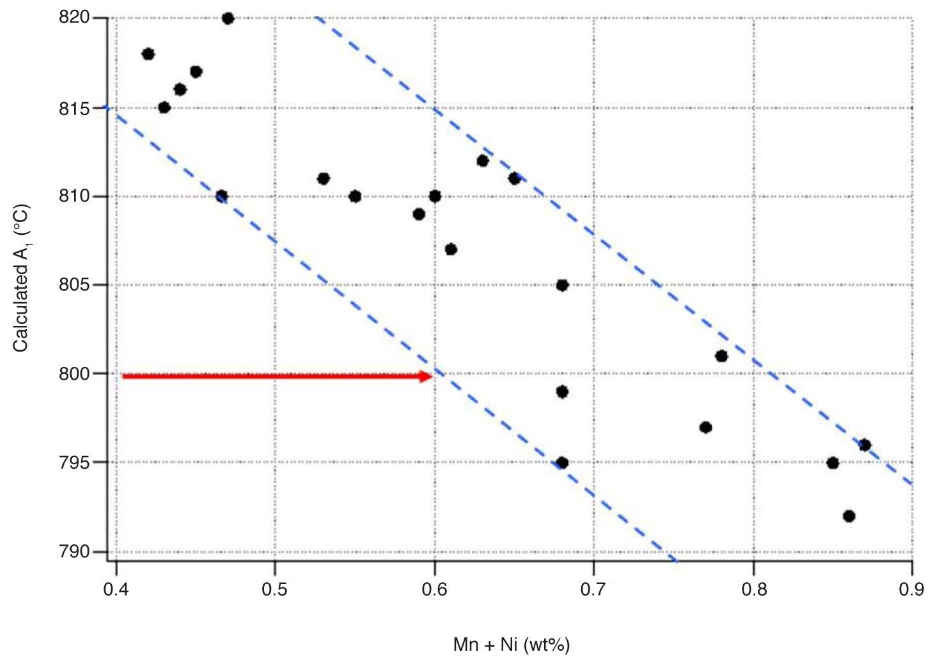

Figure B-3
Calculated A_1 temperatures as a function of "Ni+Mn" content for actual product heats [29]

The results showed that the higher the (Ni+Mn) content, the lower the A_1 temperature. When (Ni+Mn) content is less than 0.6, A_1 temperature always is greater than 800˚C (1472˚F). Santella and Shingledecker [29] summarized that the lowest A_1 temperature possible is calculated to be 760˚C (1400˚F) for material satisfying the Grade 91 material specifications, but 780˚C (1436˚F) for Grade 91 material representing typical commercial melting practice recommendations.

For many Grade 91 weld deposits, the calculated A_1 temperatures are significantly lower than those of the associated base metals due to the higher content of nickel (up to 1.0 wt%) and manganese (up to 1.25 wt%). Santella and Shingledecker's results [29] showed that the A_1 temperature for Grade 91 weld deposits could be calculated to be as low as 676˚C (1250˚F) based on the specification established by ASME for SFA 5.23 B9. An example of A_1 temperature as a function of (Ni+Mn) content is presented in Figure B-4 for Grade 91 weld metal [30]. From this figure it is apparent that at a (Ni+Mn) value less than 1.5 the A_1 temperature for Grade 91 weld metal will be above 1400˚F (760˚C).

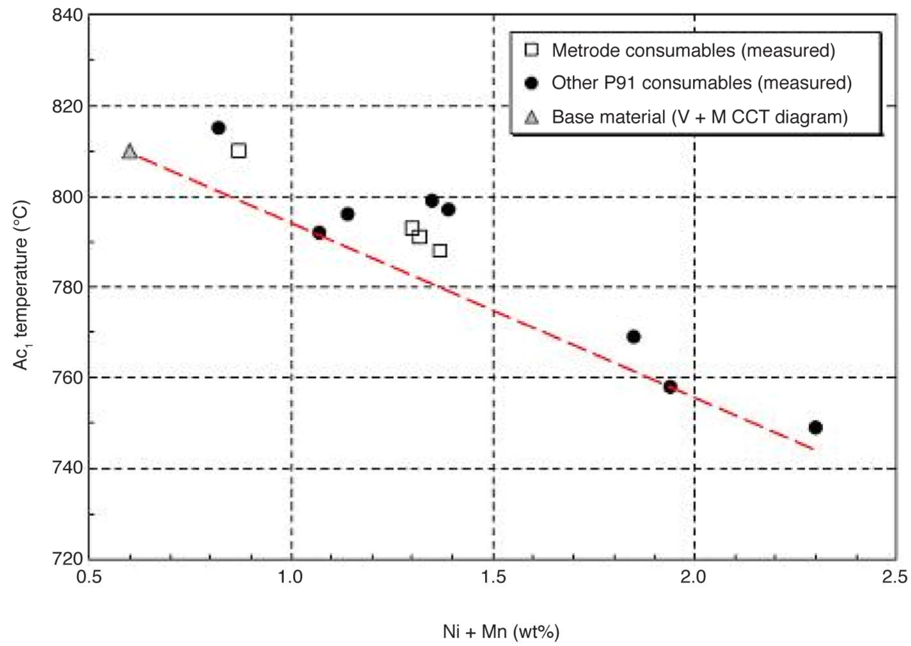

Figure B-4
Variation of Ac_1 temperatures as a function of "Ni+Mn" content for Grade 91 weld metal [30]

Proposed rule changes are currently being considered by ASTM and ASME B&PV Code Committees which will limit the maximum Ni+Mn to 1.0 weight percent in Grade 91 base (pipe, fittings, etc.) and weld metal specifications. Many owner-users are already specifying a maximum Ni+Mn content for weld metal of 1.0 weight percent. This limitation is a further step to prevent an excursion over the A_1 temperature during PWHT. Many filler metal manufacturers are therefore offering lower Ni+Mn levels in consumables for used with all welding processes. This limitation in Ni+Mn is not believed to cause any detrimental effects during welding, and is not believed to significantly reduce the impact toughness of these weldments, Figure B-5 [31].

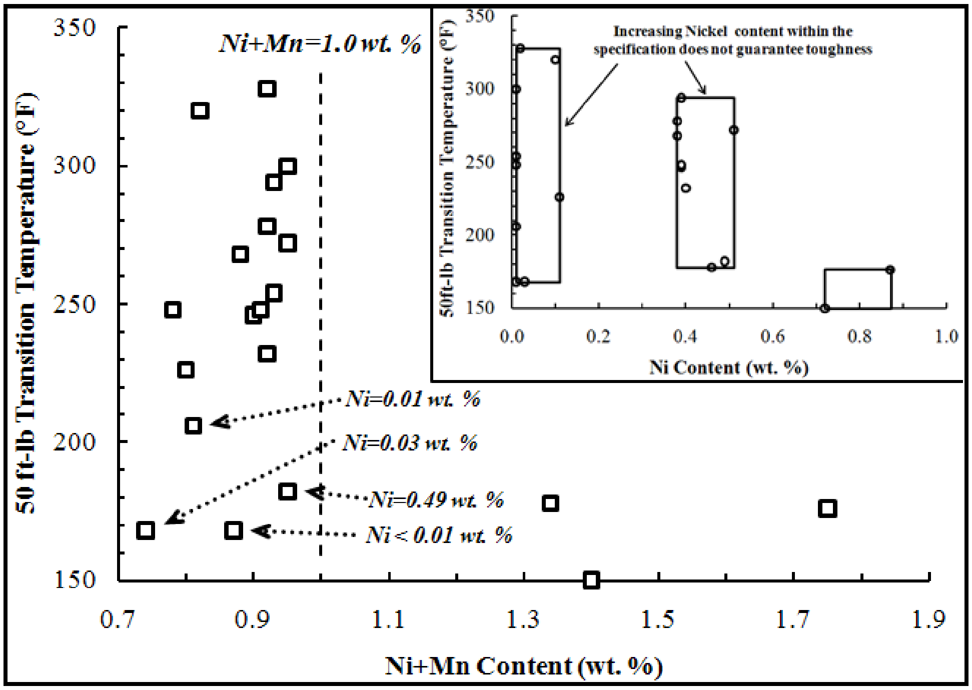

Figure B-5
Fracture appearance transition temperatures for Grade 91 weldments tempered at 1400°F/1h followed by air cooling [31]

Appendix C: Background on Heat Treatment

C.1 Introduction

The following sections outline good practice regarding heat treatment. This advice is included since experience suggests that heat treatment is often performed in a less than ideal manner. Common problems found with heat treatments include:

- Normalizing or tempering above specified range
- Normalizing or tempering below specified range
- Lack of uniformity in temperature during heating or holding so that different parts of a component experience different peak temperatures for different times
- Lack of knowledge regarding specific temperatures reached because inadequate or inaccurate monitoring is involved
- Variability in cooling rate so some parts of a component cool at significantly faster rates than others
- The majority of these issues have also been identified associated with postweld heat treatment (PWHT)

Thus, the background given here is aimed at ensuring that sufficient measurements are made using accurate, properly installed instrumentation to demonstrate that all heat treatments are performed according to requirements. Further information is provided in the recent report related to field PWHT [14].

In all cases, if the heat treatment processes will result in surface scale formation or to other surface modification that could compromise the required wall thickness, then the heat treatment should take place in a suitable controlled environment.

C.2 Calibration and Control of Instrumentation

Heat treatment equipment must be properly calibrated, and the producer must furnish evidence of the calibration for review prior to the beginning of any heat treatment operation. For furnaces, the heat treatment supplier must demonstrate that the largest variation in temperature between any two points in the furnace does not exceed 40°F (22°C). This should be demonstrated by placing thermocouples on metal samples that are placed in the furnace so that the

temperatures along the length and across the width of the furnace are accurately indicated. For resistance-type heaters, the heat treatment supplier must demonstrate that the temperature at the control thermocouple can be maintained within ±5˚F (±3˚C) of the target temperature. The heat treatment supplier should demonstrate that for a given component the temperature is controlled within the specified temperature range through placement of properly shielded thermocouples at a sufficient number of location along the length and around the circumference of tubular-shaped components, or along the length and across the width of flat components. For piping the pattern of thermocouple placement recommended in AWS D10.10 is a useful guide and should be followed as a minimum standard wherever possible. In all cases, thermocouples should be directly connected to the components by either mechanical peening or electric discharge and the metal temperature of the components must be measured to control the heat treatment process.

For other types of heating, such as induction heating, the heat treatment supplier must demonstrate the ability to maintain the temperature at all points on the component being heat treated within the required temperature range. The device and parameters for induction heating must be established in such way to insure that the components can be heated uniformly through the thickness of all parts and be held at the target temperature for sufficient time.

If multiple components are to be processed as part of a single heat treatment cycle, all pieces must be properly separated to avoid non-uniform heating and cooling, particularly during the normalizing heat treatment. Suppliers must provide a detailed heat treatment procedure and record for each product purchased, if required. For heating methods that cannot easily be calibrated, such as torch-heating, their use shall be prohibited for the heat-treating of Grade 91 components except where a special procedure is approved prior to implementation. That procedure will include as a minimum provision for accurate monitoring of the temperature of the component at all locations affected by the heating.

C.3 Normalizing

Normalizing of all product forms is to be performed within the range of 1920-1975˚F (1050-1080˚C). Once the full thickness of the component has reached the target normalizing temperature, the time at temperature should be a minimum of 10 minutes. If the heating is performed in a furnace, then the product should be air cooled outside of the furnace and away from any source of heat that would retard the rate of cooling. If the heating is performed using resistance heating pads or induction heating, then the heat source or any insulating material should be removed as soon as is practicable upon the completion of the heating so that the component can undergo uniform cooling in air. Care must be taken to insure that all areas of the component are allowed to cool uniformly. Cooling shall be continuous down to at least 200˚F (95˚C) at the center location before tempering. The rate of cooling through the temperature range 1650-900˚F should be controlled to be no slower than 5˚C/min. (9˚F/min.).

The key to properly normalizing Grade 91 steel is to accurately control the normalizing temperature and the subsequent rate of cooling. The normalizing temperature must be adequate to insure that a sufficient amount of the critical precipitate-forming elements are dissolved. The dissolution of these elements is diffusion controlled and, therefore, requires a certain minimum amount of time at a given temperature to achieve the required reaction.

C.4 Tempering

Tempering for all product forms is to be performed within the temperature range of 1350-1440˚F (732-782˚C). Time at the tempering temperature shall be sufficient to satisfy the specified hardness requirement. The product may be cooled in still air from the tempering temperature, so long as excessive distortion or excessive thermal stress is avoided.

All sub-critical thermal processing steps (tempering and PWHT), regardless of their specific function, will alter the material's structure in ways that will influence the final properties of the material. A ***total*** tempering effect should be considered to insure that in the final heat treated condition the structure of a component fabricated from this material is in an optimum condition with regard to the material's elevated temperature strength. The most effective way to control the sub-critical heat treatment of Grade 91 material is to use a tempering parameter. One of the most common tempering parameters currently in use is the Holloman-Jaffe parameter (HJP) [32], as expressed in the follow equation:

$$HJP = (T+460) \times (C + \log_{10} t)/1000$$

Where: T is tempering temperature in ˚F, t is holding time in hours and C is the HJP constant. A common default value for C is 20; however, limited analysis for Grade 91 material has suggested that the constant C could have a value in the range of 19 to 23, depending on the characteristics of a particular heat of material.

C.5 Control of Heating and Cooling Rate

With the exception of the minimum recommended cooling rate of 5˚C/min. following the normalizing portion of the heat treatment, no additional limits on the rate of heat-up or cool-down are specified for either the normalizing or the tempering processes. However, for thick-walled components, or for assemblies of complex shape, an appropriate rate of heat-up or cool-down, as determined by experienced engineering judgment, shall be adopted to minimize distortion and residual stresses. With specific regard to the cool-down practice, it is emphasized that a sufficiently rapid rate of cooling must be maintained by accelerated cooling from the austenitizing temperature down to a temperature of less than 1000˚F (540˚C) at the center of the work piece to insure avoidance of detrimental precipitation of carbides or other non-martensitic transformation products. Below 1000˚F (540˚C), for thick-walled components or components of complex shape it is recommended that the cooling be performed in still air or the equivalent down to below 200˚F (95˚C).

Note: for components greater in thickness than 3" (76 mm), forced air-cooling or oil quenching or the equivalent from the normalizing temperature to an internal work piece temperature below 1000°F (540°C) may be necessary to achieve the required metallurgical structure and mechanical properties.

C.6 Excessive Oxidation

Precautions shall be taken to avoid excessive material loss due to oxide scaling during all heat treatment operations. This requirement is particularly important for tubing and other thin-walled components in those cases where the original heat treatment, or heat treatments, applied by the fabricator are nullified by misapplication, requiring the repetition of the normalizing heat treatment, which, in the absence of a controlled and protective atmosphere in contact with all heated surfaces may cause rapid and excessive scaling. Oxide scale on the ID surface of tubing intended for heat transfer service in a boiler must either be minimized during the heat treatment or must be removed following the heat treatment, because the presence of the oxide can result in unacceptable overheating of the tubing in service.

C.7 Carburization and Decarburization

For tubular products, or other thin-walled product, the vendor must verify that the total thickness of material decarburized during processing (i.e., OD decarburized layer plus ID decarburized layer) does not exceed 7% of the minimum wall thickness value specified for the product. The vendor must determine the total thickness of decarburized material by performing microstructural analysis of a representative polished and etched cross section of the product at a magnification of 100X from each heat treatment lot. Carburization, defined as a visible increase in the surface carbon content as a result of processing, should be determined by similar microstructural analysis.

Note: if hardness testing is required during, or after processing and, if the hardness measurement will be made on the surface of the component, then the material supplier must verify that the test specimen is free of the effects of decarburization or carburization at the point of test.

For plate-formed or piping-related components, it might be considered appropriate in certain circumstances to negotiate with the manufacturer to design these components with additional thickness (approximately 8% of the minimum wall thickness value) to compensate for any decarburized layer, which then will facilitate any subsequent metallographic assessment (both hardness testing and metallographic replication) of the components.

Appendix D: Background on Hardness Measurements

D.1 Introduction

Because of risks of brittle failure of untempered martensite, specifications initially included a requirement not to exceed a maximum hardness. Thus, even from the earliest applications of Grade 91 hardness has been used as a method of quality checking. More recently, experience has shown that components can experience incorrect heat treatment which results in incorrect “ferrite” type microstructure. These structures are typically relatively soft so there has been wide use of hardness testing as a method of screening.

In view of the importance of this screening, there have been several investigations regarding the use of field hardness techniques to monitor component hardness [33,34]. These should be referred to as reference information. The information here outlines application of hardness as a means of tracking quality through a fabrication procedure.

D.2 Measurements for Piping and Headers

Assessment of component hardness should always be carried out using qualified procedures, trained staff and calibrated equipment. In most pressure part component applications hardness should be measured at four locations equally spaced around the circumference, unless the diameter of the component is ≥ 24” (600 mm), in which case the hardness should be measured at eight locations equally spaced around the circumference on both sides of the joint. The following points should be taken into consideration:

- The hardness should be measured using established portable testing methods, such as the rebound method (e.g., the Proceq Equotip testers or the GE DynaMIC testers), the UCI method (e.g., the GE MIC10 or MIC20 testers), or the manual Brinell methods (e.g. the Telebrineller or the Pin Brinell Tester). However, the rebound method should not be used on any component with an actual wall thickness less than ¾” (19 mm).
- In all cases the hardness measuring instrument must be properly calibrated before testing, and the test surface shall be prepared to a finish that will optimize test accuracy for the particular instrument being used. For the

rebound and UCI type testers, the surface shall be ground to at least a smooth 240 grit finish. For the manual Brinell type testers a surface finish of 80 grit or its equivalent is satisfactory.

- Measurements should be made using personnel who have been properly trained.
- 100 % inspection is recommended, however, for cost savings or low risk components, the following strategy may be considered: 1) initially evaluate 10% of the total components; 2) if problems are found in the initial 10% evaluation, then the number of components to be inspected should increase to 25%; and 3) if additional problems are found the number of components inspected should increase to 100%.

Although Section 2.4 recommends a minimum hardness of 190HB, due to the variability of hardness testing and the potential for material damage, if at any location the measured hardness of the component is below 195HB, then additional testing should be performed. Typically, the additional hardness testing will be carried out after grinding to remove surface decarburized material. Care must be taken during grinding not to encroach on the minimum wall thickness requirements of the component. If, following the additional testing, the hardness still is below 195HB then further testing should be conducted to accurately characterize the material condition. This further testing typically includes the taking of metallographic replicas or the direct examination of sample material removed from the component. If the component is found to be in an unacceptable condition the effected section may be re-normalized and tempered. A final alternative is component replacement.

If the measured hardness of the piping is between 195HB and 200HB, then the PWHT operation should be controlled to a low tempering parameter value within the specified range of PWHT temperature – i.e., 1350-1400˚F (732-760˚C).

Prior to the beginning of welding, the hardness of the component base metal adjacent to the weld, specifically that portion of the piping that will be subjected to the full heat of the PWHT operation should be assessed. Following completion of the PWHT, the hardness of both the base metal adjacent to the weld, specifically that portion of the component that was subjected to the full heat of the PWHT operation, and the weld metal, itself, shall be measured at four locations equally spaced around the circumference of the joint. For the base metal, measurements shall be made on the component on both sides of the joint. If the measured hardness of the base metal or weld metal at any location is below 195HB, then additional testing shall be performed to verify the serviceability of the material. If, following the additional testing, the measured hardness of any portion of the weld metal or the base metal is below 190HB, then the weld and the affected piping either shall be replaced or shall be removed, re-normalized and tempered, and hardness tested to ensure the metallurgical condition of the piping prior to re-welding. After the completion of re-welding and PWHT, if the measured hardness of the weld metal at any test location is above 280HB, then the joint shall be re-heat treated to achieve a weld metal hardness below 280HB, taking care to maintain the base metal hardness at all locations above 190HB.

Appendix E: Background on Cold Work

Cold-forming, such as cold bending of boiler tubes, is a common practice in boiler manufacture. Recent R&D efforts [35] have revealed the following:

1. Cold-work induced during all cold-forming processes does have an adverse effect on the creep rupture strength of Grade 91 material, as shown in Figure E-1. Results to date indicate that there is no obvious threshold value below which the effect is absent, but that the magnitude of the effect increases with the level of cold strain induced.
2. The magnitude of the creep life reduction was proportional to the increase in the amount of cold work and, therefore, to the increase in hardness caused by the cold-work, as documented in Table E-1 and Figure E-2.

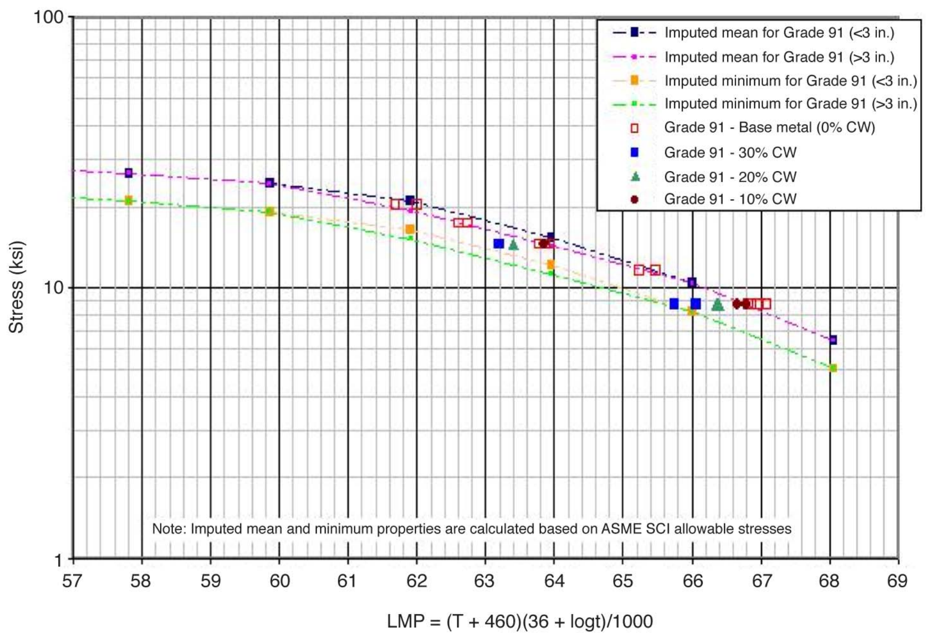

Figure E-1
Effect of cold-work on the creep rupture behavior of Grade 91 material in comparison with the behavior of the unstrained base metal [35]

Table E-1
Creep Life Reduction as a Function of Cold-Work and Hardness

Sample ID	Hardness (HB)	Hardness Difference ($HB-HB_0$)	Life Reduction (%)	
			Relative to Base Metal	Relative to Imputed Mean
Grade 91 BM (0%) (HB0)	218	0	0	-16~+144%
Grade 91 (30% CW)	240	+22	-(59~80)%	-(62~75)%
Grade 91 (25%CW+1350 °F/30 min.)	225	+7	-65%	-56%
Grade 91 (25%CW+1425° F/60 min.)	210	-8	-60%	-50%
Grade 91 (20% CW)	228	+10	-(46~54)%	-(42~50)%
Grade 91 (20%CW+1350 °F/30 min.)	224	+6	-36%	-20%
Grade 91 (20%CW+1425° F/60 min.)	212	-6	-25%	-7%
Grade 91 (15%CW+1350 °F/30 min.)	223	+5	-5%	+18%
Grade 91 (15%CW+1425° F/60 min.)	206	-12	-25%	-6%
Grade 91 (10% CW)	220	+2	-49~0%	-(7~18)%

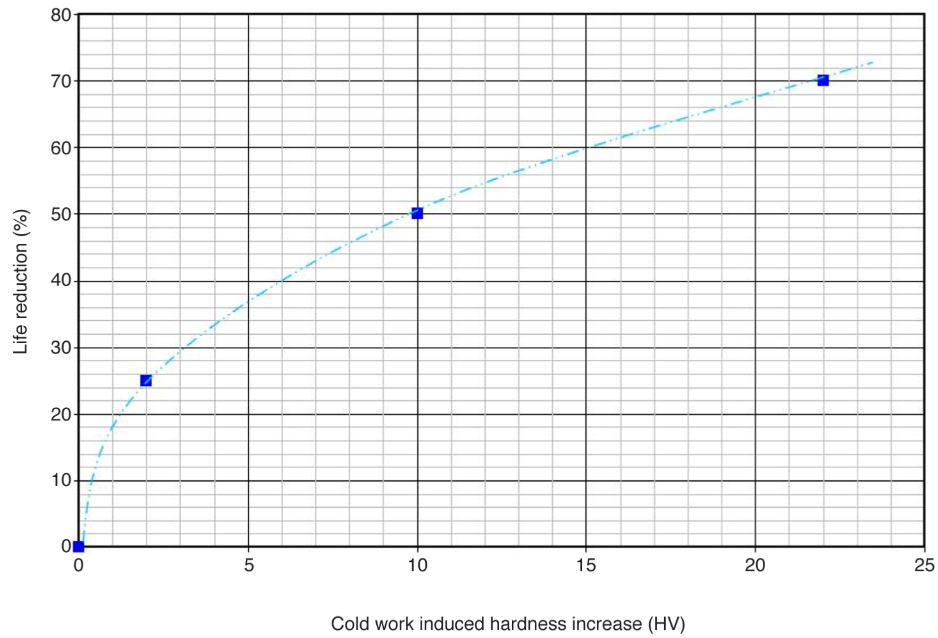

Figure E-2
Creep life reduction as a function of hardness increase induced by cold-work [35]

1. If the full strength of the Grade 91 material is required to ensure satisfactory service life, then when the amount of tensile strain induced during cold bending exceeds approximately 20%, the full length of the tubing should be re-normalized and tempered.
2. Based on limited test results, a post-forming subcritical heat treatment conducted at tempering parameters commonly used in the fabrication of Grade 91 tubular components provided no significant benefit with regard to restoration of the creep rupture strength of cold-worked Grade 91 material as illustrated in Figure E-3. However, such a sub-critical heat treatment may reduce susceptibility to other damage mechanisms, such as stress-corrosion cracking.

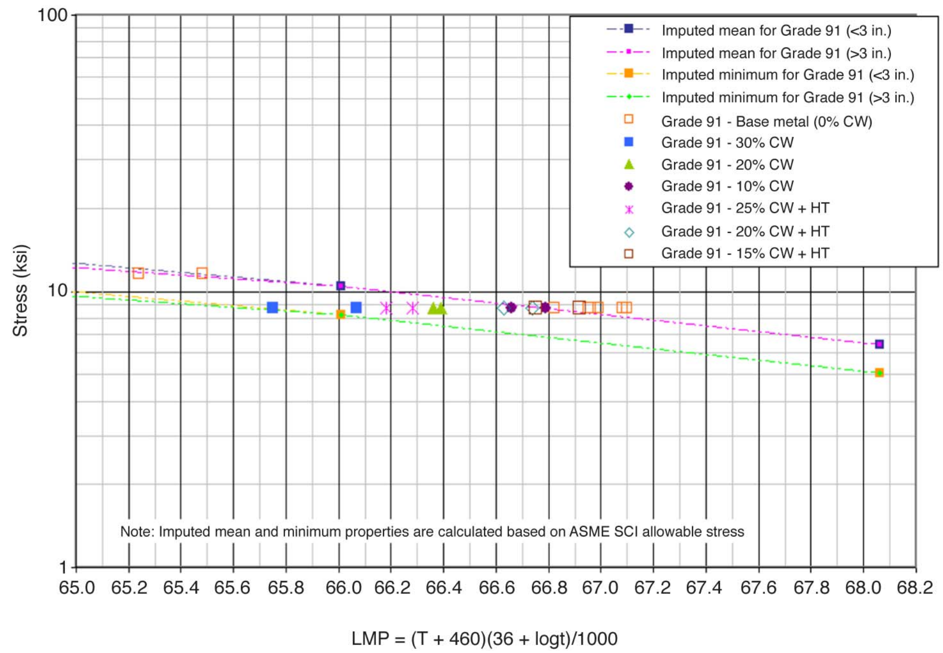

Figure E-3
Effect of a post-forming sub-critical heat treatment on the creep rupture behavior of the cold-worked Grade 91 test material compared with the behavior of the unstrained base metal and the cold-worked material with no post forming heat treatment [35]

Appendix F: Stress Corrosion Cracking

Higher-chromium martensitic steels can be highly susceptible to stress-corrosion cracking (SCC) when left for prolonged periods in a fully hardened or under-tempered condition. This potential danger was recognized in the past, since the susceptibility to SCC was well established for many of the early high chromium alloys. For example, in the 1930's the susceptibility of the 400-series stainless steels to stress-corrosion cracking in the as-welded or hardened condition necessitated the implementation of special rules for fabrication to avoid cracking.

Recent experience has shown that the higher-chromium creep-strength enhanced ferritic steels, when left in the untempered or under-tempered condition, are susceptible to stress-corrosion cracking in what would otherwise be considered "benign" environments. A comparison of recent cases of unexpected cracking in Grade 91 boiler components found no common factors with regard to fabrication or service history, other than the fact that in each case the components had been left in a fully hardened condition for an extended period of time before the final tempering post fabrication heat-treatment was applied.

In general, there are three metallurgical factors responsible for SCC, including the metallurgical condition of the material, the level of stress, and the environment. Among these factors, metallurgical condition and stress level can be managed through design and/or manufacturing procedure. However, the environmental factor typically is more difficult to control, and it often is necessary to implement indirect control factors, such as the maintenance of a minimum temperature on the component to eliminate the chance of moisture forming on the component surface.

The R&D results [36] demonstrated that both *hydrogen embrittlement* and *active path corrosion* are potential damage mechanisms involved in the SCC behavior of Grade 91 material. With both mechanisms, SCC will be intergranular. Typical SCC is shown in Figures F-1 and F-2.

The SCC fracture behavior where hydrogen embrittlement is involved is accurately reflected by a Charpy-type transition curve, as shown in Figure F-3. Hydrogen embrittlement involves a poisoned cathode reaction, and the fracture behavior is closely linked to the material's "toughness". On the other hand, the SCC fracture behavior under active path corrosion is more accurately characterized by a "C-curve" type behavior, as presented in Figure F-4. Active path corrosion involves an anodic reaction in which a chromium-depleted zone immediately adjacent to the grain boundaries is rapidly corroded. The

"sensitizing" temperature range where this chromium depletion occurs extends from approximately 600˚F (315˚C) to 1130˚F (610˚C), based on the limited test data available at this time.

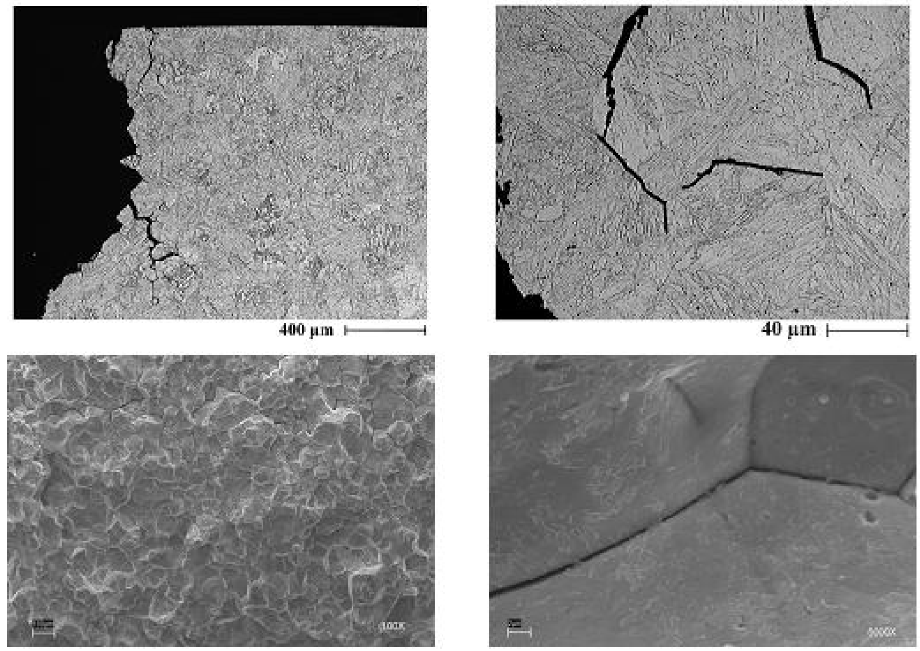

Figure F-1
Typical optical metallographic and SEM fractographic features of SCC where hydrogen embrittlement is the dominant mechanism of damage [36]

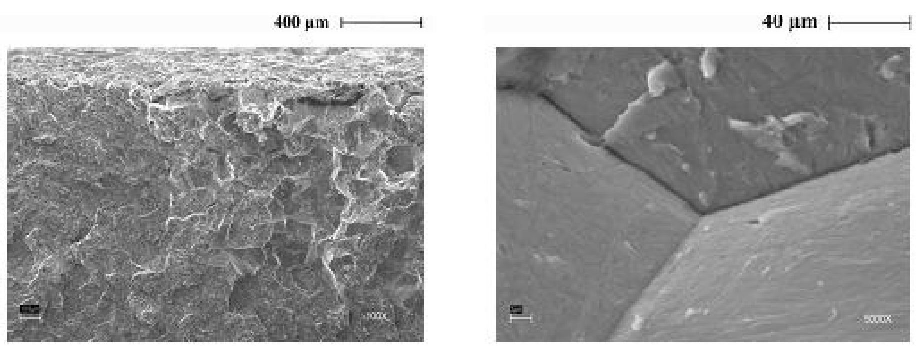

Figure F-2
Typical SEM fractographic features of SCC where active path corrosion is the dominant mechanism of damage [36]

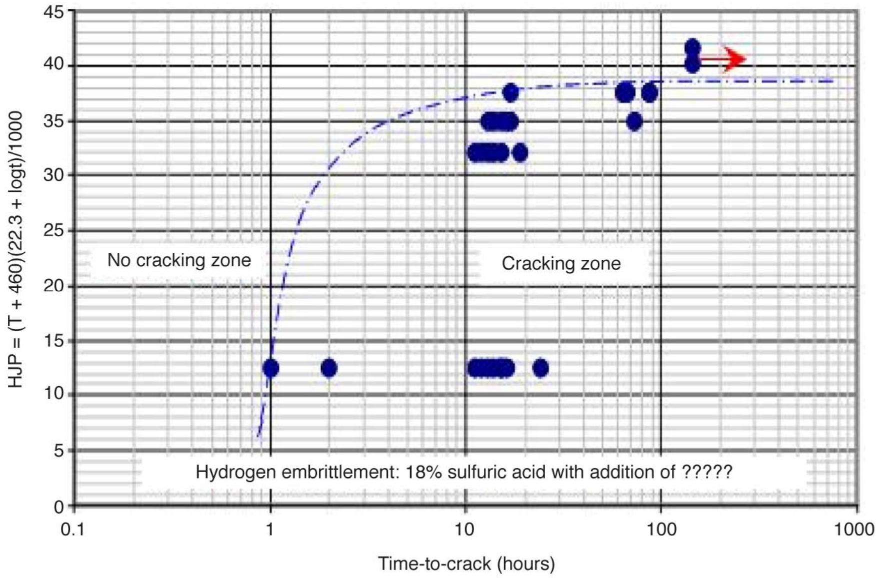

Figure F-3
SCC behavior where hydrogen embrittlement is the dominant damage mechanism (Holloman-Jaffe Parameter vs. Time-to-Crack) [36]

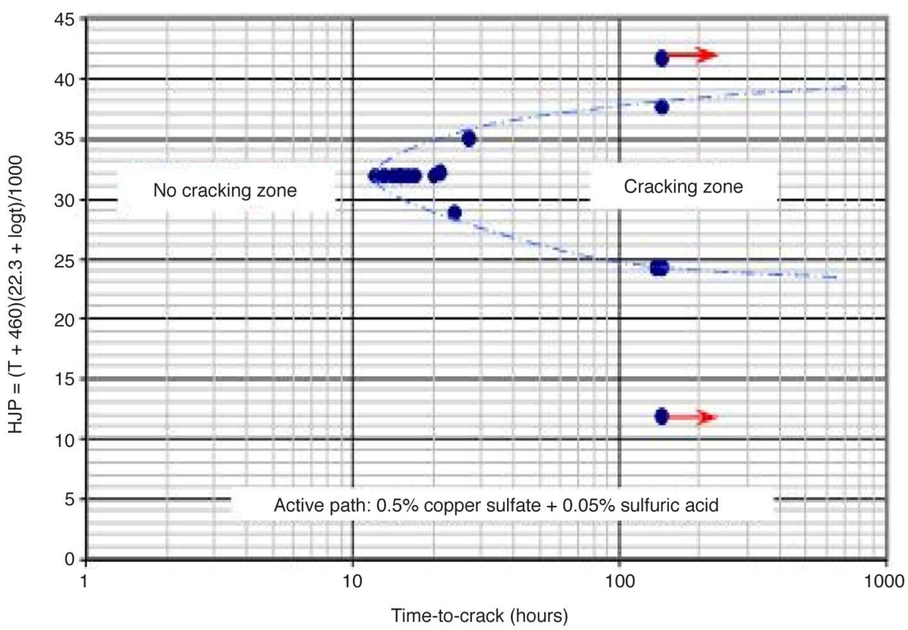

Figure F-4
SCC behavior where active path corrosion is the dominant damage mechanism (Holloman-Jaffe Parameter vs. Time-to-Crack) [36]

Test results have demonstrated that full tempering of Grade 91 material eliminates susceptibility to SCC by both damage mechanisms. Tempering or PWHT at 1375˚F (746˚C) was shown to confer complete immunity to SCC on the heats tested, and it is believed that any tempering or PWHT temperature above 1300˚F (705˚C) will be effective in eliminating susceptibility to SCC. However, in view of the practical realities involved in manufacturing or construction, it is not always possible to apply the PWHT immediately after completion of welding. In that case, protection of the weld areas from exposure to any potential corrosive agents is the key to avoiding SCC. Since the SCC only can occur if there is moisture present, and since in most cases the only source of moisture is condensation due to changes in ambient temperature, all Grade 91 weld joints should be maintained at temperatures above the dew point, or they should be kept in a humidity controlled environment until the required PWHT can be performed.

Appendix G: Background on Welding

G.1 Introduction

It is clear that the welding process introduces additional complexities associated with the thermal cycles involved and the variations in composition between filler and parent. It is apparent that welding needs to be carried out carefully using qualified staff and appropriate procedures, further background is provided in reference [37]. The following section provides information and guidelines regarding these issues.

- The use of filler materials with (nickel + manganese) contents exceeding 1.2% may require that the component be cooled to temperatures below 200°F (95°C) to ensure an acceptable degree of austenite transformation to martensite prior to PWHT. It should be noted that for field welds subject to high applied loads, this requirement may involve a significant risk of fracture of the weld.
- Both manufacturing and field experience have demonstrated that, under certain specific conditions, preheat can be removed after welding and the component returned to ambient temperature for a period of time prior to the application of the final post-weld heat treatment. The **essential** conditions under which this can be done successfully include at least the following:
  - The amount of diffusible hydrogen present in the weld is carefully controlled during welding. For highly stressed components, a hydrogen bake should be performed before allowing the temperature of the material to drop to room temperature (see section 2.6.3 for details – also note that the solubility of hydrogen is substantially greater in austenite than in martensite, so as complete a transformation as possible should be made prior to the hydrogen bake).
  - The component is kept in a clean, dry environment until the postweld heat treatment is completed.
  - The joint is not subjected to significant thermal reaction or other applied loads in the as-welded condition.
- Particular care should also be exercised prior to moving or transportation of components. In addition to all of the above precautions associated with good fabrication practice, it is important that no "incidental" welding or harmful heat treatment is associated with transportation.

Appendix H: Reference Documents

This section provides a listing of selected relevant documents.

H.1 EPRI Documents

1. 1004702 Optimal Hardness of P91 Weldments
2. 1011352 Effect of Cold-Work and Heat Treatment on the Elevated-Temperature Rupture Properties of Grade 91 Material
3. 1004516 Performance Review of P/T91Steels
4. 1006590 Guideline for Welding P(T)91 Materials
5. 1004915 Normalization of Grade 91 Welds
6. 1009758 Evaluation of Filler Materials for Transition Weld Joints between Grade 91 to Grade 22 Components
7. 1004916 Development of Advanced Methods for Joining Low-Alloy Steel
8. 1009757 Temperbead Repair Welding of Grade 91 Materials
9. 1009758 Evaluation of Transition Joints between grade 91 and Grade 22 Components
10. TR-101394 Thick-Section Welding of Modified 9Cr-1Mo (P91) Steel
11. TR-108971 Review of Type IV Cracking in Piping Welds
12. 1006299 Conference on 9Cr Materials Fabrication and Joining Technologies -- Myrtle Beach
13. 1004516 Performance Review of P/T91Steels
14. 1004703 Post Forming Heat Treatment of P91 Materials
15. TR-106856 Properties of Modified 9Cr-1Mo Cast Steel
16. TR-103617 P91 Steel for Retrofit Headers -- Materials Properties

17. TR-104845 Creep Behavior of Modified 9% CrMo Cast Steel for Application in Coal-Fired Steam Power Plants

18. TR-105013 Material Considerations for HRSGs in Gas Turbine Combine Cycle Power Plants

19. TR-114750 Materials for Ultra Supercritical Fossil Power Plants

20. 1001462 Advances in Material Technology for Fossil Power Plants—SWANSEA (2001)

21. 1011381 Advances in Materials Technology for Fossil Power Plants – Hilton Head (2004)

22. TR-111571 Advanced Heat Resistant Steels for Power Generation

23. 1018151 Service Experience with Grade 91 Components

24. 1019575 Evaluation of Ex-Service Grade 91 Material

H.2 International Specifications and Codes

Applicable ASTM materials designations for Grade 91 material are provided in Table H-1.

Table H-1
Summary of applicable ASTM materials specifications for Grade 91 material

Specification and Grade	Country	Description
SA-182, F91	United States	Forged or rolled alloy-steel pipe flanges; forged fittings, valves, and parts for high-temperature service
SA-213, T91	United States	Seamless ferritic and austenitic alloy-steel boiler, superheater, and heat exchanger tubes
SA-217	United States	Specification for Steel Castings, Martensitic Stainless and Alloy, for Pressure Containing Parts, Suitable for High Temperature Service
SA-234, WP91	United States	Piping fitting of wrought carbon steel and alloy for moderate and elevated temperature
SA-335, P91	United States	Seamless ferritic alloy-steel pipe for high-temperature Service
SA-336, F91	United States	Alloy Steel Forgings for Pressure and High Temperature Parts
SA-369, FP91	United States	Carbon and ferritic steel forged and bored pipe for high-temperature service
SA-366, F91	United States	Steel forgings, alloy for pressure and high-temperature parts
SA-387, Grade 91	United States	Pressure vessel plates, alloy steels, Chromium-molybdenum
SA-691	United States	Carbon and alloy steel pipe, electric-fusion-welded for high-pressure service at high temperatures
SFA-5.5*	United States	Specification for Low Alloy Steel Electrodes for Shielded metal Arc Welding*
SFA-5.23*	United States	Specification for Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*
SFA-5.28*	United States	Specification for Low Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*
SFA-5.29*	United States	Specification for Low Alloy Steel Electrodes for Flux Cored Arc Welding*

Note *These specifications include B9 welds

A summary of selected international materials specifications for Grade 91 steel are presented in Table H-2. Specifications in Japan are KA-SCMV28, KA-STPA28 and KA-SFVA28 for plate pipe and forgings respectively. The details of these specifications mirror those of ASME.

Table H-2
Summary of selected information from ASME Materials Specifications for Grade 91 Steel

Specification and Grade	Country	Description
DIN 17 175 VdTUV511/2 X10CrMoVNb9-1	Germany	Seamless tubes made from heat-resistant steels
BS 3604-2 Grade 91 (now withdrawn)	UK	Steel pipe and tubes for pressure purpose, ferritic alloy steel with specified elevated temperature properties
BS 3059-2 Grade 91 (now withdrawn)	UK	Steel boiler and superheater tubes. Part 2 specification for carbon alloy and austenitic stainless steel tubes with specified elevated temperature properties
EN 10 216-2 X10CrMoVNb9-1 Steel No 1.4903	Europe	Seamless steel tubes for pressure purposes technical conditions of delivery. Part 2 Ferritic and martensitic steels with specified elevated temperature properties
EN 10 222-1:1998 X10CrMoVNb9-1 Steel No 1.4903	Europe	Steel forgings for pressure purposes – Part 1: General requirements for open die forgings.
EN 10 222-2:2000 X10CrMoVNb9-1 Steel No 1.4903	Europe	Steel forgings for pressure purposes – Part 2: Ferritic and martensitic steels with specified elevated temperature properties.

H.3 Comparison of Information

While much of the information is included in the various Codes and Standards, it is noteworthy that in some cases the specifications are different. Selected differences are summarized in Table H-3.

Table H-3
Summary of differences between materials specifications for Grade 91 steel

Spec	P %	S %	Normalization Temp	Cooling Rate	Tempering Temp	Yield	Tensile	Hardness
SA 182	0.02	0.01	1900 to 1975°F	Air cooled	1350 -1470°F	60 ksi	85 ksi	248 HB max
			1040 – 1080°C		730 – 800°C	415 MPa	585 MPa	
SA 335	0.020	0.010	1900 to 1975°F	NS	1350 – 1470°F	60 ksi	85 ksi	250 HB, 265 Hv, 25 HRC
			1040 – 1080 C		730 – 800°C	415 MPa	585 MPa	
SA336	0.025	0.025	1900 to 1975 F	NS	1350 -1470°F	60 ksi	85-110 ksi	Not Specified
			1040 – 1080°C		730 – 800°C	415 MPa	585 – 760 MPa	
SA387	0.020 HA - 0.025 PA	0.010 HA – 0.012 PA	1900 to 1975°F	NS	1350 -1470°F	60 ksi	85 - 110 ksi	Not Specified
			1040 – 1080°C		730 – 800°C	415 MPa	585 – 760 MPa	
SA691	See SA387	See SA387	1900 to 2000°F	NS	1350 – 1440°F	60 ksi	90 ksi	241 HB
			1040 – 1095°C		730 – 780°C	415 MPa	585 MPa	

H.4 Supporting Documents and Standards

The following documents form a part of this guideline to the extent specified herein. Unless approved otherwise, the latest edition shall apply.

ASTM A450/A450M – Specifications for General Requirements for Carbon Ferritic Alloy and Austenitic Alloy Steel Tube

ASTM A530/A530M – Specification for General Requirements for Specialized Carbon and Alloy Steel Pipe

ASTM E8 – Standard Test Methods for Tension Testing of Metallic Materials

ASTM E18 – Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials

ASTM E21 – Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials

ASTM E94 – Standard Guide for Radiographic Examination

ASTM E112 – Standard Test Methods for Determining Average Grain Size

ASTM E139 – Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress Rupture Tests of Metallic Materials

ASTM E165 – Standard Test Method for Liquid Penetrant Examination

ASTM E213 – Practice for Ultrasonic Examination of Metal Pipe and Tubing

ASTM E309 – Practice for Eddy Current Examination of Steel Tubular Products Using Magnetic Saturation

ASTM E381 – Method of Macroetch Testing, Inspection, and Rating Steel Products, Comprising Bars, Billets, Blooms, and Forgings

ASTM E527 – Practice for Numbering Alloys and Metals

ASTM E570 – Practice for Flux Leakage Examination of Ferromagnetic Steel Tubular Products

ASTM E1417 – Standard Practice for Liquid Penetrant Examination

ASTM E 1742 – Standard Practice For Radiographic Examination

Appendix I: Illustration of a Component Purchasing Document

Contents

Technical Specification for the Design, Manufacture, Supply and delivery of Replacement components in Grade 91 Steel

1 Introduction

The Principal is seeking to replace selected welded components on the Main Steam Pipe of XXXX units comprising a Wye and Tees. The reason for replacement is due to Type IV cracking of the original branch weld after X0,000hrs of operation. It is understood that the design of the original branch welded components resulted in high surface stresses greater than the maximum allowable design stress for Grade 91 steel. Other branch welds also expected to experience cracking and will require replacement.

[Utility to modify above paragraph separately to suit individual circumstances]

It is important to emphasize that the technical requirements contained within this document represent controls on the production of Grade 91 material that supplement those contained in the ASME Boiler & Pressure Vessel Code. They are considered mandatory to ensure the satisfactory long-term serviceability of any component fabricated using this grade of material. It is understood that the requirements contained in the ASME Code represent a set of minimum requirements considered essential, but not guaranteed to be sufficient, to provide for the overall safety and reliability of components constructed from Grade 91 material.

2 Scope of Work

The scope of work involves the Design, Manufacture, Quality Assurance, Testing and Delivery to XXX Power Station of new components to replace the existing main steam pipe Wye and Tees as shown on drawings ***XXX*** and ***XXX*** using either:

(i)Forged and machined Grade 91 components, or

(ii)Welded components fabricated using seamless P91 pipe with a full re-normalisation and temper (N&T) heat treatment following fabrication

Respondents may submit offers for either (i) or (ii) or both. The principal shall nominate the selected method of manufacture to be utilised. Further requirements are detailed in the following sections.

The following fabrication methods are not permitted:

(i)Use of seam-welded pipe

(ii)Welded components fabricated using seamless P91 pipe without carrying out a full re-normalization and temper (N&T) heat treatment following fabrication

(iii)Use of any materials other than Grade 91 steel

2.1 Separable Portions

The scope of work consists of the following separable portions:

Separable Portion 1

Separable Portion 2

Separable Portion 3

Separable Portion 4

Separable Portion 5

[Utility to complete this section separately regarding ordering conditions.]

2.2 Terminal Points

The terminal points for each of the components shall be as specified on drawings ***XXX*** and ***XXX***. The respondent may submit alternative offers based on alternative terminal points, if it can be demonstrated that the total cost of component supply and installation is minimized.

2.3 Design of Replacement Components (Separable Portion 1)

This section describes the scope of work for Separable Portion 1. The Respondent shall provide a stand-alone detailed design for all components for approval by the Principal prior to ordering and fabrication of the remaining separable portions. The design shall be jointly owned by the Principal and the Respondent. The components shall be designed according to the following requirements:

(i) Designed in accordance with ASME code for Power Piping B31.1 2010 Edition and ASME Boiler and Pressure Vessel Code 2010 Edition.

(ii) Finite Element Modelling shall be used to determine the maximum stresses at the design temperature and pressure and including piping system loads.

(iii) Branch reinforcement shall be shared between the main pipe and nozzle in order to reduce the maximum stress and reduce stress concentration

(iv) The current (cold and hot) main steam piping system hanger loadings shall be reviewed and any changes to hanger loadings (cold and hot) following the installation of the new piping components shall be determined. If any modifications or changes to settings are required these shall be identified by the Respondent.

(v) The design shall specifically mitigate the historical mode of failure by Type IV cracking

(vi) The design shall consider combined creep-fatigue loading

(vii) Design pressure and temperature shall be as per the existing piping design (Utility to double check and then provide the design vs operating temperature and pressure)

(viii) Ends of piping components shall be designed and supplied machined in preparation for manual butt welding

(ix) The design shall be verified and approved by a Registered Professional Engineer.

The Respondent shall provide the following deliverables at the completion of the design phase for approval by the Principal:

(i) General arrangement drawings

(ii) Detailed fabrication drawings

(iii) Erection drawings

(iv)Design Calculations

(v)Heat Treatment procedure including details of any transportation of components in as-welded state

(vi)Engineering Report detailing the expected service life, possible failure modes of the new components and results of Finite Element Modelling.

(vii)Installation procedure including details of all welds and spool pieces (if required), weld procedures, support points, cold pull, fit-up tolerances, procedures, hanger settings and loadings and any other information relevant to installation of the components.

The Principal will provide the documents listed as input to the design phase.

2.4 Quality Assurance

The Supplier's Quality Assurance System shall be certified to ISO 9001. The new piping components shall be supplied stamped with ASME 'S' stamp. The Respondent shall also supply the following documentation for approval by the Principal prior to start of fabrication of each Separable Portion:

[Utility to modify above paragraph separately to suit individual circumstances]

(i)Inspection and Test Plan (ITP)

(ii)All procurement records showing traceability of supplied materials for piping and welding consumables

(iii)Material certificates for base materials and welding consumables

(iv)Non Destructive Testing (NDT) procedures

(v)Heat treatment procedures and equipment calibration records

(vi)Welding documentation (i.e. WPS, WQR, Welder qualifications)

(vii)Hydrostatic test procedure

The Respondent shall provide full manufacturing data records (MDRs) with the completed components as follows:

(i)Completed Inspection and Test Plan (ITP) signed off for each activity

(ii)All procurement records showing traceability of supplied materials for piping and welding consumables

(iii)Material certificates for base materials and welding consumables

(iv)Non Destructive Testing results and equipment calibration records

(v)All Heat treatment charts and equipment calibration records

(vi)Welding records

(vii)Hydrostatic test records and equipment calibration records

(viii)Records of dimensional checks

(ix)Records of any non-conformances experienced during any stage of the manufacturing/ fabrication process

(x) As-built Drawings

Acceptance of the equipment shall be subject to inspection by the Principal and/or the Principal's authorised representative. The Principal shall nominate hold and witness points for its own inspections in the Inspection and Test Plan (ITP) supplied by the Respondent. The Principal shall have the option to inspect the works at the Supplier's factory. The Respondent shall provide a minimum of seven (7) days notice prior to any witness or hold points being reached.

The above information is essential in demonstrating to the Principal that all critical aspects of the manufacturing process have been satisfied in accordance with design requirements prior to accepting the completed piping assembly.

2.5 Inspection during Installation

During the course of the installation works, the Respondent shall conduct periodic inspections of the installation and testing process to ensure that all work is proceeding to the satisfaction of the Respondent. Any non-conformances identified during the course of works shall be immediately brought to the attention of the Principal. On completion of component installation and testing, and prior to the plant returning to service, the Respondent shall verify in writing the main steam pipe components have been installed to the approved procedure. Failure by the Respondent to highlight issues during the installation shall be deemed as acceptance of the installation process.

2.6 Delivery

[To be specified according to individual requirements]

2.7 Codes and Standards

The components shall conform to the following codes and standards:

(i) Designed and fabricated to the ASME code for Power Piping B31.1 2010 Edition and ASME Boiler and Pressure Vessel Code 2010 Edition.

(ii) All welds shall also be non destructively examined and compliant to XXXX and addenda

3 Materials and Manufacturing Requirements

This section provides specific requirements for the materials and manufacturing processes to be used in the manufacture of the components for all separable portions 2 to X. ***[Utility to specify depending on number of separable portions]***

3.1 Chemical Composition of Parent Metal

The chemical composition of all Grade 91 parent steel shall be measured during steel making and from the final component sections. The composition of the components in weight percent shall conform to the following elemental restrictions:

Composition (Weight %):

Carbon 0.08-0.12

Manganese 0.30-0.60

Phosphorus 0.020 (max)

Sulphur 0.010 (max)

Silicon 0.20-0.50

Chromium 8.20-9.50

Molybdenum 0.85-1.05

Vanadium 0.18-0.25

Nitrogen[1] 0.035-0.070

Nickel 0.20 (max)

Aluminium[1] 0.020 (max)

Columbium (Niobium) 0.06-0.10

Titanium 0.01 (max)

Zirconium 0.01 (max)

Copper[2] 0.25 (max)

Arsenic[2] 0.012 (max)

Tin[2] 0.010 (max)

Antimony[2] 0.003 (max)

Notes:

1. The ratio of Nitrogen to Aluminium shall be a minimum of 4, however, higher values of this ratio are preferable,

2. The limits identified for these elements, which currently are not controlled by the ASTM/ASME material specifications, are target values only at this time; the content of these elements must be reported on the Material Test Report (MTR) supplied with each heat of material.

The Respondent shall provide the producing mill's Certified Material Test Report (CMTR) with the results of the chemical analyses for each individual heat of steel to verify compliance with the requirements of this specification. Upon receipt of the Grade 91 steel by the Respondent, the

Respondent shall verify that each parent steel section complies with the specified compositional requirements. This verification shall be reported to the Principal prior to beginning final fabrication.

Any material supplied outside of the above specification requirements shall be deemed as a non-conforming and shall be rectified by the Respondent at its own expense.

3.2 Heat Treatment

The Respondent shall provide all details of heat treatment procedures, including the type of equipment to be used for heat treatment of Grade 91 components, method(s) of monitoring temperature during the heat treatment (e.g., number and placement of thermocouples for each heat treatment lot, procedure for attaching thermocouples to the work pieces, etc.), prior to the beginning of any heat treatment on those components. These procedures shall be approved by the Principal's representative prior to the commencement of works.

During heat treatment of Grade 91 material, precautions shall be taken to avoid excessive material loss due to oxide scaling during all heat treatment operations. The Respondent shall inform the Principal in writing of the steps that will be taken to minimize oxidation of the product prior to the beginning of heat treatment of the Grade 91 components.

3.2.1 Normalizing

For all product forms normalizing is to be carried out using a suitable furnace within the temperature range of 1920-1975°F (1050-1080°C) to produce a fully martensitic microstructure. Once the full thickness of the component has reached the target *normalizing* temperature, the time at temperature shall be a minimum of 10 minutes. The product shall be air cooled outside of the furnace and away from any source of heat that would retard the rate of cooling.

Care must be taken to ensure that all areas of the component are allowed to cool uniformly. In cases where multiple components are processed as part of a single heat treatment cycle, the individual pieces must be separated in such a way that each piece will cool without interference from an adjoining piece.

Cooling shall be continuous down to at least 200°F (95°C) at the centre location before tempering. Note that for components greater in thickness than 3" (76 mm), forced air-cooling or oil quenching or the equivalent from the normalizing temperature to an internal work piece temperature below 1000°F (540°C) may be necessary to achieve the required mechanical properties.

Heating using resistance heating pads or induction heating is not permitted for normalizing.

3.2.2 Tempering

For all product forms tempering is to be performed within the temperature range of 1350-1400°F (730-760°C). Note that because of the risk of stress-corrosion cracking that exists when Grade 91 material is in the fully hardened condition, once the normalizing heat treatment has been completed, the material shall not be allowed to remain at a temperature below 100°F (40°C) for more than eight (8) hours before the tempering heat treatment is begun unless precautions are taken to keep the material dry on both the inner and outer surfaces.

The tempering temperature selected and the time at the *tempering* temperature shall be controlled to satisfy the specified hardness requirement. The product may be cooled in still air from the *tempering* temperature, so long as excessive distortion or excessive thermal stress is avoided, or, as an alternative, where expedient, furnace cooling is acceptable provided the cooling rate exceeds 100°F (55°C)/hr until the internal temperature is below 1200°F (650°C).

Cautionary note: No additional limits on the rate of heat-up or cool-down are specified for either the normalizing or tempering processes. However, for thick-walled components, or for assemblies of complex shape, an appropriate rate of heat-up or cool-down, as determined by experienced engineering judgment, shall be adopted to minimize distortion and residual stresses. With specific regard to the cool-down practice, it is emphasized that a sufficiently rapid rate of cooling must be maintained by accelerated cooling from the austenitizing temperature down to a temperature of less than 200°F (93°C) at the centre of the work piece to ensure avoidance of detrimental precipitation of carbides or other non-martensitic transformation products. Below 1000°F (540°C), for thick-walled components or components of complex shape it is recommended that the cooling be performed in still air or the equivalent down to below 200°F (93°C).

3.2.3 Equipment

Equipment used for heat treating Grade 91 steel must be properly calibrated and the Respondent shall furnish evidence of the calibration for review by the Principal prior to the beginning of any heat treatment operation. In particular, for furnace heat treatments the Respondent shall provide evidence that the controlling thermocouple or thermocouples can be maintained within ±5°F (±3°C) of the target temperature during a heat treatment cycle and that the largest variation in temperature between any two points in the working zone of the furnace does not exceed 40°F (22°C). This can be demonstrated by placing thermocouples on metal samples positioned within the furnace so that the temperatures in the furnace's working zone are accurately recorded

For resistance-type heaters, the Respondent shall provide evidence that the controlling thermocouple or thermocouples can be maintained within ±5°F (±3°C) of the target temperature during a heat treatment cycle. Further, the Respondent shall demonstrate that for a given cylindrical component the temperature can be controlled at all locations on the component within the specified temperature range through the placement of properly shielded thermocouples at a sufficient number of locations along the length and around the circumference of the component. For piping, the recommendations for thermocouple placement provided in AWS D10.10 shall be followed as a minimum standard.

For other types of heating, such as induction heating, the Respondent shall demonstrate the ability to maintain the temperature at all points on the component being heat treated within the required temperature range for the entire duration of the heat treatment cycle. This specifically includes a requirement that it be demonstrated that the induction heating equipment can achieve the necessary temperature uniformity through the thickness of components that exceed 1" (25mm) in thickness for the entire duration of the heat treatment cycle.

Heating using resistance heating pads or induction heating is permitted for post weld heat treatment only and shall not be used for final normalizing and tempering of the components.

3.2.4 Documentation

Upon completion of the heat treatment of all Grade 91 steel, the Respondent shall provide a certified temperature/time record for each Grade 91 component or lot of components processed as a single batch. Heat treatment equipment test and calibration certificates shall also be provided.

3.3 Microstructure

Metallurgical replication shall be carried out on the completed components to validate that the correct microstructure consisting of tempered martensite has been achieved. A sufficient number of locations shall be tested to ensure that the whole component has the correct microstructure.

3.4 Steel Hardness

All Grade 91 components produced for the Principal shall be evaluated by hardness testing following each thermal processing step as detailed in the following sections.

3.4.1 Procedure

Prior to the beginning of any hardness testing, the Respondent shall submit to the Principal a detailed written test procedure that identifies the type of hardness tester that will be used, calibration procedure, equipment calibration records/certificates, nature of the surface preparation for the hardness testing, level of operator training required, and the method for obtaining a hardness reading at a particular location (e.g., the number of individual readings at a test spot, method of averaging, procedure followed if any single reading is outside of the specified range, etc.). The Principal will review and comment on the acceptability of this information. Only a procedure which has been approved by the principal shall be used to document the hardness of Grade 91 steel components.

With respect to the base materials supplied from the mill for subsequent fabrication, the hardness of the Grade 91 material shall be a minimum of 200HB/210HV (93.4HRB) and a maximum of 250HB/263HV (24.2HRC). It is noted that standard hardness conversion tables are available in ASTM E 140. However, the hardness conversion tables that show the Brinell and Vickers Hardness numbers to be identical within the range 180-250 shall not be used.

Note that any surface decarburization will influence the results of hardness testing performed on the outer diameter of a section of piping and shall be removed in order to obtain an accurate measurement of the material hardness.

The component wall thickness after removal of any non representative surface layer shall be greater than the Design minimum wall thickness.

The material hardness of every piece shall be tested in the following manner:

(i)The hardness shall be measured at both ends of each piece and at intervals along the length of the piece no greater than 8’. All measurement methods and the number of locations will be agreed with the purchaser. The hardness measurements at the ends of the piece may be made on the outer diameter or on the cross section.

(ii)At each test plane a minimum of four measurements shall be made equally spaced around the circumference of the piece. All measurements performed on welds shall include the parent material, weld material and HAZ.

(iii)If the measured hardness at any location on the piece fails to meet the minimum or maximum hardness requirement, then that piece shall be rejected. The Principal shall be notified promptly in writing if pieces are rejected because of failure to meet the minimum hardness requirement and provided with details of the recovery plan.

(iv)Pieces that do not meet the minimum hardness requirement shall only be accepted if approved in writing by the Principal. In this case the Principal may request proof that the material exhibits the desired microstructure of tempered martensite

3.4.2 Data Recording

All hardness test results for all components tested shall be recorded and submitted to The Principal for review prior to final acceptance of the material.

3.5 Mechanical Properties

The room temperature mechanical properties of the as-supplied base material shall meet the following limits:

(i)Tensile Strength: 90 - 110 ksi (620 – 760 MPa)

(ii)All other mechanical properties shall be as indicated in the applicable material specification of SCII of the ASME B&PV Code.

(iii)All results of mechanical properties testing shall be recorded on the Certified Material Test Report.

3.6 Forming Processes

All working or heating of Grade 91 material has the potential to compromise the microstructure and thereby compromise the material's long-term elevated temperature strength. All hot and cold forming operations shall be carefully controlled as detailed in the following sections.

3.6.1 Forgings

For all products produced from a solid forging, the cross-sectional area of the forging shall have been subjected to a minimum reduction relative to that of the original ingot in the ratio of 3:1.

3.6.2 Hot Pressing (Squeezing & Sizing) and Hot Bending

After all hot pressing or hot bending operations the entire component shall be normalized and tempered in accordance with Section 3.2.

3.6.3 Hot Adjustments to Shape

By definition, hot drawing or hot adjusting is carried out for short periods of time at temperatures between 1300°F (705 °C) and 1450°F (790°C). Where that limit is observed, no post-adjustment heat treatment is required. However, if the 1450°F (790°C) limit is exceeded during the operation, then a full normalize and temper of the entire component shall be performed in accordance with Section 2.4. If the overheated zone is to be retained with full serviceability

restored. An alternative corrective action would be to remove the overheated zone and either re-normalize and re-temper the piece containing the overheated zone in accordance with Section 0 above before re-insertion in the component, or to replace the overheated zone with new material.

3.6.4 Cold Pressing (Swaging, Pointing, Squeezing and Sizing)

Any component subjected to cold pressing shall be given a full normalizing and tempering heat treatment in accordance with Section 3.2.

3.6.5 Hot Forming of Fittings and Special Products

After the hot forming of any fittings or special products, a full normalizing and tempering heat treatment of the entire component shall be performed in accordance with Section 3.2.

3.7 General Welding Practice

Where welding will be performed on Grade 91 steel as part of the component production process, the following requirements shall be satisfied.

3.7.1 Preheat

Prior to the beginning of any welding on Grade 91 material, the preheating method including the procedure for control of the preheat temperature, shall be described in detail and submitted to The Principal for approval. This method will normally involve electrical heating only with continuous monitoring and recording of temperature.

(i)For any welds made on Grade 91 material using the shielded metal arc process (SMAW) or the submerged-arc process (SAW), a minimum pre-heat temperature of 400°F (205°C) shall be maintained for the duration of the welding.

(ii)For welds on Grade 91 material made using either the gas metal arc process (GMAW) or the gas tungsten arc process (GTAW) with a solid wire filler metal, a preheat temperature of 300°F (150°C) shall be maintained.

(iii)For welds made using either the GMAW or GTAW processes with a filler metal other than solid wire (i.e., metal core), a minimum preheat temperature of 400°F (205°C) shall be maintained.

(iv)In order to avoid stress-corrosion cracking, if welding is interrupted, preheat temperature shall be maintained, or if the joint temperature drops below preheat temperature, the interrupted weld shall be kept dry until the welding is resumed with the proper pre-heat

3.7.2 Interpass Temperature

The maximum interpass temperature during welding shall be 700°F (370°C).

3.7.3 Hydrogen Bake

A Hydrogen Bake is best practice and should be considered for all joints. The bake should be performed in the temperature range of 500-750°F (260-400°C) for a minimum of two hours for all welds.

Prior to the beginning of the hydrogen bake, the temperature throughout the weld zone should be reduced to below 200°F (93°C).

3.7.4 Post-Weld Heat Treatment

Following completion of welding, the temperature of the component shall be reduced below 200°F (90°C) at its centre to ensure an acceptable degree of austenite transformation. The component then shall be post-weld heat-treated within 8 hours of the completion of welding. If for any reason this is not possible, a hydrogen bake should be performed and one of the following steps shall be taken:

- The component should be maintained at a minimum temperature of 175°F (80°C)
- The component should be stored in a humidity-controlled environment to ensure that no condensation can occur at any time on either the OD or ID surfaces prior to the post-weld heat treatment.

The Principal shall be notified in writing of which of the above two options shall be followed, with specific details of how the selected option will be implemented.

If the welded component is to be renormalized and tempered **immediately** after welding then the detailed specification given in Section 0 for component heat treatment must be followed. The whole component containing the branch welds must be renormalized and tempered using appropriate heat treatment facilities.

If the welded component is to be renormalized and tempered at **a later date** following the completion of welding, an immediate post-weld heat treatment should be performed in the subcritical range of temperature, that is within the range of 1350 - 1400°F (730 - 760°C).

The temperature control requires the use of appropriately located and installed thermocouples. The arrangement for thermocouple installation for both control and monitoring of PWHT temperature must comply with the requirements of Section 3.2.

Prior to the application of the PWHT to welds in Grade 91 components, the weld metal and portions of the Heat-Affected Zones are vulnerable to brittle fracture if subjected to unusually high mechanical loads during handling. Care shall be taken, therefore, in the handling of Grade 91 components containing welds that are in the as-welded condition to minimize the risk of brittle fracture.

3.7.4 Weld Filler Metals:

The chemical composition of the filler materials used shall conform to the limits specified in Table 3-1 below and the following requirements:

(i)The sum of the Mn plus the Ni contents shall not exceed 1.0%, and

(ii)The ratio of N to Al shall be a minimum of 4.

Good practice in the usage of weld filler materials shall be followed at all times to minimize the risk of weld-related cracking and defects. Accordingly the following precautions shall be observed:

(i)All SMAW electrodes to be used in the welding of Grade 91 product shall be issued directly from the sealed container or from a heated master storage bin. Unused electrodes left outside of rod ovens for more than four (4) hours shall be discarded

(ii)All SMAW electrodes shall be certified to the H4 designation

(iii)Welding wires shall not be removed from the packing container until ready for use. If welding is interrupted for more than twelve (12) hours, the reel either shall be stored in a container heated to a minimum temperature of 175°F (80°C) or they shall be discarded

3.7.6 Weld Repair

Any repairs to parent or weld metal by welding shall be pre-approved by the Principal in writing, and if approved full details should be provided in the support data package.

Table 3-1 Chemical Composition Requirements for Grade 91 steel Matching Weld Filler Materials

	Composition (Weight %)			
Elements	**SMAW Electrodes SFA 5.5:2008 E901X-B9**	**GMAW/GTAW Bare Solid Electrodes/ Rods SFA 5.28:2008 ER90S-B9**	**SAW Weld Deposit (Wire/Flux Combination) SFA 5.23:2007 EB9**	**FCAW Electrodes SFA 5.29:2008 E9XT1-B9**
C	0.08-0.13	0.07-0.13	0.08-0.13	0.08-0.13
Mn	0.70-1.20	0.70-1.20	0.70-1.20	0.70-1.20
Si	0.30 (max)	0.15-0.30	0.08 (max)	0.30 (max)
P (max)	0.010	0.010	0.010	0.015
S (max)	0.010	0.010	0.010	0.015
Ni (max)	0.40	0.40	0.40	0.40
Cr	8.5-9.5	8.30-9.50	8.0-9.50	8.5-9.5
Mo	0.85-1.20	0.85-1.20	0.85-1.20	0.85-1.20
V	0.15-0.30	0.15-0.23	0.15-0.25	0.15-0.30
Cu (max)	0.25	0.20	0.25	0.25
Al (max)	0.02	0.02	0.02	0.02
Cb (Nb)	0.02-0.10	0.02-0.10	0.02-0.10	0.02-0.10
N	0.03-0.07	0.03-0.07	0.03-0.07	0.03-0.07
Ti (max.)	---	0.01	--	---
Co (max.)	---	0.05	--	---
B (max.)	---	0.001	--	---
W (max.)	---	0.20	--	---
As (max.)	---	0.010	--	0.010
Sn (max.)	---	0.005	--	0.005
Sb (max.)	---	0.003	--	0.003
O (max.)	---	0.005	--	---

4 Surface Protection and Painting

External surfaces shall have red oxide surface protection suitable to prevent corrosion during transport and storage. Weld preparation surfaces shall be coated with Aluminium Oxide or equivalent to a distance of 50mm both internal and external back from the weld preparation. Ends shall be capped and tightly sealed and internal surfaces to be protected from corrosion by use of Vapor Phase Inhibitor (VPI) powder or equivalent.

5 Work to be Performed by the Principal

The Work to be performed by the Principal shall be as follows:

(i)Perform quality assurance inspections during manufacture and packing

(ii)Arrange unloading of the components at the place of delivery

(iii)Carry out all installation works including rigging, cutting, welding, post weld heat treatment, non-destructive testing, removal and installation of insulation and cladding and adjustment of piping supports.

[Utility to modify above paragraph separately to suit individual circumstances]

6 Transportation requirements

The respondent shall provide details of packing for shipping and short term storage to prevent any mechanical damage or corrosion.

Handling of Grade 91 components should be carried out without using attachments welded to the components.

Components shall be packed to facilitate unloading by overhead crane using slinging or lifting points.

7 Site storage requirements

The Respondent shall provide details of short term and long term site storage requirements prior to installation.

8 Delivery Schedule

[To be completed separately by Utility]

9 Warranty

The Respondent shall warrant that the supplied components are free from defects in design, manufacturing and workmanship that may prevent the component from achieving the designed service life or cause the component to not comply with the design codes.

The warranty period (defects liability period) shall be fifty-four (54) months from the time of installation in the plant.

The Respondent shall make allowance in its tender to witness and verify in writing that the installation of the components is to its satisfaction as per Section 0.

[Utility to modify above paragraph separately to suit individual circumstances]

10 Principal Supplied Documents

Documents & drawings relevant to the tender

[To be completed separately by Utility]

11 Technical Schedules

The Respondent shall complete the following schedules:

Item	Description	Response
11.1	Manufacturing method: (i) forged & machined, or (ii) welded	
11.2	Design phase (Separable Portion 1) duration (weeks)	
11.3	Lead time for delivery of each Separable Portion (months)	
11.4	Country of manufacture	
11.5	Country of origin for all raw materials	
11.6	Details of design to prevent early failure by Type IV cracking or other mechanisms (Their methodology utilised to complete this process i.e. use of FEA (Program Utilised), Standards, Experience etc	
11.7	Inspection schedule and associated NDT procedures and processes to be undertaken in the warranty period. Callide C and Tarong North Power Station unit outage scheduled dates shall be taken into consideration.	
11.8	Warranty period (months)	

11.9	Delivery method	
11.10	Packing and storage method	
11.11	Provide details of manufacturing facility and equipment utilised in the manufacturing processes	
11.12	Provide details of experience in completion of projects of a similar nature (Include at least five references). (DD: Separate schedule in CSE RFP)	
11.13	Provide details of the key personnel in the design and manufacture process and their experience in projects of a similar nature. (DD: Separate schedule in CSE RFP)	
11.14	Short term storage requirements	

12 Right of Access

[To be completed by Utility]

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