Guidelines and Specifications for High-Reliability Fossil Power Plants

Best Practice Guideline for Manufacturing and Construction of Grade 92 Creep Strength Enhanced Ferritic Steel Components

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THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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This report is complementary to *Guidelines and Specifications for High-Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components*, 2nd ed. (EPRI, Palo Alto, CA: 2015 [3002006390]). The template for presenting the information here is generally consistent with those of the previous reports. However, this report provides guidance specific to Grade 92 steel.

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

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ABSTRACT

The benefits of using tempered martensitic steels in high energy applications were largely identified through the development of the alloy known as Grade 91. Grade 92 steel was developed by Nippon Steel, and a submission to the American Society of Mechanical Engineers (ASME) resulted in approval for Code Case 2179 in 1994. There have been a series of modifications and updates since that time, but as of 2019, Grade 92 steel has not been formally incorporated in the ASME Code. Product forms conforming to SA-182, SA-213, SA-335, SA-336, SA-369, and SA-1017 are permitted for manufacture to Code Case 2179-8.

Grade 92 has achieved acceptance within industry for use in fabricating a variety of critical pressure part components, including tubing, headers, and high energy piping systems. Designers generally favor using creep-strength-enhanced ferritic (CSEF) steels, because, within a specific temperature range and when properly processed, this class of steels provides superior elevated temperature strength at substantially lower cost than the austenitic stainless steels. CSEF steels also have the advantageous thermal–physical properties of a ferritic alloy. The recent reduction in the Grade 91 steel stress allowable values will increase the attractiveness of Grade 92 for similar types of applications.

The longest in-service experience of production components is with Grade 91 steels, and there are specific EPRI reports detailing case studies. However, experience with components made from Grade 92 steel now exceeds 50,000 hours, and experience with systems which were properly designed and constructed is generally satisfactory. However, some problems have been reported and fabrication irregularities can result in components entering service with substantially deficient elevated temperature properties. In addition, as the number of tests on Grade 92 steel has increased, it is apparent that under component relevant conditions, high temperature low creep ductility fracture can occur. These critical performance issues are linked to factors such as steel making, steel processing, and component manufacture. Wide variability in performance causes very serious concerns to end-users because of the implications for safety of plant personnel, reliability of equipment, and inability to institute a life management protocol.

This guideline synthesizes an extensive knowledge base to give the information necessary to minimize issues of variability (and hence uncertainty). Maximizing safety by minimizing risk requires that an optimum microstructure and subsequent mechanical properties be achieved. EPRI guidelines thus pertain to how the material should be ordered, how it should be processed, how quality control should be maintained during processing, and how the material should be inspected in the shop and the field to determine its condition before or soon after installation. In combination with other EPRI reports, these guidelines should enable suppliers to control the quality of the material, from purchase through manufacturing and construction. The intent is to ensure that deficient material is never installed. Specific technical areas where the present version of ASME CC2179-8 is insufficient are highlighted to ensure Grade 92 steel of the required minimum quality is manufactured and supplied.

This report establishes requirements for optimizing manufacture and construction practices for Grade 92 components based on the best available information. It is expected that revisions to this guideline will be required as the results of on-going and future research increase the overall body of knowledge and understanding for this complex CSEF steel.

Keywords

Creep-strength-enhanced ferritic (CSEF) steel
Grade 92
Manufacturing practice
Purchasing guideline
Quality control
Specification

FOREWORD

Based on more than two decades of extensive experience with 9%Cr creep strength enhanced ferritic (CSEF) steels, it is emphasized that industry service experience continues to demonstrate that achieving approval for an ASME B&PV Code Case does **not** guarantee a CSEF steel alloy will achieve:

- An implied level of performance reflected in the Code minimum allowable stress values
- A reasonable level of uncertainty in the time-dependent regime regarding strength and/or ductility
- Cross-weld creep behavior which is close to that of base metal, i.e. for typical CSEF steel welds there will be a life reduction (sometimes this reduction is considerable and temperature dependent)
- Damage will be more likely to lead to a leak rather than a break in the pressure boundary

Thus, the objective of this document is to address issues associated with the manufacture of components using Grade 92 steel and to limit the variability in high temperature performance inherent to components fabricated to a minimum set of requirements.

Every attempt has been made to ensure the details of the specification are consistent with industry best practices. These best practices have been developed as a result of knowledge created by research from the Electric Power Research Institute over three decades including at least three major projects. The most recent research has identified issues and recommendations linked to Life Assessment of Grade 92 Steel components. As far as possible, the references provided in the report give technical background linked to specific points within the best practices section. It should be recognized, however, that the metallurgy and performance of all CSEF steels are complex and that a full review of references is recommended to provide a complete understanding.

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1 INTRODUCTION

Grade 92 steel was originally developed by Nippon Steel [1,2,3] (now Nippon Steel Corporation [NSC]) and is consistent with the alloy design philosophy characteristic of creep strength enhanced ferritic (CSEF) steels. Grade 92 steel is intended to be an optimized version of Grade 91 steel, and the material should transform to 100% martensite upon air-cooling.

As a result of the research and development performed by Nippon Steel, in 1994 Grade 92 steel gained acceptance in the ASME Boiler and Pressure Vessel (ASME B&PV) Code as Code Case 2179 [4]. The approval was limited to tubing and piping for Section I construction. It is important to note that ASME approval for use of Grade 92 steel is still governed in 2019 by Code Case 2179 “9Cr-2W UNS K92460 Material”, approved for use in Section I and Section VIII Division 1, and is on its 8th revision, e.g. 2179-8.

It should be noted that the information contained in ASME Code Cases is considered as non-mandatory [5]. It has been stated [5] the most appropriate way to answer the question “What is a Code Case?” is to consider the information provided in the ASME B&PV Code, which states:

> “The Boiler and Pressure Vessel Code Committees meet regularly to consider proposed revisions and additions to the Code and to formulate Cases to clarify the intent of existing requirements or to provide, when the need is urgent, rules for materials or constructions not covered by existing Code rules.”

It is thus generally considered that the use of Code Cases is to provide a “try-before-you-buy” approach and as such Code Cases are intended to be temporary [5]. Protocol in the Code within the last decade has fundamentally changed the way in which Code Cases are reviewed and ultimately upheld. These actions have philosophically changed Code Cases from a temporary document with a stated renewal period to a process in which Code Cases *are not* subjected to a periodic review. Thus, even when further laboratory data and/ or information from in-service experience is available, this new information does not necessarily trigger a Code Case review. The end result is that Code Cases have become more-or-less permanent, with a continued risk within the ASME B&PV Code of the potential to design critical components by Code Case rather than by the rules contained in the relevant book section.

The allowable stress values for Grade 92 steel were developed in 1994 as Code Case 2179 [4]. At the time, the longest, available laboratory creep rupture data was approximately 40,000h in duration. The standard approaches to fitting available creep rupture data and to provide an estimate of long term creep life by extrapolation of the data fit involved use of the Larson-Miller parameter [6] (LMP). This method is based on the following equation:

$$LMP = T\ (C + \log(t)) = f(\sigma)$$

Where T is the absolute temperature, t is the time in hours and C is a constant. The basis of the LMP approach is that results obtained at high temperatures (that is above or even very much above the expected maximum use temperature) can be used to represent long term data at lower temperatures where the steel would be used. Indeed, one of the primary conclusions from [6] is “application of this relation allows the use of short-time tests to determine long-time data with remarkable accuracy." It is clear that such simplistic conclusions, in a paper from 1952, cannot be widely utilized for complex materials such as Grade 92 which show a clear change in deformation and/or damage behavior with increasing test time and/or reductions in stress and/or temperature.

At the time of data submission for Grade 92 (e.g., early 1990s), it was considered appropriate to seek to establish an overall "best fit" to all the available data. Thus, the analysis performed include relatively high stress short term results as well as data at lower stresses and longer times. The "best fit" was developed so as to minimize the errors when describing the available rupture results. In general, this approach will weight the outcomes towards the stresses where the majority of data are available, i.e. to the short creep lives. The approach was, in part, based on the primary conclusion illustrated in the previous quotation and believed to be (circa early 1990s) generally relevant for time-dependent assessment regardless of the material. Based on a review of the data package, it was considered that the best-fit parameter constant, C, was a value of 36. There are on-going concerns over the methods advocated in such an approach including:

- The methodology relies on a statistical fit to the available data. The 'best fit' values of the constants are related to minimizing the perceived errors to the data available. There is no attempt to consider or modify parameters based on physical significance. Moreover, a result where the test life is ten hours is given the same significance in the analysis as a test duration ≥10,000 hours or even ≥100,000 hours. No attempt is made to assign a weighting factor to the data to realistically balance the paucity of data in the long-term. It is clear and a continued challenge to address the reality that many more data exist for rupture lives <10,000 hours compared to the amount of data exist for lives >10,000 hours.
- The methodology assumes that data developed at 700°C (1,292°F) are relevant to behavior at 600°C (1,112°F) or at the maximum permissible temperature of 650°C (1,200°F). For metallurgically complex alloys this assumption is rarely, if ever, valid. In many cases, this effect will be such that the initial extrapolations are too optimistic, i.e. predictions of long-term performance are too long and will necessitate reductions in the allowable stress values to compensate for the data.
- The methods assume that any variation in the data recorded is a random function and cannot be linked to specific heats of the same steel. This approach promotes expediency in the assessment method and by 'lumping' data from many product forms provides the appearance that a large set of data is being analyzed. Clearly if the performance can be explained by heat-to-heat variability, product form, heat treatment or other factors in the manufacturing methods, the individual sets of results must be considered as unique datasets as opposed to a single set of data.
- It is assumed that the only manufacturing variables which significantly influence creep performance are those specifically defined in the Code Case and associated product specifications. It is however implicitly recognized that, particularly for complex steels such as Grade 92, this assumption may not be valid. Thus, ASME typically seeks that the organization making the application for approval undertake and report sufficient information to facilitate informed conclusions by the relevant Code committee(s). To some extent this latitude is at least one reason for the "try-before-you-buy" approach [5].

A creep rupture trend for a range of applied stress values in the range of ~ 30 to 300 MPa (4.35 to 43.5 ksi) for Grade 92 base metal creep data is shown in Figure 1-1. Although the results appear to establish a reasonable trend it should be pointed out that even for these data where the heat treatment conditions were controlled at a stress of 100 MPa (14.5 ksi) the rupture life varies by over an order of magnitude, Figure 1-2. Furthermore, and to the point illustrated above, the extrapolation of a simple LMP relationship for data in the range of 100 to 300 MPa (14.5 to 43.5 ksi) would grossly overpredict behavior for data <100 MPa (14.5 ksi), Figure 1-3. The apparent reduction in variability of the results at lower stresses, and in particular ≤80 MPa (11.6 ksi), is a direct consequence of the paucity of results.

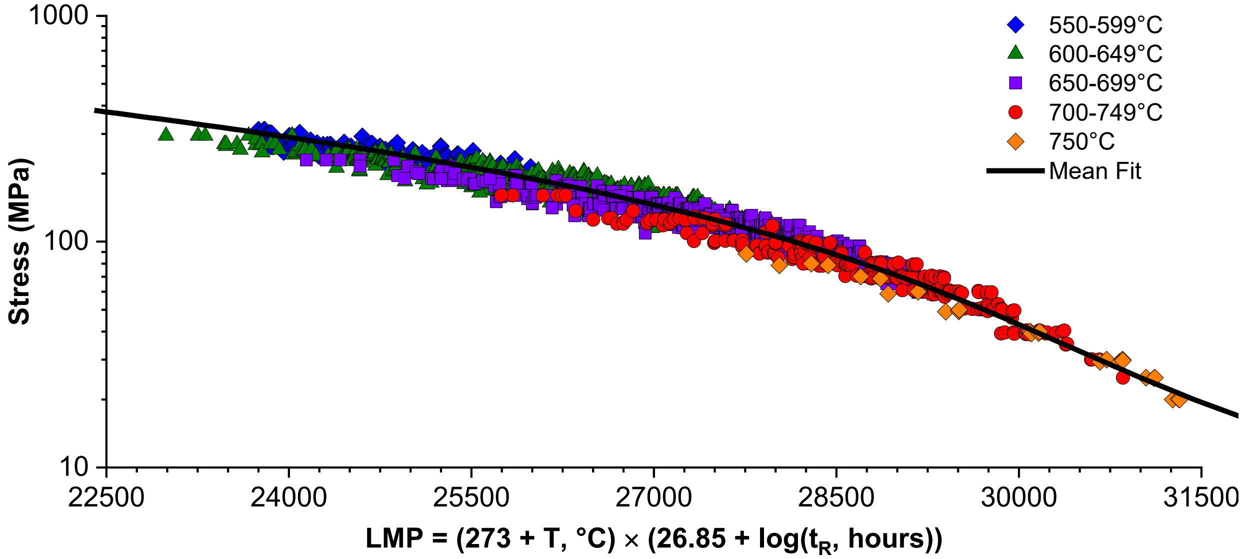

Figure 1-1
Variation of the Larson Miller Parameter with applied stress for base metal Grade 92 steel creep tests with temperatures in the range 550 to 750°C (1,022 to 1,382°F); note the 'mean fit' considers the entire dataset

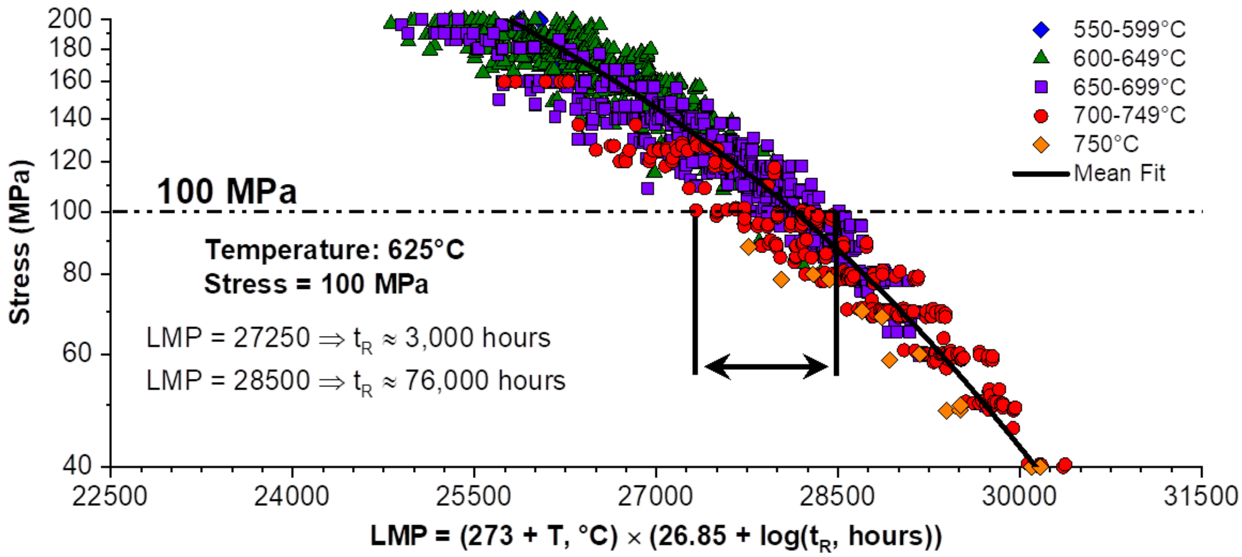

Figure 1-2
Illustration of the variability in Grade 92 steel creep test data for an assumed temperature of 625°C (1,157°F) and an assumed stress of 100 MPa (14.5 ksi). The variation on life is ~25X.

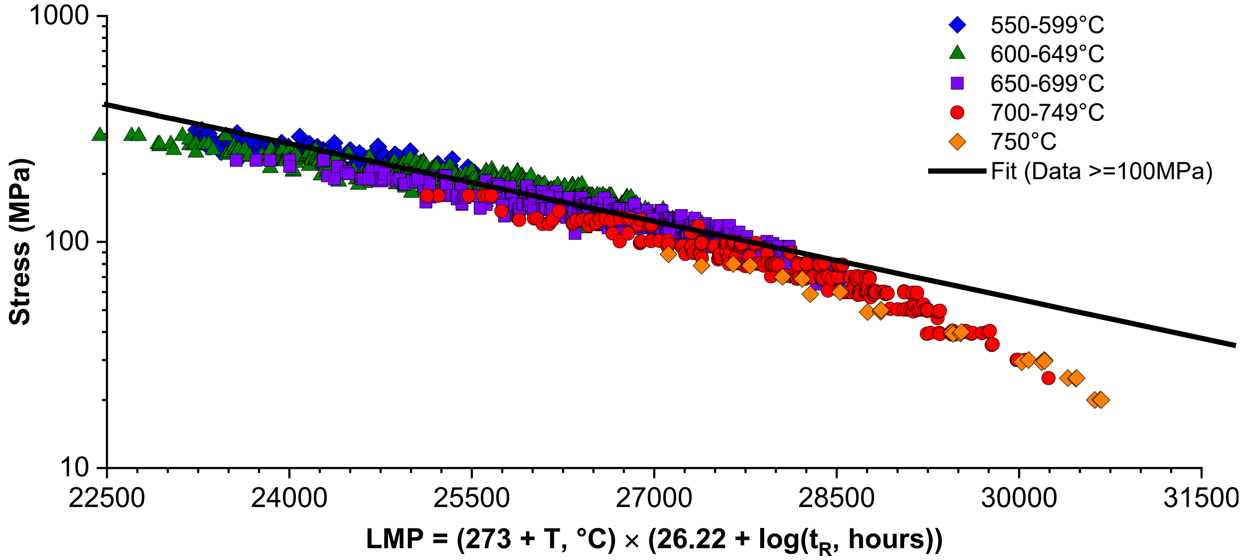

Figure 1-3
Variation of the Larson Miller Parameter with applied stress for base metal Grade 92 steel creep tests with temperatures in the range 550 to 750°C (1,022 to 1,382°F); note the 'fit' considers only the data for an applied test stress of ≥100 MPa (14.5 ksi)

Selected details of the original Code Case and subsequent amendments are provided in Section 2 of this report. It should be appreciated that the original values of the creep rupture strength on which the stress allowable values were developed were reviewed by the Japanese technical community. The result of this review included a substantial downgrade of the allowable stress values for Grade 92; this outcome was recommended to ASME B&PV Code in 2006 [7].

The reassessment of stress allowable values within ASME B&PV Code again utilized the LMP method, but the review recognized that it was erroneous to represent the short-term (high stress) and the long-term (low stress) sides of the stress-time to rupture curve as being continuous. The analysis of the entire set of data using a single relationship was clearly inappropriate. A modified approach was considered, e.g., the splitting of the dataset in accordance with stress as a function of the proof stress (half value of 0.2% proof stress [7]). Using this approach, it was thus deemed that only the low stress data set should be used to determine 100,000h strength, and furthermore that the optimal value for the parameter constant with respect to the entire data set was 24.8 [7]. This value was obviously and considerably lower than the original value of 36 for all data set. As a general statement, higher values of the LMP constant can lead to overestimates in long term creep performance.

Based on recommendations from Japan, as well as re-evaluation of European datasets [8], ASME B&PV Code committees undertook their own reconsideration of allowable stress values previously issued in Code Case 2179. The result was to lower the allowable stress values incorporated in the ASME Code. It should be noted that because the design factor with respect to tensile strength were changed from 4.0 to 3.5 in the ASME Code in 2001, the allowable stress value as determined by tensile strength increased, but the values determined by creep strength decreased substantially. The allowable stress values >550°C (1,022°F) for Grade 92 steel components were subject to considerable reduction.

The high temperature performance of Grade 92 steels is complex. Factors which influence behavior include the elements from which the steel is made, the specific processes involved in steel making and refining, the manner and the temperature in which the solid steel is worked, and the final or quality heat treatment. Most end-users do not seek to deconvolute every aspect governing the complex interactions and outcomes associated with Grade 92 steel. It is, however, critical to emphasize that the knowledge included here is taken from a synthesis of a large knowledge base. Much of the baseline information has been produced directly by EPRI. Three major collaborative projects have been undertaken and these are summarized below:

1. A major project entitled "Advanced 9Cr /12Cr materials for thick section boiler components" was initiated in 1990 (EPRI Project reference 1403 – 50). Key reports from this work include the detailed results in [9-11].
2. A project funded through EPRI's Technology Innovation Program which developed data required for assessing creep, fatigue and creep/fatigue. This project compared behavior of three different Grade 92 steels with testing at 600°C (1,112°F), 625°C (1,157°F) and 650°C (1,202°F). Key reports from this work are provided in [12, 13].
3. A life management of Grade 92 steel project that was initiated in 2011. This project involved engagement with a broad range of Stakeholders involved in the Design, fabrication and use of Grade 92 (and other CSEF) steels. Key reports from this work include the details in [14-16].

The understanding that underpins the present EPRI recommendations regarding manufacture and purchase of Grade 92 steel components is the direct result of a comprehensive database combining advanced metallographic characterization with performance assessment of base metal and welds. No comparable knowledge base linking the effect of manufacturing variables to high temperature component behavior is available. This direct knowledge is critical to understanding the basis for the specific aspects of the research and provides the ability for EPRI to affirm the relevance and the rigor of the information provided.

Knowledge has been shared and extracted from key reports and papers published by expert collaborators and from discussion with the relevant power generation stakeholders involved with designing, fabricating, installing and operating high energy components. The direct personal involvement of EPRI staff elevates the usefulness and value of the research results shared by others in the field of CSEF steel research. These collaborations have also provided a critical means of reviewing and checking the validity of the data, the accuracy of the analysis and the relevance of the recommendations. References are supplied and these source documents should be reviewed to ensure the realization of a full appreciation for both the breadth and depth of knowledge that has been compiled and assessed.

1.1 Benefits Derived from EPRI Guidance

Experience to date demonstrates that when properly processed Grade 92 steel achieves excellent creep strength and fracture resistance. However, it is clear from detailed study of in-service components that Grade 92 steel can be supplied and enter service with a very wide range of creep performance. Thus, *one key benefit of applying the EPRI recommendations and information in this report should be that even in the worst case the components will achieve the minimum Code performance expectations.*

In addition to problems with control of as-supplied properties there are also concerns regarding the expected long term creep behavior. These concerns have been highlighted both in terms of the creep strength and the fracture behavior. For example, there have been several data assessments carried out by ASME since the use of Grade 92 steel was first permitted in 1995 by the approval of Code Case 2179.This report speaks directly to how improved specifications and control during fabrication and installation, significantly reduce the **risks** associated with **in-service cracking** and the associated **cost of repeated outages and inspections**. Thus, the *second key benefit of this report is that improved safety and reliability will be achieved, in a cost-efficient manner, and reduce the extent of variability that is inherent to the basic requirements outlined in Code Case 2179-8.*

1.2 Objectives of this Report

The objective of the research performed were to resolve, to the extent possible given the current state of knowledge, what might be called “front-end” issues, that is, the issues that pertain to how the material should be ordered to avoid purchase of components with poor properties. Proper control includes how the steel is made, how it is processed, how the quality control is maintained during processing, how the material should be inspected in the shop, and how the material should be inspected in the field to determine its condition prior to or soon after installation. The original EPRI report for Grade 91 steel [17] developed necessary specifications and procedural documents that enabled 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; this work was intended to ensure that deficient Grade 91 steel was never installed. Thus, in a similar manner, this report is intended to be a comprehensive guideline that provides information on critical aspects of the ordering, manufacturing, and construction of components fabricated from Grade 92.

Context for the recommendations are provided though summary descriptions of design approaches. These descriptions provide a context for how the information on properties is used as an input to influence design. Additional guidelines published by EPRI provide information on the influence of steel making [18, 19], test methods which are used to check quality, including hardness testing and other NDE methods to verify material properties as well as a recommended life assessment strategy. It is invariably the case that the source documents should be reviewed.

1.3 Component 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 [20]. This section illustrates the different approaches with particular reference to the methods define in the ASME Code.

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.” The conservatism implicit in this approach is directly linked to the value of the maximum “allowable” stress defined. Thus, reductions in allowable stress values should be evidence that the conservatism expected has not been realized. Because of the critical nature of the allowable stress values to design by rule, specific background regarding the ASME decisions and the subsequent Code Case specifications for Grade 92 steel are summarized in detail in an *The Grade 92 Steel Handbook* report which is expected to be published by EPRI in 2021.

The *design-by-analysis* approach typically involves performing detailed stress analysis to categorize the stresses by type and directionality for specific operational conditions. These multiple stress estimates are then checked against a series of permissible limits. Historically ASME has not provided information on the expected limits for Grade 92 steels. The lack of consensus on publishing specific values for the design of Grade 92 components means that application of *design-by-analysis* can only be performed by equipment manufacturers who have developed robust corporate procedures. These procedures are normally confidential to the entity performing the calculations and are based on in-house knowledge and data. 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 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 [12].

The design basis for pressure parts covered by Section I [21] 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—this is true for homogeneous structure and isotropic properties. 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 with the specified allowable stress being the lower value at the design temperature. First, the design stress at the specified temperature is limited to 0.314 times the expected tensile strength at temperature (1.1/3.5); the factor prior to 2001 was 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 stress which will produce a creep rate of 1%/100,000 hours for an average material,
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.

ASME B&PV Code Section I thus does not mandate 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 rules, but these complications are not explicitly considered in the design. Thus, ASME B&PV Code Section I has no explicit rules to account for secondary stresses, which 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 must exceed the design considerations outlined by the rules of ASME B&PV Code Section I to assure long service life.

By steadfastly remaining in the *design-by-rule* category, ASME B&PV Code 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 paper by Roberts [22]. Several problems were used to illustrate some of the deficiencies in components constructed to code rules [22]. 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
e) In-service environmental degradation
f) Consideration of welds and highlighted by a reality that cracking at high temperature occurs predominately at welds

Particular problems are likely to be encountered when local creep and fracture properties may be compromised. It is very unlikely that tensile testing and inspection to check for "soundness" will be able to detect these deficiencies. The design expectation then is that there is sufficient conservatism in the estimates of an allowable stress to prevent problems. For CSEF steels in general and welded CSEF steel components in particular these expectations are NOT valid.

It is incumbent on the designer to recognize these limitations with the ASME Code. In this sense, the ASME 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 ASME Code documents, **the Code is not a handbook and cannot replace education, experience, and the use of engineering judgment**.

1.3.2 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” than a simplified method 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. However, as the operating regimes of components become more complicated because ‘base load’ operation is being replaced by ‘flexible’ operation, and components are being designed to the maximum permissible temperature, the greater complexity of design by analysis maybe justified. Not least because in *design-by–rule*, uncertainty requires that safety factors are applied; thus, making the components thicker. In general, the philosophy is that a thicker component will reduce primary pressure stresses, thus making design safer. However, under conditions of temperature cycling, thicker components can cause thermal stresses to be higher, so that the desired conservatism is NOT achieved.

1.4 Report Organization

The high temperature behavior of Grade 92 steel is complex. Thus, there are many different factors which can influence behavior. These factors start at the beginning of the manufacturing process with issues such as:

- What are the processes required for a final product form?
- How are the parameters for each critical process selected and checked?
- Lastly, how is the billet, ingot or starting material produced and refined?

The processes involved in steel making influence the quality of the final product; these include the manner and the temperature in which the steel is worked, the cooling rate between stages and all aspects of subsequent heat treatment.

Most end-users do not seek to deconvolute every aspect of the product manufacturing process, nor do they seek to understand the complex interactions which can have a marked impact on the final product form. Thus, the current document simply strives to provide key summaries of information which underpin the detailed EPRI guidelines for use in purchasing Grade 92 steel components. However, it must be emphasized that in most cases, poor choices and control in one aspect of the initial steel making and processing steps cannot simply be undone or 'fixed' by a final heat treatment procedure. It is thus the case that the careful definition of procedures, subsequent control of the processes, and necessary quality checks are equally and vitally important. One approach to validation of product quality is through adopting a process to 'qualify' vendors based on review of experience and to maintain this list of vendors to prevent procurement of deficient material and/or components through a standard procurement process.

This document contains specific guidance on technical issues which need to be controlled, as far as possible, to ensure that components manufactured from Grade 92 steel meet the minimum expectations of performance. It is recognized that many of the factors will be open for negotiation between the end-user and suppliers. Thus, in some cases the information presented should be considered an aim for target rather than a formal specification. It should be emphasized that the guidelines are, in some cases, more stringent than the requirements outlined in the material standards or construction codes. The more stringent recommendations have been justified and detailed in previous papers, for example in [17-19].

Information regarding the specific Guidelines is provided in Section 2. Appendix A provides a template purchasing document and outlines how the guidelines may be interpreted to aid component purchase. This document is provided for illustration only and should be read, edited and modified by the end-user. <u>The referenced Appendix containing the purchasing document should not be simply copied and pasted into a purchasing document</u>.

2 PURCHASING INSTRUCTIONS

2.1 Introduction

This document provides a series of EPRI recommendations for the purchase of Grade 92 steel components. These requirements are considered necessary to ensure the satisfactory serviceability of any component fabricated using this material. It is important to note that poor control during steel making and component fabrication cannot simply be compensated by subsequent heat treatment. Similarly, the properties of all parts can be compromised by poor definition and processing during 'downstream' operations. The required in-service performance is achieved when ALL aspects of component supply and installation are properly controlled. Confidence that the necessary controls have been used can be achieved through the application of methods such as the use of experienced vendors, including the adoption of a formalized qualified vendor assessment program, and the application of quality assurance approaches linked to appropriate specifications.

In general, the component should exhibit a uniform microstructure of tempered martensite. It is important to emphasize that if an optical micrograph does not have a martensitic microstructure then it is highly likely that the heat treatment was incorrectly performed. However, the microstructural factors which govern long-term stability in the time-dependent regime cannot be simply or concisely evaluated using standard metallographic techniques which rely on light optical microscopy. Thus, the critical microstructural factors which control the high temperature performance of Grade 92 steel are associated with microstructural features which can only be properly identified using advanced characterization techniques including widely available electron microscopy methods.

The foreword of all ASME B&PV Code sections states 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*" [21]. This statement is an acknowledgement of the fact that equipment has a finite life. However, ASME B&PV Code Section I disavows an intent for a specific design life and contents itself with construction that gives a "reasonably long, safe period of usefulness."

The ASME B&PV Code Section I method of achieving safe boiler design is a relatively simple approach and relies on four foundations as follows:

- Requires all of the features considered necessary for safety are included (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
- Limits the materials to those contained in the specifications in Section II, Parts A and B with the design allowable stress values 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 a direct bearing on the need for the present 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 by the American Society for Testing Materials (ASTM), and then adopted by ASME for its own use. On occasion, modifications considered to be essential for safe operation of the equipment are made by ASME. 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 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. This is emphasized by the stated 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."

The subsections in this Chapter provide basic information which should be considered when purchasing Grade 92 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 within the elemental restrictions specified in Table 2-1 to the extent that commercial conditions permit. Detailed evidence and discussion regarding metallurgical influences in tempered martensitic steels is provided in the EPRI position papers [18, 19].

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 92 heats be validated at the fabricator's site using positive material identification (PMI) testing. An excellent background summary concerned with this form of testing has been provided previously [23]. 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 (C), Nitrogen (N) or Aluminum (Al) content. 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, surface preparation, 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 nor does it provide any information about materials properties. EPRI has published a detailed report which describes approaches for obtaining the composition of components from shavings, scoop samples and bulk samples [24].

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 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. However, it should be emphasized that if a supplier will provide no measurements of the composition of trace elements (for example copper, tin, arsenic antimony) nor assurances regarding the levels of these elements, then purchasers are in a 'buyer beware' position.

It is apparent that 9%Cr tempered martensitic, Grade 91, steel components with excessive levels of trace elements have developed cracks in service and have been replaced within 80,000 hours of operation. 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 this reason, it is useful to ask the producer for comprehensive information regarding "typical" production chemistries to determine whether it is necessary to commercially enforce the more restrictive requirements for that producer. In the minimum, the end-user should request that tramp elements such as As, Cu, Pb, Sb and Sn be reported on the CMTR or other formal document, even if only for informational purposes. For independent assessment of composition, recommended practice and surveying of relevant elements is given in a recent EPRI report [24].

Table 2-1
Recommended chemical composition requirements for component base material (product analysis, given in weight percent).

Elements	Recommended Range	Code Case 2179
Carbon [C]	0.08 to 0.12	0.07 to 0.13
Manganese	0.30 to 0.50	0.30 to 0.60
Phosphorus	0.020 (max.)	0.020 (max.)
Sulfur [B]	0.005 (max.)	0.010 (max.)
Silicon [B]	0.20 (max)	0.50 (max.)
Chromium	8.50 to 9.50	8.50 to 9.50
Molybdenum	0.30 to 0.60	0.30 to 0.60
Vanadium	0.18 to 0.25	0.15 to 0.25
Columbium [B]	0.04 to 0.07	0.04 to 0.09
Boron [B]	0.001 to 0.004	0.001 to 0.006
Nitrogen [BC]	0.035 to 0.060	0.030 to 0.070
Nickel [B]	0.20 (max.)	0.40 (max.)
Tungsten	1.50 to 2.00	1.50 to 2.00
Aluminum [B]	0.020 (max.)	0.02 (max.)
Titanium	0.01 (max)	0.01 (max.)
Zirconium	0.01 (max)	0.01 (max.)
Copper [A]	0.10 (max.)	Not specified
Arsenic [A]	0.010 (max.)	Not specified
Tin [A]	0.010 (max.)	Not specified
Antimony [A]	0.003 (max.)	Not specified
Lead [A]	0.001 (max)	Not specified

Notes:

[A] These elements are not required to be controlled by current ASME/ASTM specifications for base material product forms, but the values above should be considered target levels. In ALL cases as a minimum, the content of these elements should be reported on the CMTR supplied with each heat of material. If not on the actual CMTR then the elements should be reported in an accompanying document. In addition to consideration of the levels of individual elements it is good practice [25] to ensure that the following relationship holds sum of As + Sn + Sb <0.015 weight percent.

[B] Different from Code Case 2179

[C] Carbon + Nitrogen > 0.12

Note: EPRI review of CMTRs for Grade 92 steels has demonstrated that high quality steel suppliers can, and indeed have been, providing steel components which complies with these recommendations for some time.

2.3 Heat Treatment of Grade 92 Steel at the Mill

2.3.1 Introduction

The large number of elements present in CSEF steels makes the process of achieving a fully homogeneous microstructure and substructure more difficult than for simple steels. Technically aware fabricators recognize that there is a significant risk of compositional segregation during casting from the melt. When casting segregation is present, it is impossible to remove the effects simply by using a conventional austenitizing heat treatment. Thus, it is usual under these situations to reheat the ingot or billet to elevated temperature well above the range accepted for austenitization. Homogenization is only possible for a sustained period of exposure to temperature of ~1,250°C (2,282°F). Forging operations are typically performed at a similar temperature and have two primary objectives:

- To modify the shape of the part, and
- To achieve a uniform composition.

The early processing stages do NOT facilitate formation of a final microstructure with sufficient high temperature creep properties. However, it does provide the basis for subsequent final or quality heat treatment processes to achieve the desired microstructure.

All forms of Grade 92 product, including plate, tubing and piping, should be austenitized. Simply applying the austenizing process to components which have significant variability in composition, inclusions and/or precipitates through the wall thickness will **NOT** provide for a homogenous product form. Hence, significant care should be exercised in the control of the steel making process (melting and casting) as well as the initial aspects of fabrication (such as hot forging/forming/processing) to reduce the extent of segregation in the final product form.

A primary concern in Grade 92 exists regarding the formation of BN particles. These particles have been identified in commercial heats of Grade 92 steel, by multiple researchers, and are present in a sufficient size and distribution to cause concern with respect to long-term behavior. If BN is present, not only does a distribution of damage-susceptible particles exist, but the long-term stability to creep deformation will be compromised.

Attempts to resolutionize the BN are possible during the austenitization heat treatment, but at a temperature well above the allowable range in Code Case 2179-8. This concern, in part, is one potential explanation why the recently approved Code Case 2839 allows for a non-conventional anneal in the range of 1,070 to 1,170°C[1].

Controlled experiments suggest that austenitizing at temperatures ≥1,150°C (2,102°F) followed by rapid cooling is required. However, the maximum selected temperature must be balanced against the susceptibility to form and stabilize delta ferrite during the heat treatment. Such considerations are important as the dissolution of BN provides the best opportunity for

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[1] It is noteworthy that the most recent 9%Cr tempered martensitic steel known as Grade 93 was approved by ASME in Code Case 2839 on October 15th 2015. This steel was developed by Nippon Steel Corporation. ASME CC 2839 identifies that normalized and tempered 9Cr-3W-3Co-Nd-B steel should be normalized in the range 1,070 to 1,170°C (2,138°F). The data package presented to ASME identified steel where the only normalizing temperature used was 1,150 °C (2,102°F). The defined tempering conditions in CC2839 are 750 to 790°C (1382 to 1454°F).

maximizing the beneficial influence of B on the stability of long-term creep deformation resistance in Grade 92 components. In light of this critical detail, should future Code Cases contain modification of the current requirements, EPRI would recommend removing the maximum limit of 1,080°C (1975°F) to permit austenitization at a temperature of 1,150°C (2,102°F) followed by accelerated cooling.

The following comments should be considered with respect to heat treatment of Grade 92 components at the mill:

1. Metallurgical differences between Grade 91 and 92 steel include the fact that Grade 92 contains additional, controlled levels of W and B. Thus, it is established that in many components large BN particles will be formed in Grade 92 unless specific steps during fabrication are taken to prevent this. For typical production heats, austenitizing Grade 92 steel at a peak temperature of 1,080°C (1,975°F) will not dissolve BN if it has formed during the processing steps (a significant likelihood considering the evaluation of Grade 92 steel in the EPRI database, and as reported in the literature).
2. In the original development of NF616, Nippon Steel reported results for steels normalized in the range 1,050 to 1,100°C (1,922 to 2,012°F). It was analysis of these data which resulted in the approved Code Case 2179 which contained a minimum austenitization temperature of 1,040°C (1,900°F). No evidence from Grade 92 steel has subsequently been presented (to the Code) demonstrating the need for a specified upper temperature limit. Indeed, published analysis from the ECCC indicates that detrimental creep ductility in Grade 92 steels is more likely when the austenitizing treatment as defined by a time-temperature-parameter (TTP) is inadequate [26].
3. It is technically well established that both time and temperature influence metallurgical changes during austenitization. Thus, to ensure full compliance with objectives, austenitizing conditions should stipulate BOTH the temperature and the time when the full component thickness has achieved the stated temperature. Simple thermal analysis shows that the required time for thick walled, >12.7 mm (0.5 inches) and thin walled ≤12.7 mm (0.5 inches) can be different. For example, the following are suggested:
    a. Thick walled, >12.7 mm (0.5 inches), a minimum of one hour with an additional hour for each 25.4 mm (inch) of thickness above 25.4 mm (one inch),
    b. Thin walled, ≤12.7 mm (0.5 inches), a minimum of ten minutes provided the manufacture can demonstrate with evidence that the duration used results in a uniform through-wall transformation to austenite. Without evidence, the minimum time should be 30 minutes.
4. It is clear that cooling rate after heat treatment from temperatures at or above 1,040°C (1,904°F) will be important in influencing the microstructure and the substructure formed. In CC 2179-8, there is no singular requirement for heat treatment and cooling rate control. Instead these requirements are implemented from the component specific Codes. For example, in SA-336 there is the additional comment that '*accelerated cooling from the normalizing temperature shall be permitted for section thicknesses greater than 3 in. [75 mm]*'.
5. The current requirements within ASME for cooling rate state that components should be air cooled. It should be obvious that the specification of air cooling does not inherently entail a detailed set of procedures. Moreover, without specific planning, different parts of the same

component (both locally and/or through the thickness) can cool at different rates. Thus, simply stating air cooling cannot ensure that all regions of the same component achieve the technically required rate. The need for providing at least some guidance on cooling rate has been recognized by ASME in the Code Case 2864 which was approved in September 2016 for 9Cr–1Mo–V seamless tubes, seamless pipes, forged and bored pipes, fittings, forgings, and plates. This CC specifies that the rate of cooling within the temperature from 900°C to 482°C (1,650°F to 900°F) shall be no slower than 5°C/min (9°F/minute).

6. It is emphasized then that although tempering after cooling to room temperature is very important, it should be recognized that tempering cannot undo previous malpractice. Thus, the austenitizing time and temperature AND the subsequent cooling rate must be properly defined and controlled.
7. The component specifications linked to CC 2179-8 require that tempering is carried out within the temperature range of 730 to 800°C (1,346 to 1,472°F). Because of the links 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 of the instruments involved. The need for this control is emphasized in Code Case 2179-8 which states "if during the manufacture any portion of the component is heated to a temperature greater than 800°C (1,472°F) then the component must be reaustenitized and retempered in its entirety in accordance with the applicable material specification or that portion of the component heated above 800°C (1,472°F) including the heat affected zone created by the local heating must be replaced or removed, reaustenitized and retempered and then replaced in the component."

2.3.2 EPRI Recommendations

For components with homogeneous compositions which comply with Table 2-1, EPRI recommends that austenitizing should be carried out within the specified range 1,040 to 1,080°C. The hold time should be started when the whole component thickness achieves the required temperature and should be at least 10 minutes. Care should be taken to ensure the entire volume of product is allowed to cool uniformly. Cooling shall be continuous to a minimum temperature of least 93°C (200°F) or lower throughout the material thickness before tempering. The rate of cooling through the temperature range 900 to 482ºC (1,650 to 900°F) shall be controlled to be no slower than 5°C/min (9°F/min). For product with a thickness greater than 76 mm (3 in.), forced air-cooling or oil quenching or the equivalent from the austenitizing temperature to an internal work piece temperature below 93°C (200°F) may be necessary to achieve a fully martensitic structure.

For tempering, the selected temperature 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 56°C/hour (100°F/hour) until the internal temperature is below 650°C (1,202°F).

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 92 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 92 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 ±3°C (±5°F) 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 22°C (40°F) 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 ±3°C (±5°F) 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 [27]. For piping, the pattern of thermocouple placement recommended in AWS D10.10 or the more recent guidelines provided in ASME B&PV Code Section I, Non-mandatory Appendix C contains useful guidance 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 ensure 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 austenitizing heat treatment. Suppliers shall provide a detailed heat treatment procedure and record for each product purchased, if required.

2.4 Hardness

2.4.1 Introduction

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 92 steel components [29]. In all cases care should be taken to use testing equipment and methods which give a meaningful result for the actual hardness of the component. 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.

Standard hardness conversion tables are available in ASTM E140. However, the hardness conversion tables that show the Brinell and Vickers Hardness numbers to be identical within the range of 180 to 250 should not be used. Conversion should be performed using the equation developed in the EPRI life management project [29].

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 has published multiple documents detailing issues associated with hardness measurements, calibration and data analysis [29, 30].

2.4.2 EPRI Recommendations

The final (that is after all fabrication and heat treatment but prior to service) hardness values of a component base metal should be above 190 HBW (200 HV). 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 for the given component have been completed; the as-received product form hardness will need to be higher than 190 HBW (200 HV). EPRI recommends that the component fabricated hardness should be a minimum of 200 HBW (210 HV).

It should further be appreciated that in most cases the hardness of Grade 92 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 as that of the base material. For weldments that receive only a subcritical PWHT, it has been established that weld metal hardness is not a reliable indicator of weld metal toughness [31]. Thus, the maximum permissible hardness in the weld metal should be agreed upon by the end-user and supplier using good engineering judgment. 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 partially transformed region of the HAZ. This level of hardness in the partially transformed 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.

2.5 Formed Components

For components designed to ASME B&PV Code Section I, forming strains shall be calculated according to PG-19. For ASME Section VIII, Division 1, component forming strains (outer fibre elongations) shall be calculated according to the UHA- 44 (a). When the forming strains cannot be calculated according to the requirements of ASME B&PV Code Section I, PG-19 or ASME Section VIII, Division 1, UHA-44 (a) the Manufacturer shall have the responsibility to determine the maximum forming strains.

2.5.1 Cold Formed Components

In cases where Grade 92 tube material will be cold-formed (defined as strain introduced at a temperature of below 705°C (1300°F) to levels of strain exceeding 15%), the maximum acceptable as-supplied hardness of the T92 material should be reduced to 230 HBW (242 HV). This level of hardness is necessary to minimize the risk of low-ductility fracture during forming.

The following rules from CC 2179-8 should also be applied:

- For cold-formed flares, swages or upsets in tubing or pipe, the material shall be normalized and tempered in accordance with the requirements of the applicable code or standard.
- For design temperatures >538°C (1000°F), ≤601°C (1115°F) and cold forming strains >25% the material shall be normalized and tempered in accordance with the applicable code or standard.
- For design temperatures >601°C (1115°F) and cold forming strains >20% the material shall be normalized and tempered in accordance with the applicable code or standard
- For design temperatures >538°C (1000°F), ≤601°C (1115°F) and cold forming strains >5% but ≤25% the material shall be heat treated in accordance with the following: 730°C to 775°C (1346°F to 1427°F) for one hour per 25.4 mm (1 inch) of thickness or 30 minutes minimum. Alternatively, the material maybe renormalized and tempered in accordance with the applicable code or standard.
- For design temperatures > 601°C (1115°F) and cold forming strains >5% but ≤20% the material shall be heat treated in accordance with the applicable code or standard.
- For design temperatures ≤601°C (1115°F) and cold forming strains >5% but ≤25% if any portion of the component is heated >775°C (1427°F) then material shall be normalized and tempered in accordance with the applicable code or standard.
- If a longitudinal weld is made to a portion of the material that is cold strained that portion shall be renormalized and tempered in accordance with the applicable code or standard.

2.5.2 Hot Formed Components

Hot forming is defined as permanent strain introduced at a temperature ≥705°C (1300°F). For any hot formed components, the entire product must be renormalized and tempered.

2.6 Mechanical Properties

The yield strength and tensile strength properties of the as-supplied base material shall meet the limits defined in Table 2-2 and Table 2-3. The maximum use metal temperature for Grade 92 steel components should be limited to 625°C (1156°F).

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 620 to 751 MPa (90 to 109 ksi).

Table 2-2
Mechanical Strength Values for Grade 92 steel in US conventional units according to ASME CC 2179-8

Temperature °F	-20 to 100	200	300	400	500	600	700	800	900	1000	1050	1100	1150	1200
Yield Strength ksi	64.0	61.0	59.7	58.9	58.2	57.3	55.7	53.4	49.7	44.5	41.2	37.4	33.0	28.0
Tensile Strength ksi	90.0	84.0	80.6	77.9	75.8	73.7	71.2	68.0	63.8	58.1	54.5	50.6	46.1	40.9

Table 2-3
Mechanical Strength Values for Grade 92 steel in metric units according to ASME CC 2179-8

Temperature °C	-30 to 40	100	200	300	400	450	500	525	550	575	600	625	650
Yield Strength MPa	441	419	406	397	377	359	333	316	297	276	251	223	191
Tensile Strength MPa	621	621	592	563	528	504	472	452	429	404	376	344	309

2.7 Welding Practices

For the purposes of procedure and performance qualifications welds in Grade 92 steel should be considered a P-No. 15E; F-No. 4; A-No. 5 material. The procedure and performance qualification should be conducted in accordance with ASME B&PV Code Section IX. For new construction PWHT is considered mandatory. Background information regarding welding and associated temperature control of Grade 92 steel is given in [32].

2.7.1 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 preheat temperature of 205°C (400°F) shall be maintained. In a tube-to-tube butt weld, the minimum preheat is 150°C (300°F).
- 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 150°C (300°F) 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 205°C (400°F) 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 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 completely dry and free of moisture or contamination until the welding is re-started with the proper preheat.

These precautions are necessary because in the as-welded condition the joint may be vulnerable to environmentally assisted cracking mechanisms such as hydrogen induced cracking or stress-corrosion cracking.

The maximum interpass temperature during welding shall be 350°C (660°F). Most commonly specified maximum interpass temperatures are ≤300°C (600°F).

2.7.2 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 260 to 350°C (500 to 660°F) for one hour minimum for thicknesses of 25.4 mm (1 in.) or less and two hours for thicknesses greater than 25.4 mm (1 in). The hydrogen bake should take place after the part has been allowed to cool to the specified preheat temperature, if this value is ≤200°C (400°F). If it is certain that low hydrogen practices have been successful in limiting the amount of hydrogen in the weldment, a hydrogen bake is not necessary but this is still considered best practice.

2.7.3 Post-Weld Heat Treatment

Following completion of welding, the temperature of the component should be reduced to 175°C (350°F). This should be the temperature at the center of the component wall to insure complete austenite transformation to martensite. The component should then be given a PWHT within eight hours of the completion of welding. If this is not possible, either:

- The component should be maintained at a minimum temperature of 80°C (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.

The post-weld heat treatment should be performed within the range of 730 to 770°C (1350 to 1418°F). The maximum temperature at any point in the PWHT process should not exceed 770°C (1418°F). The minimum temperature differs from the minimum temperatures introduced into ASME B&PV Code Section I, PW-39-5 on the bases of EPRI research in [18] because Code Case 2179-8 specifically limits the minimum value to 730°C (1350°F).

The reduced maximum PWHT temperature of 770°C (1418°F) is intended to provide a buffer during PWHT to minimize the risk of undesirable metallurgical transformations. The temperature and time at temperature for the PWHT should be selected to ensure 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 92 welds, the weld metal and portions of the heat-affected zone may be vulnerable to brittle fracture if subjected to abnormally high mechanical loads during handling. Care shall be taken, therefore, in the handling of Grade 92 weldments in the as-welded condition to minimize the risk.

2.7.4 Filler Materials

2.7.4.1 Matching Filler

Matching filler materials that have similar chemistry and strength to the base metal should be used for all joints between Grade 92 materials. Some manufacturers have reported that in some filler metal products Co has been added to reduce Ni levels. While not precluded by Codes the use of Cobalt is considered as ‘buyer beware’.

In so far as it is possible, EPRI recommends that the chemical composition of the matching filler metal for Grade 92 type components should conform to the elemental restrictions specified in Table 2-2. In addition to the Code requirements for the elements controlled, Table 2-2 includes values reported as typical for welds made to Code requirements.

Table 2-4
Recommended chemical composition requirements (given in weight percent) for Grade 92 type filler materials. EPRI recommended 'Aim For" compositions based on typical values used are provided in in bold type in brackets [ ]

	E9015-B92 – H4	ER90S-G (92)	EG [92]	E91T1-B92 – H4
	SMAW Electrodes	GMAW/ GTAW Bare, Solid Electrodes/Rods	SAW (Weld Deposit wire/flux combination)	FCAW Electrodes
C	0.08-0.13 **[0.11]**	0.08-0.13 **[0.10]**	0.08-0.13 **[0.10]**	0.08-0.13 **[0.11]**
Mn	0.40 - 1.20 **[0.6]**	0.40 – 0.80 **[0.5]**	0.40 – 0.80 **[0.5]**	0.40 - 1.20 **[0.8]**
Si	0.40 max **[0.25]**	0.40 max **[0.30]**	0.40 max **[0.30]**	0.40 max **[0.30]**
P	0.020 max **[0.010]**	0.015 max **[0.008]**	0.015 max **[0.008]**	0.020 max **[0.017]**
S	0.02 max **[<0.010]**	0.015 max **[<0.004]**	0.015 max **[<0.004]**	0.015 max **[<0.01]**
Ni	0.80 **[0.5]**	0.80 **[0.5]**	0.80 **[0.5]**	0.30 -0.80 **[0.5]**
Cr	8.0 - 9.5 **[9.0]**	8.0 - 9.5 **[9.0]**	8.0 - 9.5 **[9.0]**	8.5 - 9.5 **[9.0]**
Mo	0.30 - 0.60 **[0.45]**	0.30 - 0.60 **[0.45]**	0.30 - 0.60 **[0.45]**	0.30 - 0.60 **[0.45]**
V	0.15 - 0.25 **[0.20]**	0.15 - 0.25 **[0.20]**	0.15 - 0.25 **[0.20]**	0.15 - 0.25 **[0.20]**
W	1.5 – 2.0 **[1.7]**	1.5 – 2.0 **[1.7]**	1.5 – 2.0 **[1.7]**	1.5 – 2.0 **[1.7]**
B	0.001 – 0.005 **[0.003]**	0.001 – 0.005 **[0.003]**	0.001 – 0.005 **[0.003]**	0.001 – 0.005 **[0.003]**
Cu	0.15 **[<0.05]**	0.15 **[<0.05]**	0.15 **[<0.05]**	0.15 **[<0.05]**
Al	0.03 max **[<0.01]**	0.03 max **[<0.01]**	0.03 max **[<0.01]**	0.03 max **[<0.01]**
Nb/Cb	0.04-0.07 **[0.05]**	0.04-0.07 **[0.06]**	0.04-0.07 **[0.06]**	0.03-0.07 **[0.04]**
N	0.03 - 0.07 **[0.05]**	0.03 - 0.07 **[0.05]**	0.03 - 0.07 **[0.05]**	0.03 - 0.07 **[0.04]**
Mn + Ni	< 1.20 **[1.00]**	< 1.20 **[1.00]**	< 1.20 **[1.00]**	< 1.20 **[1.00]**
As	**[<0.010]**	**[<0.010]**	**[<0.010]**	**[<0.010]**
Sn	**[<0.005]**	**[<0.005]**	**[<0.005]**	**[<0.005]**
Sb	**[<0.003]**	**[<0.003]**	**[<0.003]**	**[<0.003]**

Notes:

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

B. Ranges or limits expressed in parentheses [ ], are the aim for and most usually achieved values from the limits specified by the applicable ASME SFA Specification.

C. Restrictions on the lower limit for Mn helps to ensure that adequate strength and toughness can be achieved in the weld deposit. In lieu of meeting the stated minimum value of 0.70 weight percent, the Mn to S ratio should be greater than 50 to prevent crater cracking.

D. Since it is an important alloying element specific analysis should be performed (using validated procedures) to check B level.

E. Control of P, S and trace elements is prudent to avoid temper embrittlement [16]. It is desirable that the cumulative influence of these elements as indicated by the 'X" factor is controlled as follows:

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

F. It should be noted that the full specification for Flux Cored Arc Welding in AWS A5.36M depends on the Shielding Gas used: E91T 1-C1PZ-B92-H4 or E91T 1-M21PZ-B92-H4.

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 wt. %.

2.7.4.2 Under-Matching Filler

Under-matching filler materials are those that have weaker tensile and/or creep strength than Grade 92 steel base metal. Examples include: E8015-B8, ER80S-B8, E9018-B3, and ER90S-B3. These fillers may be used for transition joints between Grade 92 and lower alloy steel materials when sufficient thickness of the filler metal and a proper joint design accommodate issues associated with the design allowable stress values at the joint. Proper guidance and additional background on selection of filler material for dissimilar ferritic welds is provided in [32].

2.7.4.3 Ni-Base Filler

Nickel-based filler metals may be used for welding dissimilar metal joints in Grade 92 steels. For example, when transitioning from Grade 92 steel to austenitic stainless steels. Examples of nickel-based filler materials include Weld Alloy 82 (ERNiCr-3), Weld Alloy 182 (ENiCrFe-3), Weld Alloy A (ENiCrFe-2) and EPRI P87 (ENiFeCr-4, ERNiFeCr-4, ASME Code Cases 2733 and 2734). These fillers are generally considered inappropriate for welding Grade 92 to Grade 92 due to increased filler metal cost, inspection difficulty and a risk of failure at the fusion line in a timeframe that could be less than for a weld made with matching filler material.

2.7.4.4 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 filler materials.

a) All SMAW electrodes to be used in the welding of Grade 92 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 four 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. Discarding suspect filler material is desirable and normally the most cost-effective solution.
b) All SMAW electrodes should be certified to the H4 designation.
c) Welding wires, most notably 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 80°C (175°F), or discarded.

2.8 Forging and Forming

Grade 92 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 effect 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.

2.8.1 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 92 steel at the Mill.”

2.8.2 Hot Adjustments to Shape

Hot drawing or hot adjustment is carried out for short periods of time at temperatures between 705°C (1300°F) and 790°C (1450°F). No heat treatment is required after these operations. If the 790°C (1450°F) 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 problems 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.

2.8.3 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 565°C (1050°F) should be given a full austenitization and temper heat treatment in accordance with Section 2.3 “Heat Treatment of Grade 92 steel at the Mill.”

2.8.4 Cold Bending

If the ratio of the radius of the bend (R) to the outer diameter of the tubing (D), R/D, is ≥4, then no post-forming heat treatment is required. If R/D is ≥to 2.5, but <4, the bend region may be heat treated within the temperature range of 1350 to 1418°F (730 to 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 2.5, then the entire component should be normalized and tempered in accordance with Section 2.3 “Heat Treatment of Grade 92 steel at the Mill.”

2.8.5 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 92 steel at the Mill.”

2.9 Surface Condition

During fabrication of components from Grade 92 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 2.7.4.1 of this document.

3
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A

ILLUSTRATION OF A COMPONENT PURCHASING DOCUMENT

Contents

Contract No. XXX/XXX
Technical Specification for the Design, Manufacture, Supply and delivery of Replacement components in Grade 92 Steel

1 Introduction

The Principal is seeking to replace selected welded components. The reason for replacement is due to ***XXX***. It is understood that the design of the original welded components resulted in ***XXX***.

[End-user 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 92 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 92 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 92 components, or

(ii) Welded components fabricated using seamless pipe and/or seamless fittings with a full re-austenitization 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 utilized. 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 P92 pipe without carrying out a full re-austenitization and temper (N&T) heat treatment following fabrication

(iii)Use of any materials other than Grade 92 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

[End-user 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 2020 Edition and ASME Boiler and Pressure Vessel Code 2019 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 HAZ cracking

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

(vii) Design pressure and temperature shall be as per the existing piping design (End-user 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:

[End-user 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 authorized 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 2020 Edition and ASME Boiler and Pressure Vessel Code 2019 Edition.

(ii) All welds shall also be non-destructively examined and compliant to ***[End-user to specify]*** 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. ***[End-user to specify depending on number of separable portions]***

3.1 Chemical Composition of Parent Metal

The chemical composition of all Grade 92 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:

Table A-1
Chemical Composition Requirements for Grade 92 Steel Product Forms

Composition	Weight %
Carbon	0.08-0.12
Manganese	0.30-0.50
Phosphorus	0.020 (max)
Sulphur	0.005 (max)
Silicon	0.20-0.40
Chromium	8.50-9.50
Molybdenum	0.30-0.60
Vanadium	0.18-0.25
Nitrogen[1]	0.035-0.070
Nickel	0.20 (max)
Aluminium	0.020 (max)
Columbium (Niobium)	0.06-0.10
Boron	0.001 to 0.004
Titanium	0.01 (max)
Zirconium	0.01 (max)
Copper[2]	0.10 (max)
Arsenic[2]	0.010 (max)
Tin[2]	0.010 (max)
Antimony[2]	0.003 (max)
Lead[2]	0.001 (max)

Notes:

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 Certified Material Test Report (CMTR) 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 92 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 92 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 92 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 92 components.

3.2.1 Austenitizing

For all product forms austenitizing is to be carried out using a suitable furnace within the temperature range of 1,904 to 1,976°F (1,040 to 1,080°C) to produce a fully martensitic microstructure. Once the full thickness of the component has reached the target *austenitizing* 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 center 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 1,000°F (540°C) may be necessary to achieve the required mechanical properties.

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

3.2.2 Tempering

For all product forms tempering is to be performed within the temperature range of 1,350 to 1,440°F (730 to 780°C). Note that because of the risk of stress-corrosion cracking that exists when Grade 92 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 175°F (80°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 92 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 or ASME B&PV Code Section I Non-mandatory Appendix C 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 92 steel, the Respondent shall provide a certified temperature/time record for each Grade 92 component or lot of components processed as a single batch. Heat treatment equipment test and calibration certificates shall also be provided.

3.3 Steel Hardness

All Grade 92 components produced for the Principal shall be evaluated by hardness testing following each thermal processing step as detailed in the following sections.

3.3.1 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 92 steel components.

With respect to the base materials supplied from the mill for subsequent fabrication, the hardness of the Grade 92 material shall be a minimum of 200HB/210HV (93.4HRB). 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

3.3.2 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.

3.4 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.

3.5 Forming Processes

All working or heating of Grade 92 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.

3.5.1 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.

3.5.2 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.

3.5.3 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 before re-insertion in the component, or to replace the overheated zone with new material.

3.5.4 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.

3.5.5 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.

3.6 General Welding Practice

Where welding will be performed on Grade 92 steel as part of the component production process, the following requirements shall be satisfied.

3.6.1 Preheat

Prior to the beginning of any welding on Grade 92 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 92 material using the shielded metal arc process (SMAW) or the submerged-arc process (SAW), a minimum preheat temperature of 400°F (205°C) shall be maintained for the duration of the welding.

(ii) For welds on Grade 92 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 preheat

3.6.2 Interpass Temperature

The maximum interpass temperature during welding shall be 662°F (350°C).

3.6.3 Hydrogen Bake

A Hydrogen Bake is best practice when low hydrogen controls cannot be guaranteed and should be considered for all joints. The bake should be performed in the temperature range of 500 to 660°F (260 to 350°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).

3.6.4 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 2.3 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 reaustenitized 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 1,346 to 1,418°F (730 to 770°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 92 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 92 components containing welds that are in the as-welded condition to minimize the risk of brittle fracture.

3.6.5 Weld Filler Metals

The chemical composition of the filler materials used shall conform to the limits specified in Table 4-1 below so that the sum of the Mn plus the Ni contents shall not exceed 1.0%. 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 92 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) Cored 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

3.6.6 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 A-2
Chemical Composition Requirements for Grade 92 steel Matching Weld Filler Materials

	E9015-B92 – H4	ER90S-G (92)	EG [92]	E91T1-B92 – H4
	SMAW Electrodes	GMAW/ GTAW Bare, Solid Electrodes/Rods	SAW (Weld Deposit wire/flux combination)	FCAW Electrodes
C	[0.11]	[0.10]	[0.10]	[0.11]
Mn	[0.6]	[0.5]	[0.5]	[0.8]
Si	[0.25]	[0.30]	[0.30]	[0.30]
P	[0.010]	[0.008]	[0.008]	[0.017]
S	[<0.010]	[<0.004]	[<0.004]	[<0.01]
Ni	[0.5]	[0.5]	[0.5]	[0.5]
Cr	[9.0]	[9.0]	[9.0]	[9.0]
Mo	[0.45]	[0.45]	[0.45]	[0.45]
V	[0.20]	[0.20]	[0.20]	[0.20]
W	[1.7]	[1.7]	[1.7]	[1.7]
B	[0.003]	[0.003]	[0.003]	[0.003]
Cu	[<0.05]	[<0.05]	[<0.05]	[<0.05]
Al	[<0.01]	[<0.01]	[<0.01]	[<0.01]
Nb/Cb	[0.05]	[0.06]	[0.06]	[0.04]
N	[0.05]	[0.05]	[0.05]	[0.04]
Mn + Ni	[1.00]	[1.00]	[1.00]	[1.00]
As	[<0.010]	[<0.010]	[<0.010]	[<0.010]
Sn	[<0.005]	[<0.005]	[<0.005]	[<0.005]
Sb	[<0.003]	[<0.003]	[<0.003]	[<0.003]

Notes:

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

B. Ranges or limits expressed in parentheses [ ], are the aim for and most usually achieved values from the limits specified by the applicable ASME SFA Specification.

C. Restrictions on the lower limit for Mn helps to ensure that adequate strength and toughness can be achieved in the weld deposit. In lieu of meeting the stated minimum value of 0.70 weight percent, the Mn to S ratio should be greater than 50 to prevent crater cracking.

D. Since it is an important alloying element specific analysis should be performed (using validated procedures) to check B level.

E. Control of P, S and trace elements is prudent to avoid temper embrittlement [16]. It is desirable that the cumulative influence of these elements as indicated by the 'X" factor is controlled as follows:

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

F. It should be noted that the full specification for Flux Cored Arc Welding in AWS A5.36M depends on the Shielding Gas used: E91T 1-C1PZ-B92-H4 or E91T 1-M21PZ-B92-H4.

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 50 mm 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.

[End-user 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 92 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 End-user]

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.

[End-user to modify above paragraph separately to suit individual circumstances]

10 Principal Supplied Documents

Documents & drawings relevant to the tender

[To be completed separately by End-user]

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 creep cracking or other mechanisms (The methodology utilized to complete this process i.e. use of FEA (Program Utilized), Standards, Experience etc	
11.7	Inspection schedule and associated NDT procedures and processes to be undertaken in the warranty period. Scheduled outage 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 utilized in the manufacturing processes	
11.12	Provide details of experience in completion of projects of a similar nature (Include at least five references).	
11.13	Provide details of the key personnel in the design and manufacture process and their experience in projects of a similar nature.	
11.14	Short term storage requirements	

12 Right of Access

[To be completed by End-user]

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