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Guidelines and Specifications for High Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components, 3rd Edition

2021 TECHNICAL REPORT

Guidelines and Specifications for High Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components, 3rd Edition

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Technical Report, May 2021

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Guidelines and Specifications for High Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components, 3rd Edition. EPRI, Palo Alto, CA: 2021. 3002018025.

ABSTRACT

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

Recent service experience has confirmed that early failures can occur in components fabricated from the CSEF steels unless the required condition of the microstructure is developed and maintained during processing. This is documented in three EPRI reports 1018151, S*ervice Experience with Grade 91 Components;* 3002005089, *Service Experience with Creep Strength Enhanced Ferritic Steels in Power Plants in the Asia-Pacific Region;* and most recently 3002008548, *Review of Creep Strength Enhanced Ferritic (CSEF) Steel Experience in the Asia-Pacific Region: Detailed Case Studies*. Fabrication irregularities can result in components entering service with substantially deficient elevated temperature properties. These issues have caused serious concern as a result of the obvious implications for the safety of plant personnel and the reliability of equipment.

This report provides the information necessary to resolve issues that pertain to how the material is ordered, how it is processed, how quality control is maintained during processing, and how the material is inspected in the shop and the field to determine its condition before or soon after installation. In combination with other EPRI reports, this report should enable suppliers to control the quality of the material at every stage of its implementation. The intent is to ensure that deficient material is never installed. This report establishes requirements for optimizing manufacturing and construction practices for Grade 91 components based on the best available information. Revisions to this report will be prepared as required by improved knowledge and understanding.

Keywords

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

EXECUTIVE SUMMARY

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PRIMARY AUDIENCE: Corporate engineers responsible for asset management

SECONDARY AUDIENCE: Designers and maintenance planners

KEY RESEARCH QUESTION

Extensive case studies documented by EPRI, and as provided in reports, member presentations, conferences or workshops and other media, have consistently demonstrated the challenges linked to the fabrication and erection using complex ferritic steels like Grade 91. Implementation of the present guideline document will reduce future challenges linked to the fabrication or construction of Grade 91 steel components.

RESEARCH OVERVIEW

This report describes research sponsored by EPRI and has been authored and made publicly available to address issues associated with the manufacture of components with Grade 91 steel and reduce the overall uncertainty for installed components or systems manufactured from this creep-strength-enhanced ferritic (CSEF) steel. Following the introduction and background, a chapter provides specific details associated with the purchase of Grade 91 steel components. Every attempt has been made to ensure that the details of the specification are consistent with industry best practices. It should be recognized, however, that the metallurgy and performance of Grade 91 steel are complex and that a full review of references is recommended to provide a complete understanding.

KEY FINDINGS

The present report replaces the 2015 report, G*uidelines and Specifications for High-Reliability Fossil Power Plants, 2nd Edition: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components* (3002006390). The bulk of the information remains as originally published, and key updates have been included in this report and this report should be used. The appendices have largely been removed as over the last decade significant improvements to the knowledge base are available in the referenced EPRI reports including ~10 publicly available position papers. The information contained in this report has been produced by synthesis of more than 30 years of experience with Grade 91 material in the laboratory, in the shop, and in the field. In addition, the analysis and comments provided by the members of several projects have proved invaluable to the organization and the content of this report.

EXECUTIVE SUMMARY

WHY THIS MATTERS

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

Recent service experience has confirmed that early failures can occur in components fabricated from the CSEF steels unless the required condition of the microstructure is developed and maintained during processing. This is documented in three EPRI reports:

1. 1018151, Service Experience with Grade 91 Components
2. 3002005089, Service Experience with Creep Strength Enhanced Ferritic Steels in Power Plants in the Asia-Pacific Region and
3. 3002008548, an expansion of the report 3002005089 with additional case studies.

Fabrication irregularities can result in components entering service with substantially deficient elevated temperature properties. These issues have caused serious concern because of the obvious implications for the safety of plant personnel and the reliability of equipment.

HOW TO APPLY RESULTS

This report provides the information necessary to resolve issues that pertain to how the material is ordered, how it is processed, how quality control is maintained during processing, and how the material is inspected in the shop or in the field to determine its condition before or soon after installation. In combination with other EPRI reports, this report should enable suppliers to control the quality of the material at every stage of its implementation. The intent is to ensure that deficient material is never installed. This report establishes requirements for optimizing manufacturing and construction practices for Grade 91 components based on the best available information. Revisions to this report will be prepared as required by improved knowledge and understanding.

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PROGRAM: Materials and Repair, P229

FOREWORD

This report describes research sponsored by EPRI and has been authored and made publicly available to address issues associated with the manufacture of components with Grade 91 steel and reduce the overall uncertainty for installed components or systems manufactured from this creep-strength-enhanced ferritic (CSEF) steel. Following the introduction, there is a section that provides specific details associated with the purchase of Grade 91 steel components. Every attempt has been made to ensure that the details of the specification are consistent with industry best practices. It should be recognized, however, that the metallurgy and performance of Grade 91 steel are complex and that a full review of references is recommended to provide a complete understanding.

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- The need for measurement and control of trace elements has been formally recognized by ASME B&PV Code Section IIA.
- Modifications to the allowable post weld heat treatment (PWHT) ranges, in particular the minimum values, have been incorporated by ASME B&PV Code Section I in 2017 and by ASME B31.1 in 2018.
- The American Welding Society (AWS) will formally recognize type -B91 designations for all common welding product forms manufactured to A5.5, A.5.23, A.5.28 or A5.29.
- Clarifications have been made to details regarding welding procedures, consumables, and best practices.
- On-going discussion with end-users, OEMs and other stakeholders has resulted in rewording to clarify language in specific sections of this report.
- The outcomes of on-going research provide information to support and/or further clarify the requirements in the report.
- Knowledge from activities such as post-mortem investigations of Grade 91 steel components that were in operation for durations up to 140,000 hours has also informed requirements.

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

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INTRODUCTION

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

Grade 91 was codeveloped by the Oak Ridge National Laboratory (ORNL) and Combustion Engineering (now incorporated into General Electric [GE]) at its Metallurgical and Materials Laboratory in Chattanooga, Tennessee. Extensive study under Department of Energy sponsorship in the 1975 to 1980 timeframe demonstrated the alloy's excellent mechanical performance and thermophysical attributes [1–3]. As a result, the alloy attracted the attention of designers of boilers and pressure vessel fabricators, and, in 1983, Grade 91 gained initial acceptance in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code as tubing for Section I construction in Code Case 1943.

The ensuing years have seen broad application of the material in both the power and petrochemical industries. Major EPRI initiatives, through an industry collaborative effort, eventually materialized into acceptance of Grade 91 steel in the prerequisite product forms including pipe, plate, forgings and castings to facilitate construction of complex boiler or piping systems. The evolution of the developments resulting from major industry projects specific to Grade 91 steel and associated acceptance by ASME are summarized in Figure 1-1 with information from EPRI-specific initiatives linked to CSEF steels shown in Figure 1-2.

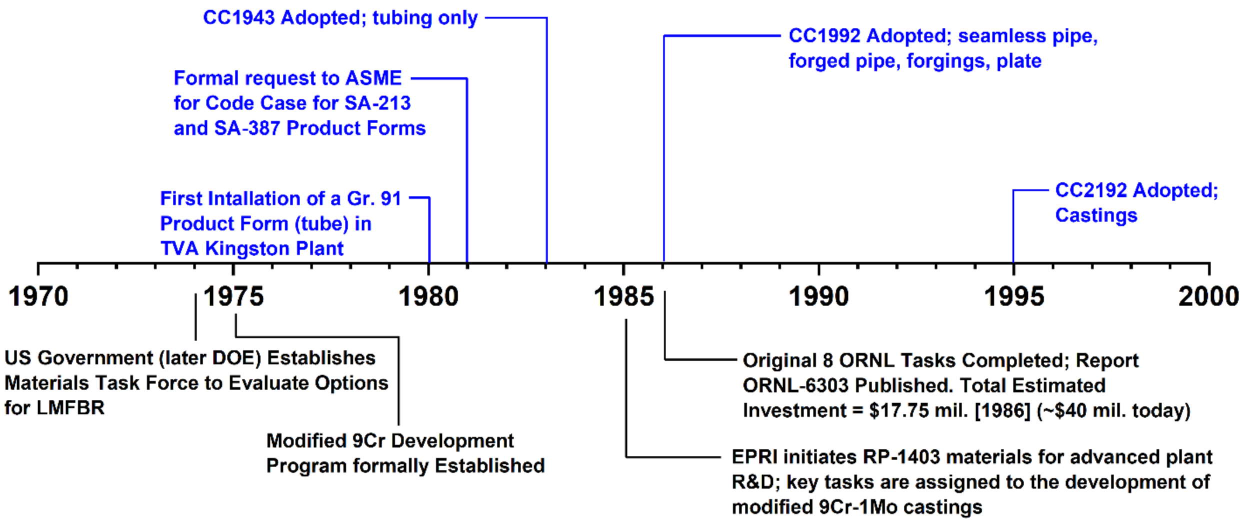

Figure 1-1
Summary of major industry-led research projects and ASME B&PV Code acceptance of Grade 91 steel product forms

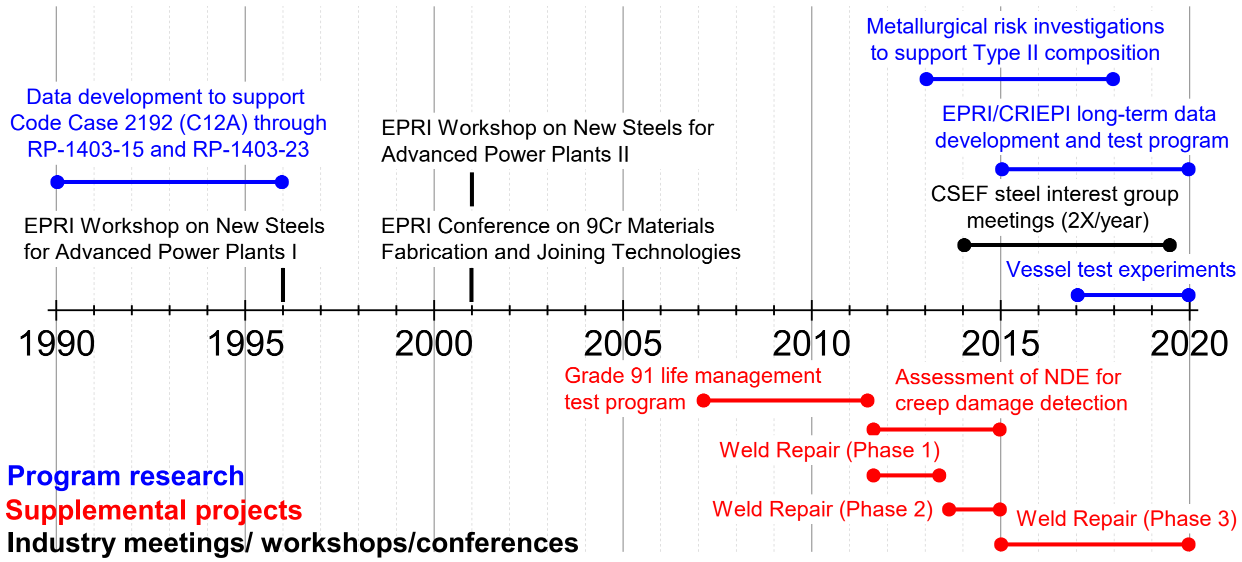

Figure 1-2
Summary of EPRI-led research projects specific to Grade 91 product forms

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

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

The high temperature performance of Grade 91 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 91 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.

The understanding that underpins the present EPRI recommendations regarding manufacture and purchase of Grade 91 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 foundation and database, largely assembled over the last 15 years, 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. In particular, a number of position papers are publicly available specific to 9%Cr CSEF steels, Table 1-1.

Table 1-1
Position papers relevant to 9%Cr creep strength enhanced ferritic (CSEF) steels and used to better inform the stakeholders in the power generation industry

Report Number	Title	Year	Category
3002003472	The Benefits of Improved Control of Composition of Creep-Strength-Enhanced Ferritic Steel Grade 91	2014	Composition
3002004370	The Influence of Steel Making and Processing Variables on the Microstructure and Properties of Creep-Strength-Enhanced Ferritic Steel Grade 91	2014	Processing
3002005350	A Well-Engineered Approach for Establishing the Minimum Allowable Post-Weld Heat Treatment for Power Generation Applications of Grade 91 Steel	2015	Fabrication & Welding
3002005351	A Perspective on the Selection of Preheat, Interpass, and Post-Weld Cool Temperatures using Grade 91 Steel as an Example	2015	Fabrication & Welding
3002007320	An Informed Perspective on the Use of Hardness Testing in an Integrated Approach to the Life Management of Grade 91 Steel Components	2016	Life Management
3002011137	Guide to Grade 91 Use Temperature Limits due to Steam Oxidation and Exfoliation	2017	Oxidation
3002012262	Integrated Life Management of Grade 91 Steel Components: A Summary of Research Supporting the Electric Power Research Institute's Well-Engineered Approach	2018	Life Management
3002012592	An Informed Perspective on the Application of Replication in an Integrated Approach to the Life Management of 9%Cr Creep-Strength-Enhanced Ferritic Steel Components	2018	Life Management
3002020389	An Informed Perspective on the Reduction in the Stress Allowable Values for Grade 91 Steel in the 2019 Edition of ASME B&PV Code Section IID	2021	Life Management

1.1 Summary of Experience

Experience to date demonstrates that when properly processed Grade 91 steel achieves excellent creep strength and fracture resistance. However, it is clear from detailed study of in-service components that Grade 91 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 [4,5]. Recent service experience has confirmed failures can occur in components fabricated from the CSEF steels very early in life if the required condition of microstructure is not developed and/or maintained during processing. Several

Electric Power Research Institute (EPRI) documents review and summarize service experience with Grade 91 steel, Table 1-2.

Table 1-2
Relevant service experience reports supporting the need for a unique specification

Report	Title	Relevant Content
1018151	*Service Experience with Grade 91 Components*	
1019575	*Evaluation of Ex-Service Grade 91 Material*	
1023837	*Thermowell and Radiographic Testing Plug Design Recommendations and Typical Practices*	Chapter 5
3002001317	*HSRG Life Assessment – Case Studies*	Case studies 2, 4-7
3002003312	*Understanding and Avoiding Early Service Life Failures of Grade T91 Tubing*	
3002004991	*Experiences in Valve Hardfacing Disbonding*	Chapter 2, Appendix A
3002008548	*Review of Creep Strength Enhanced Ferritic (CSEF) Steel Experience in the Asia-Pacific Region – Detailed Case Studies*	
3002007882	*Service Experience of Fabricated Wyes, Laterals, Branches and Seam Welded Components Manufactured from Grade 91 Steel*.	Chapter 3
3002006227	*Evaluation of an Ex-Service Ferritic-to-Ferritic Dissimilar Metal Weld Between Grade 22 and Grade 91*	
3002006759	*Cracking in Thick-section Dissimilar Metal Welds – Case Studies*	
3002007221	*Guidelines and Specifications for High-Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 to Austenitic Stainless Steel Dissimilar Metal Welds*	Chapter 4
3002011582	*Best Practice Guidelines for Fabricating Ferritic to Ferritic Dissimilar Metals Welds*	Chapter 2

It is apparent that irregularities during fabrication can result in components entering service with elevated temperature properties that are substantially deficient when compared with an average heat of material [6, 7]. These issues have caused serious concern among users because of the obvious implications for the safety of plant personnel and the reliability of equipment and generally classified by the following:

- Material procurement
- Shop fabrication
- Field erection
- Quality assurance procedures to be applied during each phase of fabrication
- Assessment of the in-service behavior of base metal and weld metal, with a particular emphasis on the provision of a comprehensive strategy for life prediction and optimization of maintenance
- Strategies for well-engineered repairs

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 the common SA-specs or design rules in commonly cited codes like ASME B&PV Code.*

It is the case that the bulk of the in-service problems encountered so far involve Grade 91 material. However, because of the fundamental similarity in metallurgy that exists between the various grades of the CSEF steels, it was anticipated that much of the information obtained from the study of Grade 91 would also apply to similar steels that are approved for use by the ASME B&PV Code, including Grade 92, and other CSEF steels recently approved by ASME Code. The development of a set of fabrication guidelines specific to Grade 92 steel was published in 2020 [8].

Recently, there has been a resurgence of research into advanced 9–12 wt. % Cr CSEF steels, leading to the introduction of new alloys that claim a modest-to-significant strength increase over Grade 91. Examples of new alloys include Grade 122 (Code Case 2180), Grade 92 (Code Case 2179), Grade 911 (Code Case 2327), VM12HC (Code Case 2781), Grade 93 (Code Case 2839) and THOR 115 (Code Case 2890). As shown in Figure 1-3, the rate at which alternative steels have become available has been increasing. Thus, it has become even more important to identify, understand and ultimately control the factors which affect long-term component performance and integrity. It is important to appreciate there may exist alloy-specific composition and processing controls to develop an optimized microstructure that will ultimately mandate a series of unique specifications and supporting research for each grade in this family of steels.

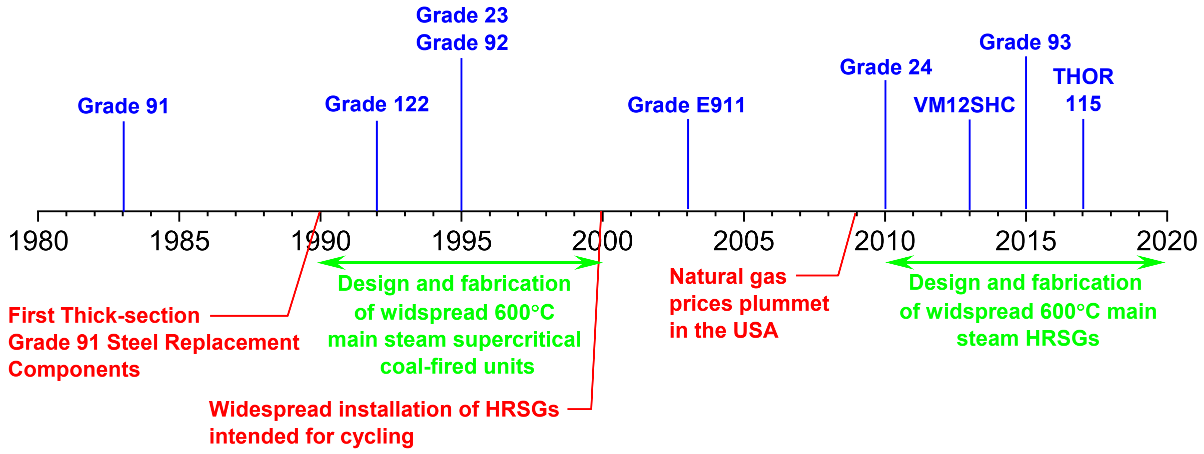

Figure 1-3
Timeline of creep strength enhanced ferritic steel code case acceptance

1.2 Summary of EPRI Databases Supporting the Recommendations in this Report

Regarding the assessment of Grade 91 steel time-dependent behavior, EPRI has generated ~7M hours in cumulative testing to support its recommendations contained in the present report. The data generated by a specific EPRI program as part of its annual research portfolio or as a consequence of a supplemental project are detailed in Figure 1-4. As highlighted, there have been several significant test programs resulting in a selection of legacy and recent EPRI reports, Table 1-3. The total EPRI funding that has contributed to the overall perspective is broken down by the following:

- EPRI legacy research projects (‘RP’) RP1403-15 and RP1403-23 to generate long-term time-dependent and supporting time-independent data from three large castings sourced from worldwide suppliers. The information later allowed for the submission and adoption of Code Case 2192 in the mid-1990s (see Figure 1-1). Total funding provided by EPRI to support these efforts is unknown.
- Supplemental projects led by EPRI Generation Sector Programs and supported by the stakeholders in the energy industry in the 2007 to current timeframe total ~$10M.
- EPRI long-range research initiatives, e.g. ‘Technology Innovation’, include the development of an ASME Code Case data package for PM/HIP Grade 91 steel product form and improved guidance for making dissimilar metal welds (DMWs) between Grade 91 and austenitic stainless steels. These projects were conducted over the 2012 to 2020 timeframe and total ~$3.5M.
- Projects included as part of the EPRI annual research portfolio, beginning in 2011 to extend the learnings from the Grade 91 life management project, have totaled ≥$5M through 2020.

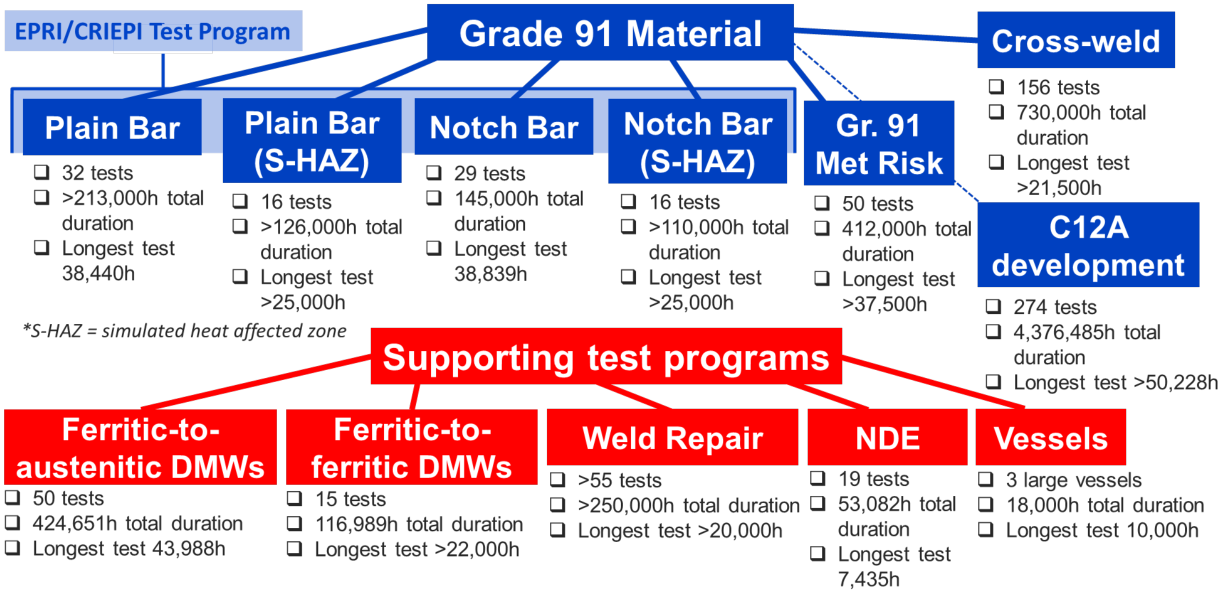

Figure 1-4
Breakdown of Grade 91 steel data to assess the influence of metallurgical risk and/or fabrication processes (blue) and supporting test programs (red) to assess specific aspects of DMWs, life management (repair + NDE) or multiaxial stress state effects (vessel tests)

Table 1-3
Supporting reports

Report	Title	Year published	Brief description
TR-104845	*Creep Behavior of Modified 9%CrMo Cast Steel for Application in Coal-Fired Steam Power Plants*	1995	Time-dependent data for cast grade 91 steel (later to become C12A)
TR-106856	*Properties of Modified 9Cr-1Mo Cast Steel*	1996	
3002000080	*Life Management of Creep-Strength-Enhanced Grade 91 Steels--Atlas of Microstructures: Base Metal*	2013	Time-dependent data for variable-quality Grade 91 steel base metal including material that had been obtained or lab heat treated in the ferritic or degraded condition. Assessment of the influence of the N:Al ratio on strength.
3002000081	*Life Management of Creep Strength Enhanced Grade 91 Steels - Atlas of Microstructures and Welds*	2013	Time-dependent data for welds manufactured in the laboratory to identify the contribution of the N:Al ratio, post weld heat treatment, and filler metal selection on the weld strength reduction factor.

Table 1-3 (continued)
Supporting reports

Report	Title	Year published	Brief description
3002005187	*Nondestructive Methods for Detection of High-Temperature Damage in Creep-Strength-Enhanced Ferritic Steels (Grades 91 and 92) as a Basis for Life Evaluation*	2015	Supporting tests to determine the resolution and/or capability of commonly utilized NDE techniques (acoustic emission and ultrasonic testing including phased-array) to identify damage in the heat affected zone of large cross-weld tests and at what life or strain fraction.
3002019026	*Development of Nondestructive Examination Coupons in Damage Tolerant and Damage Intolerant Grade 91 Welds*	2020	
3002009678	*Life Management of 9%Cr Steels: Evaluation of Metallurgical Risk Factors in Grade 91 Steel Parent Material*	2018	Isolation of specific compositional factors which contribute to poor strength and/or poor creep ductility in long-term base metal tests. More than 30 unique, commercially-sourced Grade 91 steel heats assessed.
3002011582	*Best Practice Guidelines for Fabricating Ferritic-to-Ferritic Dissimilar Metal Welds*	2020	Supporting cross-weld data for ferritic-to-ferritic DMW performance. Includes data for lab-generated and ex-service welds.
3002018021	*Creep Performance of Dissimilar Metal Welds Between Grade 91 Steel and Stainless Steel 347H*	2020	Supporting cross-weld data for ferritic-to-austenitic DMW performance. Includes data for lab-generated and ex-service welds.
3002018004	*Life Management of 9%Cr Steels–Creep Rupture and Creep-Fatigue Behavior of Grade 91 and 92 Steels (2020 Update)*	2020	Long-term test program to assess the performance of Grade 91 and Grade 92 steels as well as determine the behavior of base metal, simulated heat affected zone and multiaxial stress state effects.
3002010390	*Design, Fabrication, Quality Assurance, and Testing of Grade 91 Vessels*	2020	Three large vessel tests fabricated from an ex-service superheat outlet header containing unique welded features including simulated repairs and tested up to 10,000 hours.
3002012187	*Alternative Well-Engineered Weld Repair Options for Grade 91 Steel: Results for Creep Testing of Similar Metal and Dissimilar Metal Tube-to-Tube and Feature Welds*	2020	Feature-type cross-weld tests for alternative weld repairs manufactured in ex-service welds (including DMWs) and assessment of service-removed repairs performed to Welding Method 6.

The EPRI investment to decrease the variability in the installed component or system, increase confidence in existing life management practices through a reduction in the uncertainty in the inputs, and ‘raise the bar’ through technology transfer of critical learnings to the stakeholders in the energy industry including codes and standards is on the order of ~$20M. This is in addition to the U.S. government $40M investment in 1975 to 1985 to realize “code-acceptance” of Grade 91 steel for an initial set of necessary product forms.

1.3 Objective

The objectives of the research performed was 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 2011 EPRI report, *Guidelines and Specifications for High-Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components* (1023199), 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. EPRI report 1023199 was intended to ensure that deficient material is never installed. Therefore, it was a comprehensive guideline that provided information on critical aspects of the ordering, manufacturing, and construction of components fabricated from Grade 91 material.

The original document was updated with a number of substantive developments in 2015 (3002006390). The most recent 3rd edition of the specification (3002018025) addresses a number of recent developments, some of which are highlighted in Table 1-4 and summarized below:

- The inclusion of a Type 2 composition line for common product forms for Grade 91 steel, which was justified, in part, by EPRI position papers and thorough discussion with the relevant ASME subgroups, working groups, and committees in the 2014 to 2017 timeframe [9, 11].
- Revision of minimum post weld heat treatment (PWHT) requirements for components manufactured to ASME B&PV Code Section I or ASME B31.1 where adjustments were made in 2017 and 2018, respectively. Justification for these actions is well-detailed in an EPRI position paper [12].
- Revision of filler metal specifications to AWS type -B91 for commonly utilized filler metal product forms.
- And on-going research by EPRI, for example quantification of metallurgical risk factors, that has further refined recommendations regarding preferred compositional ranges for common Grade 91 steel product forms [13]

Table 1-4
Summary of recent developments in ASME B&PV Code where EPRI data and technology transfer efforts were essential to the change

Activity	Code	Edition reflecting update or change
Improved composition for Grade 91 steel product forms	ASME B&PV Code Section I Code Case 2864	2016
Reduced minimum PWHT requirement for P15E Group 1 materials	ASME B&PV Code Section I	2017
	ASME B31.1	2018
Type 2 composition into ASTM A- and SA- specifications	ASTM ASME B&PV Code Section IIA	2019
Reduction in the stress allowable values for Grade 91 steel and review of the values for other CSEF steels	ASME B&PV Code WG-CSEF steels	2019
Non-mandatory Appendix F on dissimilar metal welds	ASME B&PV Code Section I	2019

1.4 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 [14]. This section illustrates the different approaches with particular reference to the methods defined 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 Grade 91 steel are summarized in detail in an *The Grade 91 Steel Handbook* report which will be updated by EPRI in 2021 [15].

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 CSEF steels. The lack of consensus on publishing specific values for the design of CSEF steel 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 can far exceed that of the *design-by-rule* Codes.

1.4.1 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 [14]. The design basis for pressure parts covered by Section I [16] 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:

- The stress which will produce a creep rate of 1%/100,000 hours for an average material
- 0.67 of the average stress to cause rupture in 100,000 hours
- 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 [17]. Several problems were used to illustrate some of the deficiencies in components constructed to code rules that fall into several major categories:

- Real-world failure modes that are not included in the Code design process
- Permissiveness for fabrication practices that render the material more vulnerable to service failures
- Unfavorable metallurgical changes which occur during service exposure
- Operational modes that are more severe than anticipated
- In-service environmental degradation
- 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.

1.4.2 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 simpler 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.

1.5 Report Organization

This report contains specific guidance on technical issues that need to be controlled, as far as is possible, to ensure that components manufactured from Grade 91 steel meet the minimum expectations of performance when constructed to ASME Codes. It is recognized that many of the factors will be open for negotiation between the utility and suppliers. Therefore, 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 current specifications and Codes. These more stringent recommendations are justified or detailed in the comprehensive set of EPRI documents provided in Appendix A.

Information regarding the specific guidelines is provided in Section 2 of this report. Where possible, further technical detail related to key issues is referenced. In many cases the references include publicly available EPRI position papers and/or reports. Information regarding the specific Guidelines is provided in Section 2. Appendices B and C provide background regarding the base material or weld metal specifications, respectively. A review of PWHT changes in ASME B&PV Code Section I and ASME B31.1 are covered in Appendix D. Appendix E provides a template purchasing document and outlines how the guidelines may be interpreted to aid component purchase. Appendix E is provided for illustration only and should be read, edited and modified by the end-user.

2

PURCHASING INSTRUCTIONS

2.1 Introduction

This report represents requirements for Grade 91 steel. These requirements are considered necessary to ensure the satisfactory serviceability of any component fabricated using this grade of material. In general, the component should exhibit a uniform microstructure of tempered martensite. A typical series of images showing a tempered martensitic microstructure[1] taken from a SA-335 P91 product form are given in Figure 2-1.

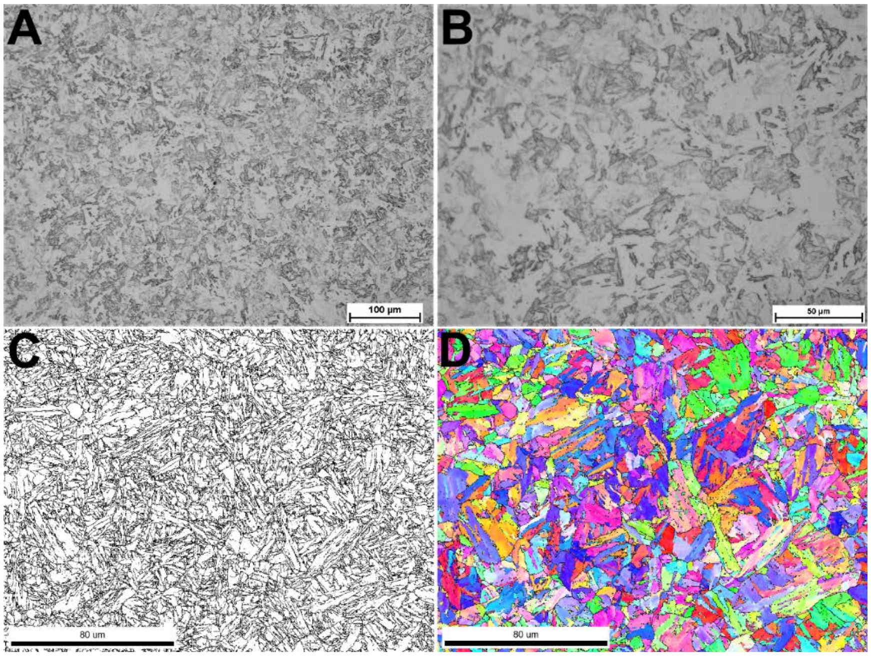

Figure 1-1
Representative tempered martensitic microstructure from a SA-335 P91 product form
A – light optical microscope image taken at a magnification of 20X, etched in Vilella's reagent
B – light optical microscope image taken at a magnification of 50X, etched in Vilella's reagent
C – scanning electron microscope electron backscattered diffraction grain boundary map image for all grain boundaries in a misorientation of 2 to 180°
D – scanning electron microscope electron backscattered diffraction inverse pole figure image

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[1] Significant challenges exist in the assessment of a tempered martensitic microstructure using optical metallography alone. The comparison in Figure 2-1 attempts to illustrate these challenges. Numerous and well-documented studies continue to reinforce the fact that it is not sufficient nor acceptable to ascertain the microstructure for Grade 91 steel using optical metallography as the sole basis for interpretation.

The foreword of all ASME Code sections states that the “objective of the rules is to afford reasonably certain protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long, safe period of usefulness” [16]. This statement is an acknowledgment of the fact that no equipment lasts forever and that boilers do have 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.”

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

- Requires all those features considered necessary for safety (for example, water gage glass, pressure gage, check valve, and drain)
- Provides detailed rules governing the construction of the various components that make up the boiler, such as tubes, piping, headers, shells, and heads
- Generally, limits the materials to those contained in the specifications in ASME B&PV Code Section II, Parts A, B and C with the design allowable stresses as tabulated in Section II, Part D
- Requires certain tests and inspections with the involvement and approval of a third-party authorized inspector

Another factor that has had a direct bearing on the need for the present report is the fact that the purchase of materials for use in ASME B&PV Code construction is controlled by material specifications that, for the most part, are contained in Section II, Parts A and B (base metals) and C (weld metals). These specifications are developed not by ASME but by ASTM International or the American Welding Society (AWS). ASME then adopts the ASTM or AWS specifications for its own use, making any modifications considered to be essential for safe operation of the equipment. By the nature of the consensus process, in which decisions are made by volunteers representing a number of different interests, including the material producer, the fabricator, the designer and the end user, it is usually difficult to incorporate into the material specification all of the requirements that reflect the primary engineering interest of the end user, which is to optimize the performance of the material and limit variability. As such, it should be understood that, although adherence to all Code requirements governing the use of a particular material will in many cases ensure adequate performance of the material relative to the Code’s objective of affording “reasonably certain protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long, safe period of usefulness,” it is unlikely that the requirements contained in the ASME B&PV Code ever will be sufficiently comprehensive to ensure optimum engineering performance of a material for a given application.

The following sections provide basic information that should be considered when purchasing Grade 91 material for Code-related construction. Background regarding the ASME B&PV Code requirements and relevant specifications are provided for reference in Appendix B for common product forms and in Appendix C for filler materials.

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. Background information outlining the effects of individual elements on microstructure and properties is provided in the position papers [8, 9], in a publication which summarizes the findings of comprehensive research studying the influence of metallurgical risk factors [11] and general good practice linked to known embrittlement mechanisms such as those detailed in [18].

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

Element	3002006390	ASTM/ASME Type 2	Aim for composition supported by [11]
C[1]	0.08–0.12	0.08–0.12	0.08–0.12
Mn	0.30–0.50	0.30–0.50	0.30–0.50
P	0.015*	0.020*	0.020*
S	0.005*	0.005*	0.003*
Si	0.20–0.40	0.20–0.40	0.20–0.40
Cr[2]	8.00–9.50	8.00–9.50	8.00–9.50
Mo	0.85–1.05	0.85–1.05	0.85–1.05
V	0.18–0.25	0.18–0.25	0.18–0.25
Nb (Cb)	0.06–0.10	0.06–0.10	0.06–0.10
N[1]	0.035–0.070	0.035–0.070	0.035–0.070
Ni	0.20*	0.20*	0.20*
Al	0.020*	0.020*	0.015*
Ti	0.01*	0.01*	0.01*
Zr	0.01*	0.01*	0.01*
Cu	0.10*	0.10*	0.15*
As[3]	0.010*	0.010*	0.012*
Sn[3]	0.010*	0.010*	0.010*
Sb[3]	0.003*	0.003*	0.003*
Pb[3]	0.001*	***	***
B		0.001*	0.001*
W		0.05*	0.05*
N/Al ratio	4.0 minimum	4.0 minimum	4.0 minimum

[1] Carbon + nitrogen > 0.12
[2] For tubing, the minimum Cr level should be 8.5%
[3] It is good practice to ensure that the following relationship holds: As+Sn+Sb+Pb < 0.015
* Maximum permissible value
*** For reporting only

Note: EPRI review of MTRs for Grade 91 steels has demonstrated that high-quality steel suppliers can provide, and indeed have been providing, steel components that comply with these recommendations for some time.

It is recommended that all raw Grade 91 heats be validated at the fabricator's site using positive material identification (PMI) testing. An excellent background summary concerning this form of testing is provided in [19]. 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 may 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 for Grade 91 or Grade 92 steel using the available, portable methods including X-ray fluorescence (XRF), laser induced breakdown spectroscopy (LIBS) and spark optical emission spectroscopy (OES) to laboratory-based procedures [20].

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. 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. Additionally, the cost increase of the product should be weighed relative to that of the 'final component.' 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 wt. % 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 [21]. 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 [20].

2.3 Heat Treatment of Grade 91 Steel at the Mill

All forms of Grade 91 product should be normalized[2] within the temperature range of 1,920 to 2,010°F (1,050 to 1,100°C) and should be tempered within the temperature range of 1,350 to 1440°F (730 to 780°C). Because of the link between the reduction in properties to the lack of control during heat treatment, it is important that the upper limits specified not be exceeded—that is, these limits should include any measurement tolerance.

For normalizing, when the full thickness of the product has reached the target normalizing temperature, the time at temperature should be a minimum of 10 minutes. Care must be taken to ensure that whole volume of product is allowed to cool uniformly. Cooling shall be continuous to ≤200°F (90°C) throughout the material thickness before tempering. The rate of cooling through the temperature range 1,650 to 900°F (900 to 480°C) shall be controlled to be no slower than 9°F/minute (5°C/minute). For product with a thickness >3 in. (75 mm), forced air cooling or oil quenching or the equivalent from the normalizing temperature to an internal work piece temperature below 200°F (93°C) may be necessary to achieve a fully martensitic structure.

For tempering, the temperature selected and the time at the tempering temperature shall be sufficient to satisfy the specified hardness range. The product can be cooled in still air from the tempering temperature, as long as excessive distortion or excessive thermal stress is avoided, or, as an alternative, where expedient, furnace cooling is acceptable, provided that the cooling rate exceeds 100°F/hour (55°C/hour) until the internal temperature is <1,200°F (650°C).

Heat-treatment equipment must be properly calibrated, and the producer must furnish evidence of the calibration for review prior to the beginning of any heat treatment on Grade 91 steel. Furnaces should be regularly surveyed for temperature uniformity throughout the work zone. For furnaces, including gas-fired furnaces, the heat-treatment supplier should demonstrate that the thermocouples that are used to control the temperature can be maintained within ±5°F (±3°C) of the target temperature and that the largest variation in temperature between any two points in the work zone of the furnace (the volume holding the components) does not exceed 40°F (20°C) above the target heat treatment temperature. This shall be demonstrated by placing thermocouples on metal samples that are placed in the furnace so that the temperatures in the work zone are accurately indicated.

For resistance-type heaters, the heat-treatment supplier should demonstrate that the temperature at the control thermocouple can be maintained within ±5°F (±3°C) of the target temperature. The heat-treatment supplier should demonstrate that for a given component the temperature is controlled within the specified temperature range through placement of properly installed thermocouples at a sufficient number of locations along the length and around the circumference of tubular-shaped components or along the length and across the width of flat components. For piping, the pattern of thermocouple placement recommended in ASME B&PV Code Section I, Nonmandatory Appendix C is a useful guide and should be followed as a minimum standard wherever possible. For other types of heating, such as induction heating, the heat-treatment supplier must demonstrate the ability to maintain the temperature at all points on the component

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[2] The combined, two-step initial heat treatment is often described as a "Normalizing and Tempering" heat treatment, because, as the term "normalizing" implies, the part is allowed to cool in still air from the austenitizing temperature. However, for thicker components some type of forced cooling may be required to ensure full transformation to martensite or bainite, in which case the term "normalizing" may not be technically appropriate.

that is 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 a 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. Additional background in EPRI reports regarding the use of resistance or induction heat treatment equipment can be found in [22-25].

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

2.4 Hardness

Hardness testing can provide a valuable tool to the fabricator, constructor, and end user with respect to QA. Its application in this capability must include proper procedures, proper analysis of the data (including remedial actions when outlier values are reported), and a general understanding of the objective of the method. The EPRI position regarding hardness of Grade 91 steel components is that a general minimum value imposed on material suppliers of 190 Hardness Brinell (HBW)/ 195 Hardness Vickers (HV)/ 90 Hardness Rockwell B (HRB) helps to ensure that subsequent fabrication and construction tempering heat treatments prevent gross deterioration of the creep life of the component. This is based on an EPRI database of soft Grade 91 steel components in which the reduction in creep strength from average material behavior can be on the order of 45%. Hardness measurements, as established by portable means, should be verified as several sources of error may be introduced and are well-established in [26].

The component properties can be modified following all thermal treatments. Therefore, checking hardness at each stage of fabrication and installation is considered an essential good practice. In most cases the hardness of Grade 91 components will decrease during service. The changes that occur will be related to the initial composition and heat treatment, as well as in-service operation. Therefore, the following guidelines should not be applied to a component after a period of service exposure.

The final (that is, after all fabrication and heat treatment but prior to service) hardness values of a component base metal should be >190 HBW(195 HV/ 90 HRB). For components subject to multiple post-weld heat treatment (PWHT) or tempering treatments, it is typically the case that hardness will be reduced following each heat treatment [27]. Therefore, to achieve the desired minimum level of hardness after all fabrication stages have been completed, the initial component hardness will need to be higher than 190 HBW (195 HV). A general recommendation for the maximum hardness value is 250 HBW (265 HV/ 25 HRC) although this requirement varies according to the product form (see Appendix B and additional clarification for tubing in 2.4.4) and should not be extended to welded fabrication (for example, hardness checks in the HAZ or weld metal).

2.4.1 Conversion

It should be noted that 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 cited in publicly available EPRI documents [27].

2.4.2 Equipment

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 a report detailing issues associated with hardness measurements and data calibration [26].

2.4.3 Weldments

Weldments that are normalized and tempered, for example in SA-234 WP91 fittings or SA-691 Grade 91 seam-welded piping or other components, should meet the same hardness requirement specified in Section 2.4 for 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 nor time-dependent behavior [12]. Therefore, 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 heat-affected zone (HAZ) of a weldment following subcritical PWHT can show hardness values below the recommended minimum because of the positioning of the indenter or the hardness test probe within the fine-grained/ intercritical/ partially-transformed region of the HAZ. This level of hardness in the so-called Type IV region of the HAZ occurs because of the local thermal effects from welding and is unavoidable and it should not be a basis for rejection of the weldment.

2.4.4 Cold-Formed Components

In cases where Grade 91 material will be *cold-formed* (defined as strain introduced at a temperature of below 1,300°F [705°C]) to levels of strain exceeding 15%, the maximum acceptable as-supplied hardness of the T91 material should be reduced to 230 HBW (242 HV/ 21 HRC/ 98 HRB). This level of hardness is necessary to minimize the risk of low-ductility fracture during forming.

Background information regarding issues associated with cold bending is presented in ASME B&PV Code Section 1, PG-20, with a summary of the issues provided in [28]. Information regarding the risk to stress corrosion cracking (SCC) is described in [29-31].

2.4.5 Exemption from Hardness Testing

It is generally not acceptable to eliminate the requirement for hardness testing prior to shipping and installation in the field. Because many problems during manufacture of Grade 91 steel components have been linked to incorrect control of heat treatment in the field or shop, and the variability in methods/procedures for shop heat treatment, alternative means of component monitoring (e.g. contact thermocouples) cannot entirely replace the use of hardness testing as a quick and economic means of QA/QC. Numerous case studies, for example in [32], have consistently shown that fabrication shops using documented procedures can introduce undesirable outcomes even when independent monitoring, such as by means of a contact thermocouple, is utilized.

Monitoring the heat treatment of the product or component by means of contact thermocouple(s) *can be* preferable provided critical and relevant locations in the component are monitored. However, careful attention should be paid to the following details:

- Multiple heat treatment cycles can reduce the hardness value to an unacceptable value so that monitoring by means of contact thermocouples alone is not sufficient for final quality checks of the component prior to shipment.
- Heat treatment cycles biased to the lower end of the allowable range will have a less significant impact on the final component hardness provided the initial hardness is properly documented either on the material certification and/or through independent assessment.
- Field installation will require an additional PWHT so that the hardness should be sufficiently >190 HBW (195 HV). This language is predicated on the fact that the target and/or actual field PWHT temperature will be unknown to the manufacturer and a further reduction in the hardness value prior to in-service operation must be considered.
- Measurement of hardness in a fabrication shop or in the field by means of a portable system may not be straightforward for all components, locations or product forms. Hardness measurements on tubing material, if not carefully executed, will provide inconsistent values and may not be appropriate for thin-walled tubing (e.g. reheater sections). Prior language in 2.4.3 addressed similar concerns in weld regions like the HAZ. More guidance can be found in [26].

If the purchaser elects to substitute hardness checks by means of contact thermocouple measurements, the heat treatment charts should be supplied as part of the data package.

2.5 Mechanical Properties

The room temperature mechanical properties of the as-supplied base material shall meet the following limit: tensile strength: 90 to 120 ksi (620 to 830 MPa). For materials that will be used to manufacture cold-formed bends, the upper strength limit should be reduced; therefore, the strength range for cold forming is 90 to 109 ksi (620 to 751 MPa). All other mechanical properties shall be as indicated in the applicable material specification in the ASME B&PV Code Section II, Part A.

2.6 Welding Practices

For the purposes of procedure and performance qualifications welds in Grade 91 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 91 steel is given in [12, 33].

2.6.1 Preheat and Interpass Temperature

A variety of methods are available, and it is mandatory to control the minimum preheat temperature, as follows:

- For welds made using the flux-cored arc welding (FCAW) process or the submerged arc welding (SAW) process or in a highly restrained component, a minimum preheat temperature of 400°F (205°C) shall be maintained.
- For welds made using the shielded metal arc welding (SMAW) process, a minimum preheat temperature of 300°F (150°C) shall be maintained until the welding is complete.
- For welds made using either the GMAW process or the gas tungsten arc welding (GTAW) process with a solid wire filler metal, a minimum preheat temperature of 300°F (150°C) shall be maintained until the welding is complete.
- For welds made using either GMAW or GTAW with a filler metal other than solid wire (that is, metal-cored or flux-cored), a minimum preheat temperature of 300°F (150°C) shall be maintained. An exception to this rule shall apply for welds that effectively are self-preheating—that is, welds involving a relatively small heat sink in comparison with the magnitude of the arc energy or heat input and that are continuously deposited so that the entire weld nugget and base metal HAZ remain above the specified minimum preheat level throughout the weld cycle.

Depending on the referenced code or standard, guidance may be mandated by the present rules. For example, ASME B31.1, Table 131.4.1-1 specifies a required minimum preheat temperature of 400°F (200°C) regardless of the welding process [34].

If welding is interrupted, preheat temperature must be maintained. Although not a recommended practice, if the joint temperature drops below the preheat temperature, the interrupted welds must be as follows:

- At least one-third of the final through-wall thickness of the component
- Given a hydrogen bake before slow cooling to room temperature
- Kept dry until the welding is re-started with the proper preheat
- These precautions are necessary because, in the as-welded condition, the joint can be vulnerable to SCC.
- The maximum interpass temperature, regardless of the welding process, shall be 660°F (350°C).

2.6.2 Hydrogen Bake

Following welding, if there is a need for the temperature of the weld to be dropped to room temperature prior to the implementation of the PWHT, to control the amount of diffusible hydrogen present in the weldments, a hydrogen bake should be performed. The hydrogen bake involves holding in the temperature range of 500 to 660°F (260 to 350°C) for 1 hour minimum for thicknesses of 1 in. (25.4 mm) or less and 2 hours for thicknesses greater than 1 in. (25.4 mm). 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 is considered good practice.

2.6.3 Post-Weld Heat Treatment

Following completion of welding, the temperature of the component should be allowed to cool to the specified preheat temperature, provided that this value is ≤400°F (205°C). Where there is specific concern of temperature inhomogeneity through the thickness of the weldment, lower post-weld cool temperatures should be considered according to the information provided in [31].

The component should be post-weld heat-treated within 8 hours of the completion of welding. If this is not possible, either the component should be maintained at a minimum temperature of 175°F (80°C) or the humidity of the environment in which the weld is stored should be controlled to guarantee that no condensation can occur at any time (for example, because of changes in temperature) on either the outer diameter (OD) or inner diameter (ID) surfaces of the joint until the PWHT can be initiated. An agreement between client and contractor should be established on the best practice to minimize the risk of SCC occurring on any Grade 91 components.

The PWHT should be performed within the range of 1,250 to 1,420°F (675 to 770°C) depending on section size. General clarification on this point follows the present guidance given in ASME B&PV Code Section I, Table PW-39-5 which states that if the nominal weld thickness is <0.50 inches (13 mm), the minimum hold temperature is 1,250°F (675°C) otherwise the minimum hold temperature is 1,300°F (705°C)

The maximum temperature at any point in the PWHT process should not exceed 1420°F (770°C). The minimum temperature is recommended based on EPRI research [18]. The maximum temperature differs from the requirements stated in ASME B&PV Code Section I, Table PW-39-5 where the stated maximum is dependent on composition, as follows [16]:

- If Mn+Ni is ≤1.0 wt. %, the maximum is 1,470°F (800°C).
- If Mn+Ni is >1.0 but <1.2 wt. %, the maximum is 1,445°F (785°C).
- If the Mn+Ni content of the filler material is not known, the maximum PWHT temperature is 1,445°F (785°C)

The ASME B&PV Code Section I and ASME B31.1 have undergone a number of changes to the PWHT requirements in the last decade. A summary of this evolution is given in Appendix D for reference.

The reduced maximum PWHT temperature of 1,420°F (770°C) provides 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 cooldown are specified for PWHT although some limits may be imposed by the referenced code. For example, ASME B31.1 Section 132.5 specifies, "Above 600°F (315°C), the rate of heating and cooling shall not exceed 600°F/hr (315°C/hr) divided by one half the maximum thickness of material in inches at the weld, but in no case shall the rate exceed 600°F/hr (315°C/h)." For thick-walled components, or for assemblies of complex shape, an appropriate rate of heat-up or cooldown, as determined by experienced engineering judgment, should be adopted to minimize distortion and residual stresses.

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

2.6.4 Filler Materials

2.6.4.1 Matching Filler Metal

Matching filler materials that have similar chemistry and strength to the base metal should be used for all joints between Grade 91 materials. Insofar as it is possible, the chemical composition of the matching filler metal shall conform to the elemental restrictions specified in Table 2-2. 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, the purchaser shall reserve the right to review and approve deviations from the limits given in Table 2-2. Newly published AWS specifications for filler metal consumables are summarized in Appendix C.

Table 2-2
Recommended chemical composition requirements (values given in weight percent) for Grade 91 matching filler materials

Element[1,2,3]	ASME SFA 5.5 (E901X-B9)	ASME SFA 5.28 (ER90S-B91)	ASME SFA 5.23 (EB91)	ASME SFA 5.29 (E91T1-B9)
	SMAW Electrodes	GMAW/GTAW Bare, Solid Electrodes/Rods	SAW (Weld Deposit Wire/Flux Combination)	FCAW Electrodes
C	0.08-0.13	0.08-0.13	0.08-0.13	0.08-0.13
Mn	0.40-1.00	0.40-1.00	0.40-1.00	0.40-1.00
Si	0.15-0.30	0.50[A]	0.50	0.50
P	0.01	0.010	0.010	0.020
S	0.010	0.010	0.010	0.01
Ni	0.40	0.40	0.40	0.40
Cr[3]	8.0-9.5	8.0-9.5	8.0-9.5	8.0-9.5
Mo	0.85-1.20	0.85-1.20	0.85-1.15	0.85-1.20
V	0.15-0.30	0.15-0.30	0.15-0.25	0.15-0.30
Cu	0.10	0.10	0.10	0.10
Al[4]	0.02	0.02	0.02	0.02
Nb (Cb)	0.02-0.10	0.02-0.10	0.02-0.10	0.02-0.10
N[4]	0.03-0.07	0.03-0.07	0.03-0.07	0.03-0.07
Co[5]	***	***	***	***
As[6]	0.010	0.010	0.010	0.010
Sn[6]	0.010	0.010	0.010	0.010

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

Element[1,2,3]	ASME SFA 5.5 (E901X-B9)	ASME SFA 5.28 (ER90S-B91)	ASME SFA 5.23 (EB91)	ASME SFA 5.29 (E91T1-B9)
	SMAW Electrodes	**GMAW/GTAW Bare, Solid Electrodes/Rods**	**SAW (Weld Deposit Wire/Flux Combination)**	**FCAW Electrodes**
Sb[6]	0.003	0.003	0.003	0.003
Mn+Ni[7]	1.00	1.00	1.00	1.00
Analysis	Weld deposit	Bare wire	Bare wire	Weld deposit

Notes:

[1] Element ranges are provided in weight percent.

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

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

[3] Cr limits: Specifying a higher minimum content than the SFA specification may be desirable in tubing products where fire-side corrosion or steam-side oxidation can be a concern. Specifying a lower maximum content than called for by the SFA specification can be desirable to help minimize the potential for formation of delta ferrite during weld metal solidification. An upper maximum limit on Cr to the permissible limit of 10.5 wt. % may be allowed pending review and acceptance by the purchaser.

[4] The ratio of nitrogen to aluminum (N/Al) should be >2

[5] If Co is intentionally added as an alloying addition the value shall be reported

[6] One of As, Sn, Sb may exceed the stated value in the table provided that the As + Sn + Sb < 0.020 wt. %

[7] The Mn+Ni value can be relaxed to 1.20 wt. % pending review and acceptance by the purchaser

[A] If the solid wire is being used for welding root passes using a waveform controlled short-circuit transfer gas metal arc welding process the minimum Si limit should be 0.35 wt. %.

2.6.4.2 Alternative Fe-Base Filler Metals

Undermatching filler materials are those that have lower tensile and/or creep strength compared to Grade 91 steel base metal, for example E8015-B8, ER80S-B8, E9018-B3, and ER90S-B3. These fillers may be used for transition joints between Grade 91 and low-alloy steel materials when sufficient thickness of the weld metal and a proper joint design overcome issues associated with the design allowable stresses at the joint. Guidance and additional background on selection of filler material for dissimilar ferritic welds are provided in a recent EPRI report which includes consideration of the end-component geometry [35].

2.6.4.3 Ni-Base Filler Metals

Nickel-based filler metals may be used for welding dissimilar metal joints in Grade 91 steel to an austenitic stainless steel. Examples of commonly utilized, commercially available nickel-based filler materials are Weld Alloy 82 (ERNiCr-3), Weld Alloy 182 (ENiCrFe-3) and Weld Alloy A (ENiCrFe-2). In at least two examples, filler materials have been specifically developed for this application, e.g. EPRI P87 (ENiFeCr-4, ERNiFeCr-4, and ASME Code Cases 2733 and 2734) and HIG370 (developed by Mitsubishi Power). Preference is not given for these listed filler materials as practical constraints linked to filler metal availability can ultimately govern selection. Regardless of the utilized filler material, the purchaser can request statistics documenting the in-service performance to increase the confidence in the proposed solution. Nickel-based fillers are generally considered inappropriate for welding Grade 91 to Grade 91 because of increased filler metal cost, increased complexity in carrying out reliable NDE, and the potential for increased susceptibility to damage caused by cyclic operation [36]. Guidance and additional background on selection of filler material for dissimilar metal welds between Grade 91 and austenitic stainless steels are addressed in a best practice guideline document [37].

2.6.4.4 Precautions with Usage of Electrodes

The following precautions should be implemented to minimize the risk of weld-related cracking and defects resulting from improper handling and/or storage of weld filler materials:

- All SMAW electrodes to be used in the welding of Grade 91 components should be issued from a heated master storage bin to field ovens, where they will be maintained until they are removed for immediate usage. Unused electrodes left outside of the rod ovens for more than 4 hours either should be re-baked in accordance with the manufacturer’s recommendations to minimize any moisture absorbed into the coating during the period of exposure or should be discarded. Discarding suspect filler material is desirable and normally the most cost-effective solution.
- All SMAW electrodes should be certified to the H4 designation.
- 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 24 hours, the reel should be either stored in a container heated to a minimum temperature of 175°F (80°C) or discarded.

2.6.5 Gas Metal Arc Welding Process

The qualification and use of solid wire gas metal arc welding (GMAW) should be approached with caution and should only be allowed when specific qualifications have been performed and all details reviewed. The current -B91 solid wire composition may be lean on deoxidizing elements (such as Mn and Si). Careful attention should be given to the Si content because a value in the lower allowable range can impact the wetting action and the risk to the introduction of lack of fusion type defects. Fabricators have qualified the GMAW process, including novel waveform controlled GMAW-S procedures but under very controlled conditions and in some cases with a solid wire filler metal composition that provides adequate deoxidizers. Few organizations have properly and effectively implemented the solid-wire GMAW process for field installation or repairs. Details and additional guidance can be referenced in [38].

2.7 Forging and Forming

Grade 91 steel attains the required elevated temperature strength through control of composition and fabrication. All processes or actions that involve working or heating can potentially have an adverse effect on the properties of the material. Hot- and cold-forming practices must be carefully controlled. For all products made from a solid forging, the cross-sectional area of the solid forging shall have a reduction by forging from that of the ingot in the ratio of not less than 3:1.

2.7.1 Hot Pressing (Squeezing and Sizing) and Hot Bending

After all hot pressing or hot bending operations, the entire component shall be normalized and tempered in accordance with Section 2.3 of this report, “Heat Treatment of Grade 91 Steel at the Mill.”

2.7.2 Hot Adjustments to Shape

Hot drawing or hot adjustment is carried out for short periods of time in the temperature range of 1,300 to 1,450°F (705 to 790°C). No heat treatment is required after these operations. If the 1,450°F (790°C) limit is exceeded during the forming operation, a full normalization 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, the affected material should be removed and should either be renormalized and tempered to restore properties or be replaced.

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

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

Any component subjected to cold forming, such as swaging, pointing, squeezing, or sizing, that is designed to operate at a metal temperature greater than 1,050°F (565°C) should be given a full normalization and temper in accordance with Section 2.3 of this report.

2.7.4 Cold Bending

If the ratio of the radius of the bend (R) to the outside diameter (D) of the tubing , R/D, is ≥4, no post-forming heat treatment is required. If the R/D is ≥2.5 and <4, the bend region can be heat-treated within the temperature range of 1,350 to 1,420°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, the entire component should be normalized and tempered in accordance with Section 2.3 of this report.

2.7.5 Hot Forming of Fitting and Special Products

After hot forming of any fittings or special products, a normalizing and tempering treatment of the entire component should be performed in accordance with Section 2.3 of this report.

2.8 Surface Condition

Preservation of the surface, under no circumstance, should allow for the use of Zn-containing paints. Numerous issues linked to Zn-embrittlement have been document in weld HAZ regions. During fabrication of components from Grade 91 steel, when weld repair of surface imperfections, such as grinding marks or arc strikes, is conducted, as permitted in the applicable engineering Code, a PWHT must be applied in accordance with the provisions of Section 2.6 of this report, “Welding Practices.”

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

3

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A
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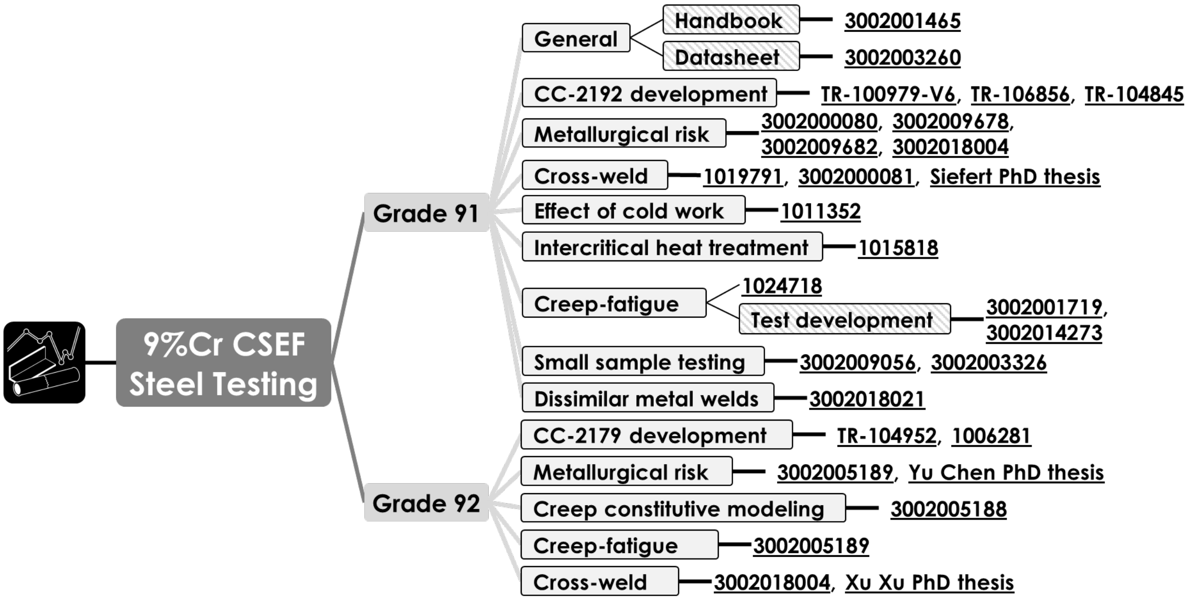

Figure A-1
Documents linked to data supporting the building of a relevant database of material properties for 9%Cr CSEF steels, welds and dissimilar metal welds

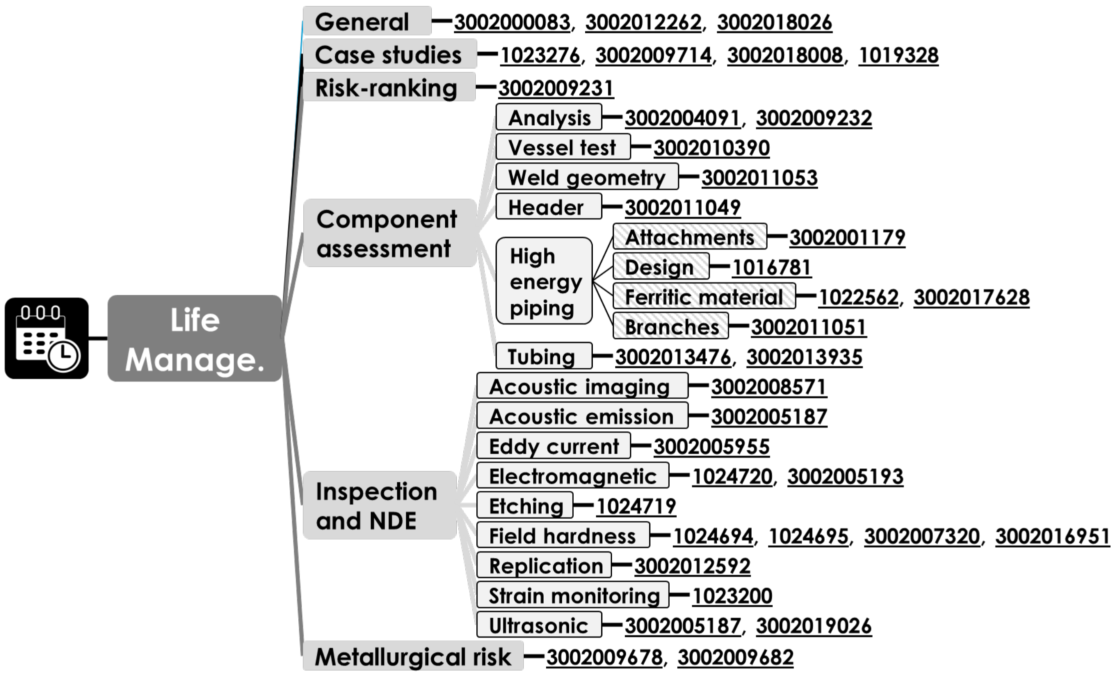

Figure A-2
Documents linked to life management practices, procedures or case studies specific to 9%Cr CSEF steel components

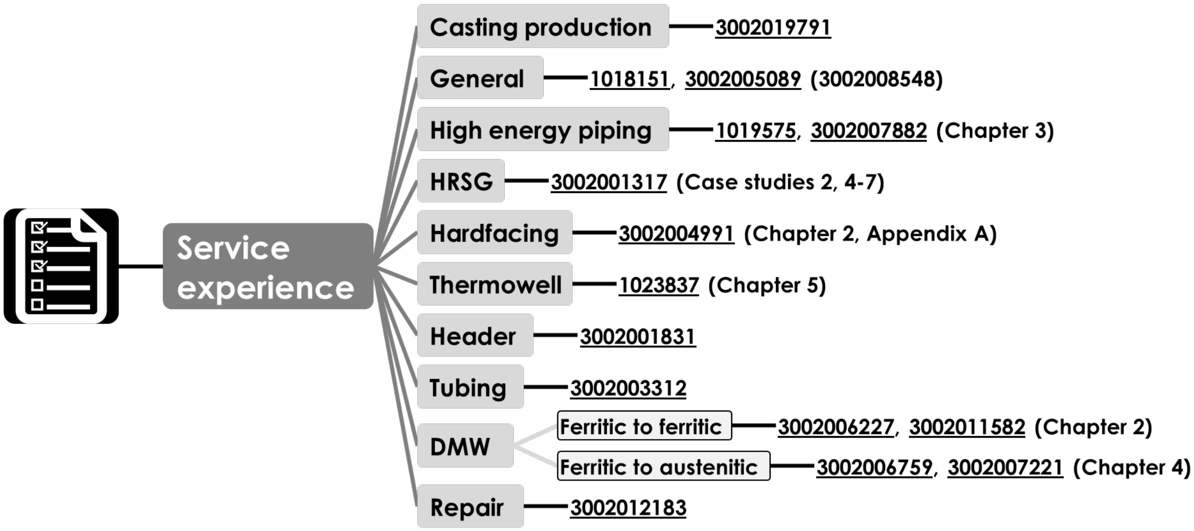

Figure A-3
Documents linked to relevant service experience

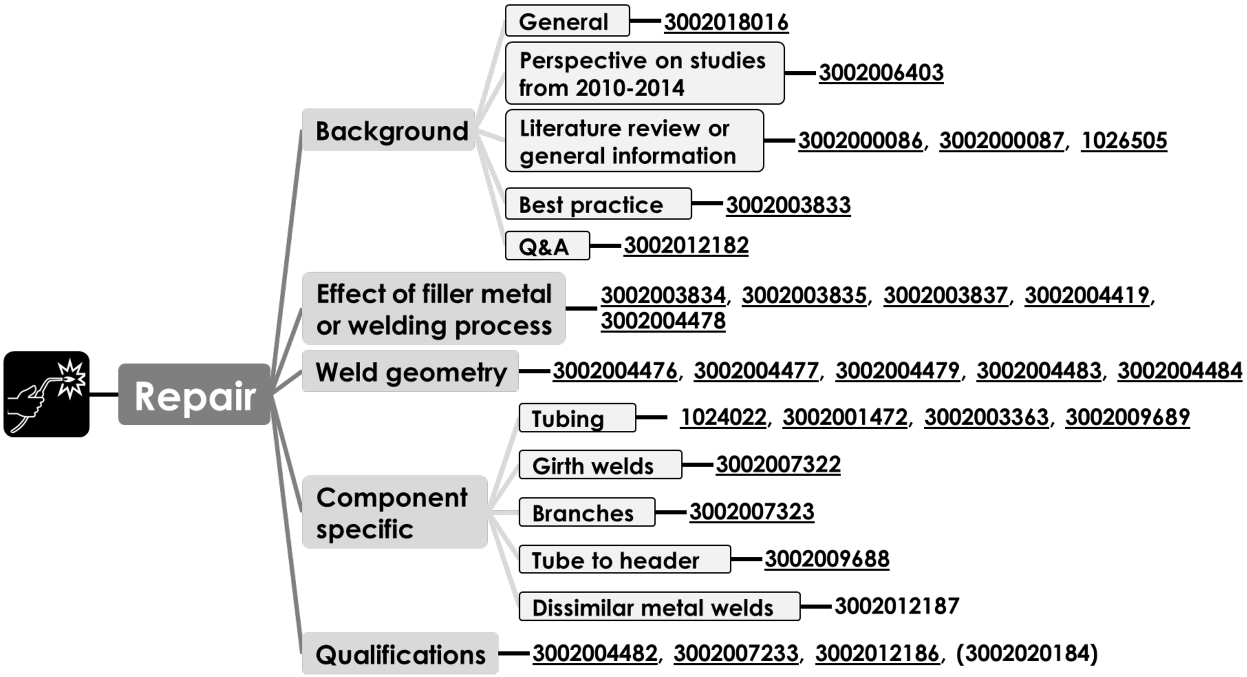

Figure A-4
Documents linked to alternative weld repair approaches in Grade 91 steel

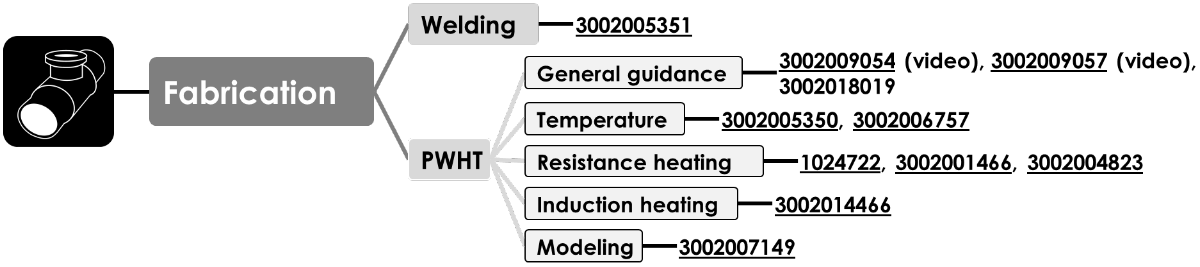

Figure A-5
Documents linked to fabrication processes in Grade 91 steel

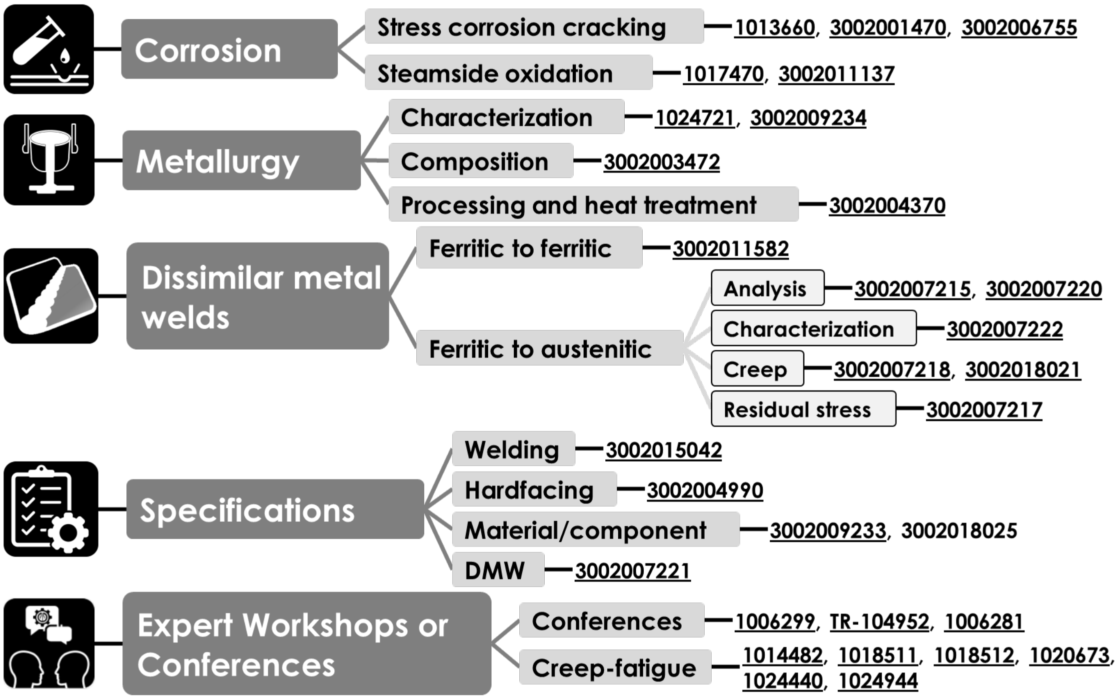

Figure A-6
Documents linked to complimentary details important in the fabrication and life management of 9%Cr CSEF steel components

B
BACKGROUND ON BASE METAL COMPOSITION

B.1 Relevant Codes, Standards and Specifications

Applicable ASME materials designations for Grade 91 material are provided in Table B-1 and a summary of selected international materials specifications for Grade 91 steel is presented in Table B-2. Specifications in Japan are KA-SCMV28, KA-STPA28, and KA-SFVA28 for plate pipe and forgings respectively. The details of these specifications mirror those of ASME.

Table B-1
Summary of relevant ASTM/ASME A-/SA-specifications for Grade 91 material

Specification and Grade	Country	Description
SA-182 F91	United States	Specification for forged or rolled alloy-steel and stainless steel pipe flanges, forged fittings, and valves, and parts for high-temperature service
SA-213 T91	United States	Specification for seamless ferritic and austenitic alloy-steel boiler, superheater, and heat exchanger tubes
SA-217 C12A	United States	Specification for steel castings, martensitic stainless and alloy, for pressure containing parts, suitable for high temperature service
SA-234 WP91	United States	Specification for piping fittings of wrought carbon steel and alloy for moderate and elevated temperature
SA-335 P91	United States	Specification for seamless ferritic alloy-steel pipe for high-temperature Service
SA-336 F91	United States	Specification for alloy steel forgings for pressure and high-temperature parts
SA-369 FP91	United States	Specification for carbon and ferritic alloy steel forged and bored pipe for high-temperature service
SA-387 Grade 91	United States	Specification for pressure vessel plates, alloy steel, chromium-molybdenum
SA-691	United States	Specification for carbon and alloy steel pipe, electric-fusion-welded for high-pressure service at high temperatures
SA-1091 C91	United States	Specification for steel castings, creep-strength enhanced ferritic alloy for pressure-containing parts, suitable for high temperature service

Table B-2
European equivalent standard for the listed specifications in Table B-1

Product form	ASME B&PV Code Specification	EN Specification and Grade	Description
Pipes and tubes	SA-213 T91 SA-335 P91	EN 10216-2:2013+A1:2019 X10CrMoVNb9-1	Seamless steel tubes for pressure purposes. Technical delivery conditions. Non-alloy and alloy steel tubes with specified elevated temperature properties
		VdTÜV WB 511/2:2014-09	Warmfester Stahl X10CrMoVNb9-1 - Werkstoff-Nr.: 1.4903 Nahtloses Rohr, nahtloser Hohlkörper
Seam welded pipe	SA-691	No equivalent: Grade X10CrMoVNbN9-1 is not included in EN 10217-2 (ERW tubes) or EN 10217-5 (SA welded tubes)	
Forgings	SA-336 F91	EN 10222-1:2017	Steel forgings for pressure purposes. General requirements for open die forgings
		EN 10222-2:2017 X10CrMoVNb9-1	Steel forgings for pressure purposes. Ferritic and martensitic steels with specified elevated temperatures properties
		VdTÜV WB 511/3:2013-09	Warmfester Stahl F 91 X10CrMoVNb9-1 - Werkstoff-Nr. 1.4903 - Stabstahl, Schmiedestück
	SA-369 FP91	No direct equivalent in EN standards	
Fittings	SA-182 F91 SA-234 WP91	EN 10253-2:2007 X10CrMoVNb9-1	Butt-welding pipe fittings. Non alloy and ferritic alloy steels with specific inspection requirements
		EN 10222-1:2017	Steel forgings for pressure purposes. General requirements for open die forgings
		EN 10222-2:2017 X10CrMoVNb9-1	Steel forgings for pressure purposes. Ferritic and martensitic steels with specified elevated temperatures properties
Castings	SA-217 C12A SA-1091 C91	EN 10213:2007+A1:2016 GX12CrMoVNbN 9-1	Steel castings for pressure purposes
Plate	SA-387 Grade 91	EN 10028-1:2017	Flat products made of steels for pressure purposes. General requirements
		EN 10028-2:2017 X10CrMoVNb9-1	Flat products made of steels for pressure purposes. Non-alloy and alloy steels with specified elevated temperature properties

B.2 Comparison of Information in ASTM/ASME A-/SA-Specifications

The ASME and international codes differ in some of the detail regarding specified chemical composition for base metal product forms. Differences in the composition are illustrated with reference to the ASTM/ASME A-/SFA-specifications in Table B-3. This table also illustrates the fact that there can be differences in specification between the heat analysis and the actual component composition. Lastly, it is noteworthy that in some cases the specifications are different for heat treatment or minimum mechanical properties (in addition to composition). Selected differences are summarized in Table B-4.

C

BACKGROUND ON WELD METAL COMPOSITION

The ASME and international codes differ in some of the detail regarding specified chemical composition for filler metal product forms and/or deposited weld metal chemistry. The commonly utilized product forms are listed in Table C-1. Differences in the composition are illustrated with reference to the AWS/ASME SFA-specifications Table C-2.

Table C-1
Summary of relevant ASME SFA- filler metal specifications for Grade 91 material

Specification and Grade	Country	Description
SFA-5.5	United States	Specification for Low Alloy Steel Electrodes for Shielded Metal Arc Welding
SFA-5.23	United States	Specification for Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding
SFA-5.28	United States	Specification for Low Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding
SFA-5.29	United States	Specification for Low Alloy Steel Electrodes for Flux Cored Arc Welding

Table C-2
Comparison of chemical composition (values given in weight percent) for common filler metal product forms and their variants listed in the referenced SFA-specifications for Grade 91 material
Note: single values represent maximum permissible limit for the given element

Product Form	SFA-5.5	SFA-5.23	SFA-5.28			SFA-5.29
	E901X		ER90S			E91T1
	-B91	EB91	-B91	-B91C	-B91CMn	-B9
Carbon	0.08-0.13	0.08-0.13	0.07-0.13	0.05-0.12	0.05-0.12	0.08-0.13
Manganese	1.20	1.20	1.20	0.50-1.25	1.20-1.90	1.20
Phosphorus	0.01	0.010	0.010	0.015	0.015	0.020
Sulfur	0.01	0.010	0.010	0.015	0.015	0.015
Silicon	0.30	0.80	0.15-0.50	0.50	0.10-0.60	0.50
Chromium	8.0-10.5	8.0-10.5	8.0-10.5	8.0-10.5	8.0-10.5	8.0-10.5
Molybdenum	0.85-1.20	0.85-1.20	0.85-1.20	0.80-1.20	0.80-1.20	0.85-1.20
Vanadium	0.15-0.30	0.15-0.25	0.15-0.30	0.10-0.35	0.15-0.50	0.15-0.30
Niobium	0.02-0.10	0.02-0.10	0.02-0.10	0.01-0.08	0.01-0.08	0.02-0.10
Nitrogen	0.02-0.07	0.02-0.07	0.03-0.07	0.01-0.05	0.01-0.05	0.02-0.07
Nickel	0.80	0.80	0.80	0.10-0.80	0.20-1.00	0.80
Cobalt			Note A	Note A	Note A	
Copper	0.25	0.25				0.25
Aluminum	0.04	0.04				0.04
Mn + Ni	1.40	1.40	Note B			1.50
Others			0.50	0.50	0.05	

[A] Analysis for Co is required to be reported if intentionally added, or if it is known to be present at levels greater than 0.20%.

[B] Mn + Ni ≤ 1.40% maximum. The B91 (1.2) designation requires Mn + Ni <1.20% maximum and also meet requirements for B91. The B91 (1.0) designation requires Mn + Ni ≤ 1.00% maximum and also meet requirements for B91 and B91 (1.2).

D

EVOLUTION OF PWHT REQUIREMENTS IN SECTION I AND B31.1

Changes have been made to the requirements for post weld heat treatment (PWHT) in ASME B&PV Code Section I and ASME B31.1 over the last decade. In some instances, these requirements have not been consistent code-to-code for Grade 91 steel, which was formerly P-No. 5B, Group 2 and more recently is now classified as P-No. 15E. The introduction of data and information from the volunteers who support the writing and improvement of these codes has necessitated the periodic edits reflected in Table D-1. The EPRI requirements for the Grade 91 specification and linked to the 1st, 2nd or 3rd editions is given in Table D-1 for comparison purposes.

Table D-1
Summary of changes to the post-weld heat treatment requirements since 2010 in ASME B&PV Code Section I and since 2007 in ASME B31.1

Document or Table	Edition	Minimum PWHT for DMWs[1]	Minimum PWHT Temperature		Maximum PWHT Temperature	
			≤13 mm	>13 mm		
ASME B&PV Code Section I (Table PW-39-5)	2010	1,300 (705)	1,325 (720)	1,350 (730)	1,425 (775)	[1,450 (790); if 1.0 ≤ Mn+Ni <1.5 wt. %] [1,470 (800); if Mn+Ni < 1.0 wt. %]
	2013, 2015	1,300 (705)	1,325 (720)	1,350 (730)	1,445 (785) [1,470 (800); if Mn+Ni < 1.0 wt. %]	
	2017	1,300 (705)	1,250 (675)	1,300 (705)	1,445 (785) [1,470 (800); if Mn+Ni < 1.0 wt. %]	
	2019	1,300 (705)	1,250 (675)	1,300 (705)	1,445 (785) [1,470 (800); if Mn+Ni < 1.0 wt. %]	
ASME B31.1 (Table 132)	2007, 2010	1,300 (700)	1,300 (700)	1,300 (700)	1,400 (760)	
	2012	1,300 (700)	1,325 (720)	1,350 (730)	1,425 (775)	[1,450 (790); if 1.0 ≤ Mn+Ni < 1.5 wt. %] [1,470 (800); if Mn+Ni < 1.0 wt. %]
	2016	1,325 (720) or 1,350 (730)	1,325 (720)	1,350 (730)	1,425 (775)[A]	
	2018, 2020	1,250 (675) or 1,300 (705)	1,250 (675)	1,300 (705)	1,425 (775)[A]	
EPRI (1023199)	1st	1,350 (730)			1,420 (770)	
EPRI (3002006390)	2nd	1,250 (675)			1,420 (770)	
EPRI (300218025)	3rd	1,250 (675)			1,420 (770)	

[1] If the filler metal is an austenitic or nickel-base or chromium content is < 3.0 wt. %

[A] The maximum may be increased up to 1,470°F (800°C) if the A_1 is measured or calculated for a known composition

E

ILLUSTRATION OF A COMPONENT PURCHASING DOCUMENT

Contract No. XXX/XXX

Technical Specification for the Design, Manufacture, Supply, and Delivery of Replacement Components in Grade 91 Steel[1]

E.1 Introduction

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

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

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

E.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:

1. Forged and machined Grade 91 components
2. Welded components fabricated using seamless P91 pipe with a full renormalization and temper (N&T) heat treatment following fabrication

Respondents may submit offers for either (1) or (2) or both. The Principal shall nominate the selected method of manufacture to be utilized. Further requirements are detailed in the following sections.

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[1] This technical specification is an illustration and it must be reviewed and modified by individual companies before using it.

The following fabrication methods are not permitted:

1. Use of seam-welded pipe
2. Welded components fabricated using seamless P91 pipe without carrying out a full renormalization and temper (N&T) heat treatment following fabrication
3. Use of any materials other than Grade 91 steel

E.2.1 Separable Portions

The scope of work consists of the following separable portions:

Separable Portion 1

Separable Portion 2

Separable Portion 3

Separable Portion 4

Separable Portion 5

[Utility to complete this section separately regarding ordering conditions]

E.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.

E.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:

1. Designed in accordance with ASME B31.1 Power Piping Code and ASME Boiler and Pressure Vessel Code.
2. Finite element modeling shall be used to determine the maximum stresses at the design temperature and pressure and including piping system loads.
3. Branch reinforcement shall be shared between the main pipe and nozzle in order to reduce the maximum stress and reduce stress concentration.
4. 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.
5. The design shall specifically mitigate the historical mode of failure by Type IV cracking.
6. The design shall consider combined creep-fatigue loading.

7. Design pressure and temperature shall be as per the existing piping design ***[Utility to double-check and then provide the design versus operating temperature and pressure]***.
8. Ends of piping components shall be designed and supplied machined in preparation for manual butt welding.
9. 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:

1. General arrangement drawings
2. Detailed fabrication drawings
3. Erection drawings
4. Design calculations
5. Heat treatment procedure including details of any transportation of components in as-welded state
6. Engineering report detailing the expected service life, possible failure modes of the new components, and results of finite element modeling
7. 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.

E.2.4 Quality Assurance

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

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

1. Inspection and Test Plan (ITP)
2. All procurement records showing traceability of supplied materials for piping and welding consumables
3. Material certificates for base materials and welding consumables
4. Nondestructive testing (NDT) procedures
5. Heat treatment procedures and equipment calibration records
6. Welding documentation (that is, WPS, WQR, welder qualifications)
7. Hydrostatic test procedure

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

1. Completed Inspection and Test Plan (ITP) signed off for each activity
2. All procurement records showing traceability of supplied materials for piping and welding consumables
3. Material certificates for base materials and welding consumables
4. Nondestructive testing results and equipment calibration records
5. All heat treatment charts and equipment calibration records
6. Welding records
7. Hydrostatic test records and equipment calibration records
8. Records of dimensional checks
9. Records of any nonconformances experienced during any stage of the manufacturing/fabrication process
10. 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.

E.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 nonconformances 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 that 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.

E.2.6 Delivery

[To be specified according to individual requirements]

E.2.7 Codes and Standards

The components shall conform to the following codes and standards:

1. Designed and fabricated to the ASME B31.1 Power Piping Code and ASME Boiler and Pressure Vessel Code.
2. All welds shall also be nondestructively examined and compliant to ***[Utility to specify]*** and addenda.

E.3 Materials and Manufacturing Requirements

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

E.3.1 Chemical Composition of Parent Metal

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

Composition (Wt%):

Carbon	0.08–0.12
Manganese	0.30–0.50
Phosphorus	0.020 (max)
Sulphur	0.005 (max)
Silicon	0.20–0.40
Chromium	8.20–9.50
Molybdenum	0.85–1.05
Vanadium	0.18–0.25
Nitrogen	0.035–0.070
Nickel	0.20 (max)
Aluminum	0.020 (max)
Columbium	0.06–0.10
(niobium) Titanium	0.01 (max)
Zirconium	0.01 (max)
Copper	0.10 (max)

Arsenic	0.010 (max)
Tin	0.010 (max)
Antimony	0.003 (max)
Lead	0.001 (max)
N/Al ratio	≥ 4

The Respondent shall provide the producing mill's material test report (MTR) with the results of the chemical analyses for each individual heat of steel to verify compliance with the requirements of this specification. Upon receipt of the Grade 91 steel by the Respondent, the Respondent shall verify that each parent steel section complies with the specified compositional requirements. This verification shall be reported to the Principal prior to beginning final fabrication.

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

E.3.2 Heat Treatment

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

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

E.3.2.1 Normalizing

For all product forms, normalizing is to be carried out using a suitable furnace within the temperature range of 1,920 to 2,010°F (1,050 to 1,100°C) to produce a fully martensitic microstructure. Once the full thickness of the component has reached the target *normalizing* temperature, the time at temperature shall be a minimum of 10 minutes. The product shall be air cooled outside of the furnace and away from any source of heat that would retard the rate of cooling.

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

Cooling shall be continuous down to at least 200°F (95°C) at the center location before tempering. Note that for components greater in thickness than 3 in. (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 normalizing.

E.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 91 material is in the fully hardened condition, once the normalizing heat treatment has been completed, the material shall not be allowed to remain at a temperature below 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, as long as excessive distortion or excessive thermal stress is avoided, or, as an alternative, where expedient, furnace cooling is acceptable provided that the cooling rate exceeds 100°F/hour (55°C/hour) until the internal temperature is below 1,200°F (650°C).

Cautionary note: No additional limits on the rate of heat-up or cooldown 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 cooldown, as determined by experienced engineering judgment, shall be adopted to minimize distortion and residual stresses. With specific regard to the cooldown 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 center of the work piece to ensure avoidance of detrimental precipitation of carbides or other nonmartensitic transformation products. Below 1,000°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).

E.3.2.3 Equipment

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

For resistance-type heaters, the Respondent shall provide evidence that the controlling thermocouple or thermocouples can be maintained within ±5°F (±3°C) of the target temperature during a heat-treatment cycle. Further, the Respondent shall demonstrate that for a given cylindrical component the temperature can be controlled at all locations on the component within the specified temperature range through the placement of properly shielded thermocouples at a sufficient number of locations along the length and around the circumference of the component. For piping, the recommendations for thermocouple placement provided in ASME B&PV Code Section I, Nonmandatory 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 in. (25 mm) 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.

E.3.2.4 Documentation

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

E.3.3 Microstructure

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

E.3.4 Steel Hardness

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

E.3.4.1 Procedure

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

With respect to the base materials supplied from the mill for subsequent fabrication, the hardness of the Grade 91 material shall be a minimum of 200 HBW/210 HV (93.4 HRB). 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 of 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 nonrepresentative surface layer shall be greater than the design minimum wall thickness.

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

1. The hardness shall be measured at both ends of each piece and at intervals along the length of the piece no greater than 8 ft. 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.
2. 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.
3. 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.
4. 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

E.3.4.2 Data Recording

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

E.3.5 Mechanical Properties

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

1. Tensile Strength: 90–110 ksi (620–760 MPa).
2. All other mechanical properties shall be as indicated in the applicable material specification of SCII of the ASME B&PV Code.
3. All results of mechanical properties testing shall be recorded on the Certified Material Test Report.

E.3.6 Forming Processes

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

E.3.6.1 Forgings

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

E.3.6.2 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 3.2.

E.3.6.3 Hot Adjustments to Shape

By definition, hot drawing or hot adjusting is carried out for short periods of time at temperatures between 1,300°F (705°C) and 1,450°F (790°C). Provided that the upper temperature limit is observed, no post-adjustment heat treatment is required. However, if the 1,450°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. An alternative corrective action would be to remove the overheated zone and either renormalize and retemper the piece containing the overheated zone before reinsertion in the component, or to replace the overheated zone with new material.

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

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

E.3.6.5 Hot Forming of Fittings and Special Products

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

E.3.7 General Welding Practice

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

E.3.7.1 Preheat

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

1. For any welds made on Grade 91 material using the shielded metal arc process (SMAW) or the submerged-arc process (SAW), a minimum preheat temperature of 300°F (150°C) shall be maintained for the duration of the welding.

2. For welds on Grade 91 material made using either the gas metal arc process (GMAW) or the gas tungsten arc process (GTAW) with a solid wire filler metal, a preheat temperature of 300°F (150°C) shall be maintained.
3. For welds made using either the GMAW or GTAW processes with a filler metal other than solid wire (that is, metal core), a minimum preheat temperature of 400°F (205°C) shall be maintained.
4. 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.

E.3.7.2 Interpass Temperature

The maximum interpass temperature during welding shall be 660°F (350°C).

E.3.7.3 Hydrogen Bake

A hydrogen bake is best practice and should be considered for all joints. The bake should be performed in the temperature range of 500 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 350°F (175°C) or agreed upon post-weld cooling temperature between the end-user and fabricator/constructor.

E.3.7.4 Post-Weld Heat Treatment

Following completion of welding, the temperature of the component shall be reduced below 350°F (175°C) at its center to ensure an acceptable degree of austenite transformation. If there is concern regarding potential thermal gradients through the thickness, this post-weld cool temperature may be further reduced to 300°F (150°C). 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 renormalized and tempered at **a later date** following the completion of welding, an immediate post-weld heat treatment should be performed in the subcritical range of temperature—that is, within the range of 1,300 to 1,420°F (700 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 91 components, the weld metal and portions of the heat-affected zones are vulnerable to brittle fracture if subjected to unusually high mechanical loads during handling. Care shall be taken, therefore, in the handling of Grade 91 components containing welds that are in the as-welded condition to minimize the risk of brittle fracture.

E.3.7.5 Weld Filler Metals

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

1. The sum of the Mn plus the Ni contents shall not exceed 1.0%.
2. The ratio of N to Al shall be a minimum of 4.

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

1. All SMAW electrodes to be used in the welding of Grade 91 product shall be issued directly from the sealed container or from a heated master storage bin. Unused electrodes left outside of rod ovens for more than four (4) hours shall be discarded.
2. All SMAW electrodes shall be certified to the H4 designation.
3. 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 it shall be discarded.

Table E-1
Recommended chemical composition requirements (values given in weight percent) for Grade 91 matching filler materials

Element[1,2,3]	**ASME SFA 5.5 (E901X-B9)**	**ASME SFA 5.28 (ER90S-B91)**	**ASME SFA 5.23 (EB91)**	**ASME SFA 5.29 (E91T1-B9)**
	SMAW Electrodes	**GMAW/GTAW Bare, Solid Electrodes/Rods**	**SAW (Weld Deposit Wire/Flux Combination)**	**FCAW Electrodes**
C	0.08-0.13	0.08-0.13	0.08-0.13	0.08-0.13
Mn	0.40-1.00	0.40-1.00	0.40-1.00	0.40-1.00
Si	0.15-0.30	0.50[A]	0.50	0.50

Table E-1 (continued)
Recommended chemical composition requirements (values given in weight percent) for Grade 91 matching filler materials

Element[1,2,3]	ASME SFA 5.5 (E901X-B9)	ASME SFA 5.28 (ER90S-B91)	ASME SFA 5.23 (EB91)	ASME SFA 5.29 (E91T1-B9)
	SMAW Electrodes	GMAW/GTAW Bare, Solid Electrodes/Rods	SAW (Weld Deposit Wire/Flux Combination)	FCAW Electrodes
P	0.01	0.010	0.010	0.020
S	0.010	0.010	0.010	0.01
Ni	0.40	0.40	0.40	0.40
Cr[3]	8.0-9.5	8.0-9.5	8.0-9.5	8.0-9.5
Mo	0.85-1.20	0.85-1.20	0.85-1.15	0.85-1.20
V	0.15-0.30	0.15-0.30	0.15-0.25	0.15-0.30
Cu	0.10	0.10	0.10	0.10
Al[4]	0.02	0.02	0.02	0.02
Nb (Cb)	0.02-0.10	0.02-0.10	0.02-0.10	0.02-0.10
N[4]	0.03-0.07	0.03-0.07	0.03-0.07	0.03-0.07
Co[5]	***	***	***	***
As[6]	0.010	0.010	0.010	0.010
Sn[6]	0.010	0.010	0.010	0.010
Sb[6]	0.003	0.003	0.003	0.003
Mn+Ni[7]	1.00	1.00	1.00	1.00
Analysis	Weld deposit	Bare wire	Bare wire	Weld deposit

Notes:

[1] Element ranges are provided in weight percent.

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

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

[3] Cr limits: Specifying a higher minimum content than the SFA specification may be desirable in tubing products where fire-side corrosion or steam-side oxidation can be a concern. Specifying a lower maximum content than called for by the SFA specification can be desirable to help minimize the potential for formation of delta ferrite during weld metal solidification. An upper maximum limit on Cr to the permissible limit of 10.5 wt. % may be allowed pending review and acceptance by the purchaser.

[4] The ratio of nitrogen to aluminum (N/Al) should be >2

[5] If Co is intentionally added as an alloying addition the value shall be reported

[6] One of As, Sn, Sb may exceed the stated value in the table provided that the As + Sn + Sb < 0.020 wt. %

[7] The Mn+Ni value can be relaxed to 1.20 wt. % pending review and acceptance by the purchaser

[A] If the solid wire is being used for welding root passes using a waveform controlled short-circuit transfer gas metal arc welding process the minimum Si limit should be 0.35 wt. %.

E.3.7.6 Weld Repair

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

E.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 aluminum 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 shall be protected from corrosion by use of vapor phase inhibitor (VPI) powder or equivalent.

E.5 Work to be Performed by the Principal

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

1. Perform quality assurance inspections during manufacture and packing.
2. Arrange unloading of the components at the place of delivery.
3. Carry out all installation works including rigging, cutting, welding, post-weld heat treatment, nondestructive testing, removal and installation of insulation, and cladding and adjustment of piping supports.

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

E.6 Transportation Requirements

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

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

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

E.7 Site Storage Requirements

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

E.8 Delivery Schedule

[To be completed separately by Utility]

E.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 X.

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

E.10 Principal Supplied Documents

Documents and drawings relevant to the tender.

[To be completed separately by Utility]

E.11 Technical Schedules

The Respondent shall complete the following schedules.

Table E-2
Schedule

Item	Description	Response
11.1	Manufacturing method: forged and machined, or welded	
11.2	Design phase (Separable Portion 1) duration (weeks)	
11.3	Lead time for delivery of each Separable Portion (months)	
11.4	Country of manufacture	
11.5	Country of origin for all raw materials	
11.6	Details of design to prevent early failure by Type IV cracking or other mechanisms (Their methodology utilized to complete this process—that is, use of FEA (Program Utilized), Standards, Experience, and so on	
11.7	Inspection schedule and associated NDT procedures and processes to be undertaken in the warranty period. Power Station ***[Utility insert name here]*** unit outage scheduled dates shall be taken into consideration.	
11.8	Warranty period (months)	
11.9	Delivery method	
11.10	Packing and storage method	

Table E-2 (continued)
Schedule

Item	Description	Response
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). (DD: Separate schedule in CSE RFP)	
11.13	Provide details of the key personnel in the design and manufacture process and their experience in projects of a similar nature. (DD: Separate schedule in CSE RFP)	
11.14	Short-term storage requirements	

E.12 Right of Access

[To be completed by Utility]

Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

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