

# Best Practice Guideline for Well-Engineered Weld Repair of Grade 91 Steel

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# Best Practice Guideline for Well-Engineered Weld Repair of Grade 91 Steel

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## Abstract

This report summarizes a proposal for submission to the National Board Inspection Code Part 3 for the acceptance of alternative weld repairs of creep strength enhanced ferritic (CSEF) steel Grade 91. The recommended approach integrates a well-engineered, damage-tolerant design with a controlled fill welding procedure so that the performance of the repair will, at the least, achieve performance that is equal to that of the weld it repairs or replaces. The report defines a best practice guidance road map for the remediation of damage in Grade 91 steel components requiring weld repair. It provides guidance on the essential considerations in a weld repair scenario, including assessment of the base material condition, identification and characterization of defects, application of root cause analysis, excavation of defects, geometry of the weld repair excavation, the weld repair fill technique, post-weld heat treatment guidance (where applicable), nondestructive evaluation of the final weldment and follow-up inspection of the weld repair, avoidance of stress corrosion cracking, and qualification to NBIC Part 3 and the ASME Boiler and Pressure Vessel Code Section IX. The report provides the end-user with a straightforward series of steps and considerations to ensure the completion of well-engineered weld repairs in Grade 91 steel components. This guideline should be included as an attachment to any specification, bid, or related document to ensure that all stakeholders in the weld repair process are properly informed.

### **Keywords**

Controlled fill  
Creep strength enhanced ferritic steel  
Grade 91  
National Board Inspection Code  
Weld repair



## Terms and Definitions

**9Cr-1Mo** – Refers to a weld consumable that is matching to 9Cr-1Mo steel. Identified by the AWS specification ending in “-B8.” Composition is listed in Appendix A.

**9Cr-1Mo-VNbN** – Refers to a weld consumable that is matching to Grade 91 steel. Often identified as 9CrMoV or by the AWS specification ending in “-B9.” A new AWS classification “-B91” is pending for the various Grade 91 filler metal product forms. Composition is listed in Appendix A.

**Cold weld repair** – Generally refers to a weld repair method for which an elevated-temperature post-weld heat treatment is not specified. An elevated-temperature post-weld heat treatment is defined as a temperature above the expected operation range of the given weld.

**Controlled fill** – Refers to a welding process in which the first layer is deposited in the excavation with a bead-to-bead overlap of at least 50%. Subsequent fill passes are deposited in a specific sequence that prevents distortion, promotes tempering, and minimizes the risk of potential weld cracking mechanisms such as reheat cracking. This process is discussed in detail in the report.

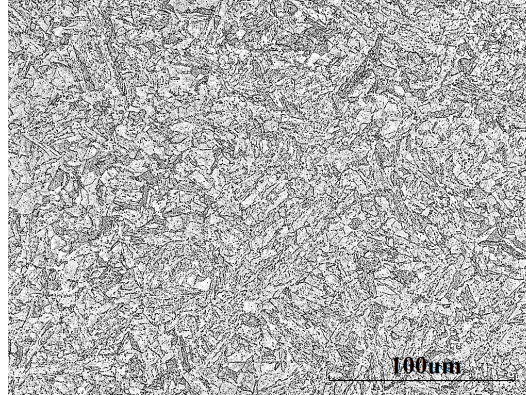
**CSEF** – Creep Strength Enhanced Ferritic. A family of ferritic steels whose creep temperature strength is enhanced by the creation of a precise condition of microstructure, specifically martensite or bainite, which is stabilized during tempering by controlled precipitation of temper-resistant carbides, carbo-nitrides, or other stable and/or meta-stable phases [1].

**EPRI P87** – Refers to a Ni-base consumable covered by ASME Code Cases 2733 and 2734. Once adopted by AWS, the filler metal will have the designation ENiFeCr-4 and ERNiFeCr-4. Composition is listed in Appendix A.

**FCAW** – Flux-Cored Arc Welding process

**GMAW** – Gas Metal Arc Welding process

**Grade 91** – A martensitic CSEF steel that lies within specified compositional ranges and, when properly processed, exhibits a homogeneous tempered martensitic microstructure, as illustrated in the following figure. Depending on product type, the steel will be referred to as C12A, F91, WP91, T91, or P91. Composition specifications for the common product forms are given in Appendix B



*Representative Tempered Martensitic Microstructure in Grade 91 Steel*

**GTAW** – Gas Tungsten Arc Welding process

**HAZ** – Heat-Affected Zone. Refers to the region of the base material that is immediately adjacent to the deposited weld metal and that does not melt, but as a consequence of local heating exhibits a series of gradually varying substructures and is distinct from either the unaffected base metal or deposited weld metal. For Grade 91 steel, the HAZ has been subdivided into specific regions, using definitions based on the classical work in bainitic steels. These substructures include:

- CGHAZ – Coarse Grained Heat-Affected Zone
- FGHAZ – Fine Grained Heat-Affected Zone
- ICHAZ – Intercritical Heat-Affected Zone
- SCHAZ – Subcritical Heat-Affected Zone

**LOF** – Lack of Fusion

**Ni-base** – Refers to a consumable that has nickel as the predominant element and includes selected filler materials classified in ASME B&PV Section IX by F No. 43. Compositions for common Ni-base consumables are listed in Appendix A.

**PWHT** – Post-Weld Heat Treatment

**SMAW** – Shielded Metal Arc Welding process



## Foreword

This guideline describes best practices that should be used for fabrication of a well-engineered weld repair for *post-construction* mitigation of damaged Grade 91 steel components. Repairs made during the course of new construction must meet the requirements outlined in a given construction Code. However, for repairs needed after components have been in service, the National Board Inspection Code (NBIC) has recognized five alternative welding methods that differ from the requirements of the original code of construction. Over the last 20 years, five methods that do not require post-weld heat treatment (PWHT) have been agreed upon for repair of low-alloy, creep-resistant steels.

It is widely recognized that there is minimal published research available justifying the application of methods used for new construction to repair scenarios. Indeed, mandating procedures of the original Code of construction when welding service-exposed steel—that is, using B9 filler materials followed by mandatory PWHT—ignores the known variability in creep and fracture resistance of Grade 91 steel components. It has been argued that PWHT performed to existing Codes and standards can remediate issues associated with the poorly controlled welding or repair activities. This position is not justified by results. Indeed, service experience has documented that many problems have been created and directly linked to inadequate control of heat treatment. There is no evidence that PWHT is required to achieve acceptable performance in a well-engineered weld repair.

The methods described in the current document are based on the findings of a state-of-knowledge review and the results of a comprehensive research study. Learning outcomes have been focused to define a well-engineered repair method for Grade 91 steel components. The recommendations embrace the key requirements of safety and damage tolerance (even though specific details differ from the current requirements allowed by the relevant codes, such as the NBIC). It must be noted, however, that NBIC has made allowances and revisions to provide alternative welding methods for CrMo steels when standard repair practices are impractical. These alternative welding methods exist in the NBIC Part 3, Repairs and Alterations, are commonly identified as “temper bead” repair procedures, and are specifically listed as Welding Methods 1–5 [2].

This guideline should be considered as a document that initiates a review process with the National Board for inclusion of material-specific repair methods into the NBIC. The Electric Power Research Institute is currently working in conjunction with the National Board to create repair methods for Grade 91 steel components that are accurate, applicable, and will improve the success of repair activities. The recommendations in this initial guideline are consistent with industry best practices and the findings of research results from the EPRI “Weld Repair of Grade 91 Steel and Components” project. These results have been widely discussed with project partners and industry experts, have been peer-reviewed in several conferences and journal publications [3-11], and have been presented in a number of EPRI reports [12-24]. Research in this area continues to be an active endeavor to provide additional details in key areas. Therefore, the information contained in this report may be revised, updated, and supplemented when necessary.

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## Section 1: Introduction

EPRI service experience reports have demonstrated that Grade 91 components have already been replaced and repaired because of poor composition and/or improper heat treatment or other challenges with construction that resulted in properties below the minimum expectation of Codes [25-26]. As the time in service continues to increase for installed components, the need for weld repair associated with long-term damage mechanisms will only continue to increase. Traditionally, repair practice refers back to the original Code of construction. Regardless of the particular Code or region, this would necessitate either a local excavation of damage or an entire replacement of a section, weld repair using a matching filler metal (for similar Grade 91 steel welds), and a post-weld heat treatment (PWHT) per the requirements of the governing Code. For Grade 91 steel, the conventional weld repair would therefore include welding with an AWS “-B9” filler metal and PWHT in the range of 1350 to 1450°F (730 to 790°C) [27].

In many cases, these requirements are very difficult if not impossible to apply to repair of components that have been in service. These difficulties arise since Grade 91 steel strength degrades within the base material HAZ following all subcritical heat treatments including PWHT and with time in service. Thus, the concept of strength matching cannot be easily achieved. Moreover, lack of control of heat treatment is known to cause significant problems, including performance outside of the expectations of Codes. Even for properly controlled heat treatment, the hardness of a given heat of Grade 91 steel can be expected to drop in the base metal by ~8-10 HBN for each typical PWHT thermal cycle. Where the PWHT thermal cycle is restricted to very near the minimum of the allowable range, the hardness may be expected to drop by ~2-4 HBN. Details of the time/temperature relationships that describe the tempering behavior of Grade 91 steels have been published by EPRI.

There has been no publicly reported evidence to justify currently used procedures for weld repair of Grade 91 steel. Grade 91 steel is sensitive to the time/temperature characteristics of each and every heat treatment. It has been established that multiple heat treatments result in microstructural degradation and softening with a resultant reduction in creep strength [28]. Furthermore, poorly controlled heat treatment processes have proven to be catastrophic with regard to high-temperature performance. The present document provides guidance regarding three alternative approaches that can be used for the remediation of damage in Grade 91 components. These approaches have been validated and documented through the results of a comprehensive series of studies detailed in [18-24].



## Section 2: Responsibilities for the End-User, Contractor/Engineer, and Inspector

Planning, execution, and approval for a weld repair in a Grade 91 steel component involves several different entities. The process is indicated in Figure 2-1 [29]. It is the collective responsibility of the different entities to oversee, monitor, and inspect the weld repair process from its initial specification and development through the completion of the weld repair. Specific responsibilities include:

- **Owner/User:** The owner or user of the unit/component or their designated representative. In cases where the owner self-performs repair activities, the functions of Responsible Engineer, Repair Contractor, and Repair Contractor Inspector may be part of the Owner/User organization if such skill sets are available. Otherwise, these functions may be contracted to properly qualified contractors if that is deemed necessary.
- **Responsible Engineer:** The owner's/user's designated representative with the full responsibility for the design and integrity (before, during, and after the repair) of the component. The Engineer is also responsible for determining and specifying the code provisions, and quality level requirements. It is common for the Engineer to be integral with the Repair Contractor's team.
- **Repair Contractor:** The owner's/user's selected entity with full responsibility for the construction/completion of the repair within the specified criteria set by the Engineer. This may be an in-house team, a specialty repair shop, or an original equipment manufacturer (OEM).
- **Repair Contractor Inspector:** A person or group of individuals designated by the Repair Contractor who acts on behalf of the Repair Contractor in all quality matters within the scope of the repair. This person or group of individuals is often referred to as the quality control inspector.
- **Verification Inspector (or Owner's Inspector):** A person or group of individuals designated by the owner who acts on behalf of the owner or the Engineer in all quality matters within the scope of the repair. This person or group of individuals is often referred to as the quality assurance inspector. The Verification Inspector may be an employee of the owner, or this function may be contracted to a third-party organization.

- **Inspector:** A third-party individual who holds a valid and current National Board commission and ensures weld repairs are being performed in accordance with the National Board Inspection Code based on local regulatory or jurisdictional requirements. The Inspector shall have the Inservice (IS) Endorsement issued by the National Board in accordance with NB-263. The Inspector shall review and sign the Form R-1 for weld repairs.
- **Quality Assurance:** An aggregate of activities including administrative and procedural to ensure that the requirements for the repair are fulfilled. Specific tasks include management of raw materials including replacement material and welding consumables and the weld repair activities to avoid any mistakes or defects. This individual(s) are designated by the owner who acts on behalf of the owner or the Engineer in all quality matters within the scope of the repair.
- **Quality Control:** An aggregate of activities (such as design analysis and inspection for defects) designed to ensure adequate quality. Quality Control consists of activities employed in detection and measurement of the variability in the characteristics of output attributable to the production system, and includes corrective responses.

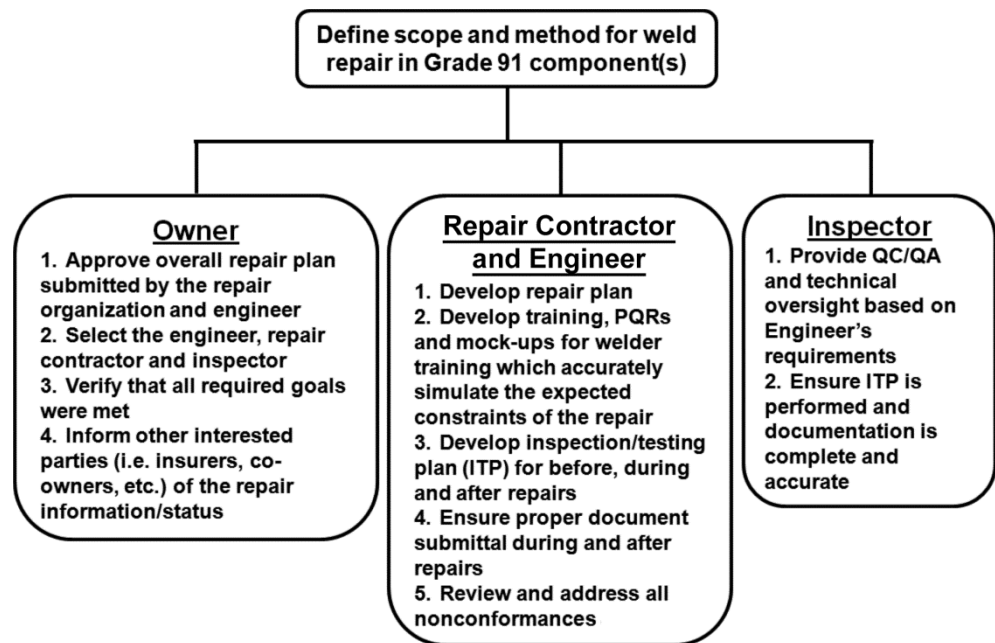


Figure 2-1  
Responsibilities for Owner, Repair Contractor and Engineer, and Inspector for Repair of Grade 91 Steel Components [29]



## Section 3: Introduction to Acceptable Weld Repair Methods

Conventional repair methods—that is, removal of damage and replacement by depositing weld metal in the affected area—cannot universally produce a repair with properties equal to or greater than those of the original construction. Following a comprehensive evaluation, three “best option” weld repair procedures have been assessed in detail. Each of these procedures has been determined to provide acceptable results for the field repair of Grade 91 steel pressure boundary components. An exemplar procurement form is provided in Appendix C to aid in the proper purchasing of welding consumables for weld repair. The excavation of damage is detailed in subsequent sections. The repair procedures are as follows:

1. **Filler Metal = 9Cr-1Mo-VNbN (matching to Grade 91) + Controlled Fill + Low PWHT (minimum temperature is 1250°F, 675°C).** The minimum time and maximum heat treatment temperature are outlined by the original code of construction. Where the Ni+Mn content is not known, ASME restricts the maximum PWHT temperature to 1425°F (775°C); note that the EPRI specification for Grade 91 steel recommends a maximum PWHT temperature of 1420°F (770°C). Rules, as specified by ASME B&PV Code Section I or ASME B&PV Code B31.1 for PWHT, are the following with regard to the required minimum holding time for PWHT [30, 31].
  - a. Minimum holding time at PWHT temperature is specified as 1 hour per 1.0 inch (25 mm) of thickness, 30-minute minimum provided the component < 0.5 inches (12.5 mm) in thickness.
  - b. Minimum holding time at PWHT temperature is specified as 5 hours plus 15 minutes for each additional 1.0 inch (25 mm) over 5.0 inches (125 mm).

EPRI research has shown that the influence of tempering time and temperature is cumulative; thus strength goes down as tempering increases. Therefore, it is advisable to reduce the minimum PWHT temperature to reduce the cumulative tempering of the Grade 91 component base metal. The acceptable PWHT temperature range depends on a variety of factors, such as the heating method, the thickness of the component, and the type of component. Selection of the necessary upper temperature must also take into account risks of exceeding the  $A_1$  during field heat treatment. In general, a reasonable reduced PWHT temperature may be 1275°F (690°C)  $\pm$  25°F (14°C). When local PWHT is used as a minimum this should be performed

in accordance with the requirements of AWS D10.10 [32]. More stringent recommendations are detailed in a later section herein to reduce the risk of improper PWHT. It should be noted that the maximum hardness values for the tempered weld metal should be on the order of <350 HV (<325 HBN). Note that these values are different from the guidance contained in [33], as recent research has shown that previous targets for upper hardness values were unnecessarily conservative.

2. **Filler Metal = 9Cr-1Mo + Controlled Fill and No PWHT.** Acceptable filler materials are detailed in Table 4-1 in the following section of the guideline.
3. **Filler Metal = Ni-base + Controlled Fill and No PWHT.** Acceptable nickel base consumables include selected ASME F No. 43 filler metals as detailed in Appendix A.

The hardenability of 9Cr-1Mo-VNbN and 9Cr-1Mo filler metals using the SMAW process has been extensively evaluated using hardness mapping. The hardness of these filler metals has been evaluated in the as-welded and simulated service condition (for 9Cr-1Mo, Appendix D) and in the as-welded and the low PWHT condition (for 9Cr-1Mo-VNbN, Appendix E).

## Section 4: General Guidelines for Acceptable Weld Repair Methods

### The Welding Process

Depending on the weld repair method, GTAW, SMAW, or FCAW process is acceptable. The GMAW process is not recommended for any of the weld repair procedures. Appendices F, G, and H contain detailed information regarding the performance of each welding procedure detailed in Table 4-1.

Table 4-1

*Acceptable Welding Processes and Filler Materials (Listed by AWS Classification) for Each of the Acceptable Weld Repair Methods for Grade 91 Steel Components*

| Acceptable Weld Repair Method |                            | Welding Process and Filler Metal AWS Classification                                                                                                                                                                         |
|-------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Filler Metal                  | Welding Procedure          |                                                                                                                                                                                                                             |
| Matching (9Cr-1Mo-VNbN)       | Controlled Fill + Low PWHT | <ul style="list-style-type: none"> <li>• SMAW – E9015-B9 or E9015-B91<sup>A</sup></li> <li>• FCAW – E91T1-B9</li> <li>• GTAW – ER90S-B9 or ER90S-B91<sup>A</sup></li> </ul>                                                 |
| 9Cr-1Mo                       | Controlled Fill            | <ul style="list-style-type: none"> <li>• SMAW – E8015-B8</li> <li>• FCAW – E81T1-B8</li> <li>• GTAW – ER80S-B8</li> </ul>                                                                                                   |
| Ni-base                       | Controlled Fill            | <ul style="list-style-type: none"> <li>• SMAW – EPRI P87<sup>B</sup>, ENiCrFe-2<sup>C</sup>, ENiCrFe-3<sup>D</sup></li> <li>• FCAW – None available</li> <li>• GTAW – EPRI P87<sup>E</sup>, ERNiCr-3<sup>F</sup></li> </ul> |

#### Notes:

Procurement of acceptable filler materials is addressed in Appendix C

<sup>A</sup> B91 AWS classification is pending for the various Grade 91 filler metal product forms (currently -B9)

<sup>B</sup> Incorporated by ASME B&PV Code as Code Case 2734 for classification as an F No. 43 filler material [34]

<sup>C</sup> Also referred to as “INCO-WELD A”

<sup>D</sup> Also referred to as “INCONEL Welding Electrode 182”

<sup>E</sup> Incorporated by ASME B&PV Code as Code Case 2733 for classification as an F No. 43 filler material [35]

<sup>F</sup> Also referred to as “Filler Metal 82”

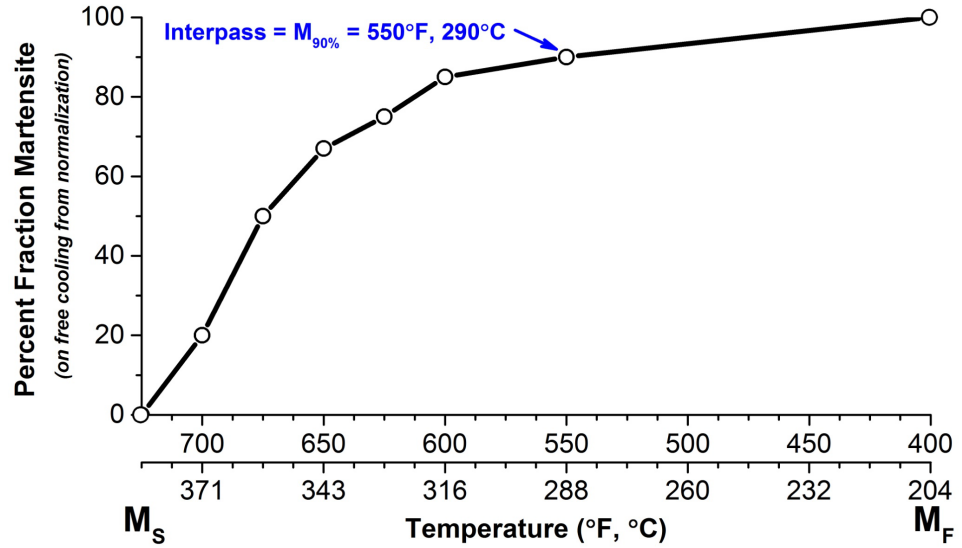
INCO-WELD A and INCONEL are registered trademarks of the Special Metals Corporation family of companies.

## Preheat, Interpass, and Electrode Usage

Typical welding procedures for Grade 91 steel include a minimum preheat of 400°F (200°C) and a maximum interpass of 600°F (315°C). Approximately 40 repair welds in Grade 91 steels have been made by EPRI using a minimum preheat of 300°F (149°C) and a maximum interpass of 550°F (290°C). No issues or problems with hydrogen-induced cracking were found (this issue has been cited as a potential problem when using a preheat temperature of < 400°F (200°C)).

Weld repair with the proper control of storage of welding consumables and prevention of hydrogen into the weld does not lead to cracking even when a minimum preheat of 300°F (149°C) is used. This lower preheat also has the advantage that it increases the range in which a Grade 91 component can be welded with the recommended lower interpass temperature. The use of a lower maximum interpass temperature of 550°F (290°C) ensures that the deposited weld metal and the Grade 91 steel HAZ are effectively transformed to martensite before subsequent layers are deposited, Figure 4-1. The “acceptable welding window,” shown in Figure 4-2, is defined in the context of the martensitic phase transformation that occurs after welding in the Grade 91 steel HAZ for all proposed procedures and also for the deposited 9Cr-1Mo-VNbN or 9Cr-1Mo filler metal. The use of a reduced preheat temperature is acceptable provided the recommended low hydrogen controls are exercised when utilizing ferritic consumables to reduce susceptibility to hydrogen-induced cracking [33]. If poor hydrogen control practice is used it is not established that cracking will always be prevented even with a higher preheat temperature.

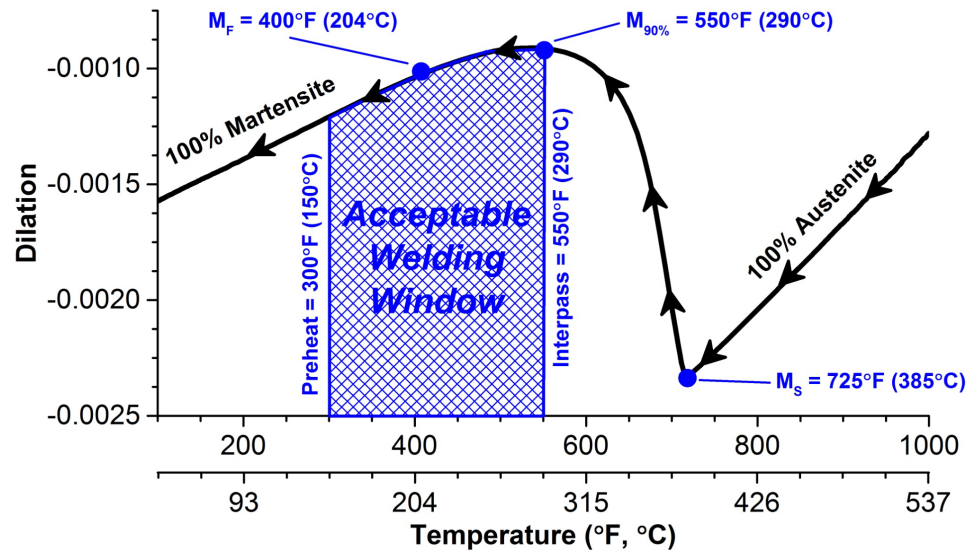
1. SMAW electrodes to be used in the welding of Grade 91 components should be issued from a heated master storage bin and transported to field ovens, where they should be maintained until they are removed for immediate usage. The use of heated weld rod caddies at the worksite is recommended to keep SMAW weld rod at the proper holding temperature up until the time of use. Many manufacturers have provided specific guidelines for storage of coated electrodes, and these should be followed. Unused electrodes left outside of the rod oven or caddies for more than 4 hours should be discarded. It is not recommended to rebake any suspect electrodes.
2. SMAW electrodes should be certified to the H4 designation.
3. Welding wires, most notably FCAW wires, should not be removed from the original sealed packaging until ready for use. If the original sealed packaging shows signs of damage or punctures, the contained welding material should not be used and should be discarded. If welding is interrupted for more than 24 hours, the reel should be discarded. Many manufacturers have provided specific guidelines for storage of FCAW wires following opening, and these should be followed.



**Note:** In this figure, the interpass is defined in the context of weld repair in Grade 91 steel as the temperature required to achieve 90% transformation of austenite to martensite.

Figure 4-1

Effect of Temperature on the Percent Fraction of Transformed Martensite on Cooling



**Note:**  $M_s$  = Initial of austenite to martensite transformation  
 $M_{90\%}$  = 90% transformed austenite to martensite  
 $M_F$  = 100% transformed austenite to martensite

Figure 4-2

Diagram Showing the Minimum Preheat and Maximum Interpass in Relationship to the Percent Fraction of Martensite Transformed on Cooling

## Advantages and Concerns for the Specific Weld Repair Method

The selection of the details for a given weld repair must be made on a case-by-case basis. Thus, a “well-engineered” repair will always be specific to the damage, the component, the skill of the welder, and post-repair inspection methodology, as needed. Table 4-2 identifies general technical considerations pertaining to each of these weld repair methods that should be carefully weighed by the end-user before selecting a method of repair.

Table 4-2

*Basic Considerations for Each of the Acceptable Weld Repair Methods*

| Acceptable Weld Repair Method |                             | Considerations                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-------------------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Filler Metal                  | Welding Procedure           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Matching<br>(9Cr-1Mo-VNbN)    | Controlled Fill<br>+ PWHT   | <ul style="list-style-type: none"> <li>• Matching filler metal is used.</li> <li>• Electrode size should always be restricted to <math>\leq 5/32</math> inch (4.0 mm) in diameter.</li> <li>• Low PWHT decreases the potential for excessive tempering in the HAZ or base material.</li> <li>• Low PWHT will decrease risk of exceeding the <math>AC_1</math> for Grade 91 by increasing the allowable range for PWHT and ensure acceptable performance.</li> <li>• Low PWHT can be expected to relieve some or most of the welding residual stresses in the component.</li> <li>• Recommend minimum PWHT temperature (1250°F, 675°C) is below ASME B&amp;PV Code minimum specified in Section I or B31.1.</li> <li>• Restraints and accommodation of thermal expansion stresses during PWHT need to be addressed to prevent unintended damage in the component.</li> <li>• Where Charpy impact toughness tests are required, a low PWHT may not be sufficient to meet the requirements of a given Code.</li> </ul> |
| 9Cr-1Mo                       | Controlled Fill,<br>No PWHT | <ul style="list-style-type: none"> <li>• Filler metal matches the creep strength of the HAZ in Grade 91 steel.</li> <li>• Filler metal is less hardenable than matching filler metal to Grade 91 (i.e., E9015-B9) and will temper more readily during welding and in service.</li> <li>• There is no concern for carbon migration as the Cr content is matching to Grade 91 steel.</li> <li>• Electrode size should always be restricted to <math>\leq 5/32</math> inch (4.0 mm) in diameter and more preferably to <math>\leq 1/8</math> inch (3.2 mm).</li> <li>• Post-repair inspection and inspection intervals will need to include weld metal and HAZ as the weld metal is matching to the HAZ in strength (depending on the creep strength of the base metal, damage may occur in either the HAZ or weld metal or both).</li> </ul>                                                                                                                                                                          |

Table 4-2 (continued)

Basic Considerations for Each of the Acceptable Weld Repair Methods

| Acceptable Weld Repair Method |                             | Considerations                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|-------------------------------|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Filler Metal                  | Welding Procedure           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Ni-base                       | Controlled Fill,<br>No PWHT | <ul style="list-style-type: none"> <li>• The electrode size for fill passes against the bevel should be 1/8 inch (3.2 mm) diameter as there have been reported difficulties in using smaller diameter electrodes.</li> <li>• The electrode size for all fill passes can be 5/32 inch (4.0 mm) diameter since there is no concern for tempering of the deposited weld metal.</li> <li>• There is increased defect tolerance in weld metal due to the high fracture toughness and creep strength inherent to filler metal.</li> <li>• NDE is more challenging during the repair (MT is not possible) and following repair (optimized procedures for UT are required to inspect the entirety of the weld repair region).</li> <li>• There is a tendency to form microfissures and/or lack of fusion defects (although detected by potential NDE techniques, such defects have not been shown to contribute to a reduction in performance).</li> <li>• The skill of the welder can be an important variable, as Ni-base fillers can exhibit poor weld pool fluidity and in general are more difficult to deposit.</li> <li>• The operating temperature of the component as welding residual stresses may not relax rapidly at temperatures &lt;550°C (1022°F).</li> <li>• Post-repair inspection and inspection intervals will need to include fusion line and HAZ as there may be a risk for damage in both locations and consistent with reported DMW failures.</li> </ul> |





## Section 5: Qualification of Weld Repair Procedures

Qualification of a selected weld repair procedure should be conducted in accordance with the requirements of ASME B&PV Code Section IX or other applicable Code. It should be emphasized that the repair welding procedures described in this document are not “temper bead” methods. Thus, they do not need to meet the additional requirements for qualification outlined in ASME B&PV Code Section IX QW-290. The definition of “temper bead,” per ASME B&PV Code Section IX QG-109 is as follows:

A weld bead placed at a specific location in or at the surface of a weld for the purpose of affecting the metallurgical properties of the heat-affected zone or previously deposited weld metal. The bead may be above, flush with, or below the surrounding base metals surface. If above the base metal surface, the beads may cover all or only part of the weld deposit and may or may not be removed following welding.

In the EPRI database of repair welds, when the filler metal meets or exceeds the creep strength of the Grade 91 HAZ, creep failures have been invariably documented in the Grade 91 HAZ region that is defined as the “FGHAZ.” In the literature, such failures are often identified as “Type IV failures.” The EPRI research has shown that provided a weld (repair or otherwise) is made without gross defects in the deposited weld metal, the failure mode is consistently associated with the Grade 91 HAZ and as detailed in Appendix H. In essence, the weld repair procedure cannot improve the metallurgical properties of the heat-affected zone because these properties are linked to those of the parent steel. The damage susceptibility of the base steel is linked to factors such as composition, steel making, and fabrication processing. It is thus impossible to impart better performance in Grade 91 weld HAZ through the welding procedure. Furthermore, and unlike CrMo and CrMoV steels which are highly susceptible to reheat cracking, the Grade 91 HAZ does not require refinement of HAZ prior austenite grains to resist reheat cracking. Reheat damage has not been documented or reported in Grade 91 steel. Indeed, excessive refinement of prior austenite grains has been identified as a contributing factor to poor creep strength in the HAZ.

Confirmation of the quality of the weld repair procedure should involve conventional tensile and bend tests and preparation and examination of a representative macro specimen of each weld cross-section. This is especially applicable when mockup welds are used, as the metallurgical examination and the cross-section will help to confirm the consistency of the weld bead deposition.

Procedure qualification tests have been conducted for each of the welding procedures proposed in this document. There were no issues recorded in passing the minimum tensile requirement. The most appropriate method for passing the side bend tests is outlined as follows, using the guidance in specific sections of ASME B&PV Code Section IX:

- Guided-bend wrap-around testing only as specified in ASME B&PV Code Section IX QW-466.3;
- The radius on the bend test should be machined to the maximum allowable per ASME B&PV Code Section IX QW-462.2;
- Where simulated repair welds are made in thick plate ( $\geq 1.5$  inches, 38 mm), bends should be split per the guidance in ASME B&PV Code Section IX QW-462.2.

Prevention of significant defects during welding is critical to ensuring appropriate performance, including passing side bend tests. For Ni-base repair qualifications, any F. No. 43 filler metal is suitable, but EPRI P87 filler metal should be avoided for qualification due to its propensity to form slag inclusions. Subsequent application of EPRI P87 for field weld repairs may introduce added difficulty in inspection if slag inclusions are present in the as-deposited filler metal. It should be noted that although these slag inclusions resulted in failed bend tests, the high-temperature performance of EPRI P87 was not affected in the simulated weld repairs where multiple slag inclusions were observed. To date, creep in EPRI P87 simulated weld repairs has been in the Grade 91 HAZ. There is ongoing work through multiple manufacturers to modify the electrode coating to eliminate the issue of slag inclusion for the SMAW process. There have been no reported issues in using EPRI P87 consumables with the GTAW process.

For repair using 9Cr-1Mo filler in the as-welded condition, side bend tests occasionally fail due to the insufficient room temperature elongation; the recorded elongation in as-deposited, all-weld filler metal tensile tests was as low as 14% (as opposed to 18% minimum for SA-387 Grade 91 or 20% minimum for SA-335 P91 [36]). Guidance is provided in ASME B&PV Code Section IX QW-466.1, which allows for base materials to be side bend tested that exhibit between 3 and less than 20% elongation values and should be referenced when issues arise with 9Cr-1Mo filler metal.



## Section 6: Training and Familiarization for Engineers, Welders, and Supervisors

The technical problems and challenges surrounding weld repair of Grade 91 steel cannot simply be overcome with code rules and/or through the addition of a detailed specification for repair. All stakeholders must understand technical issues involved with welding Grade 91 steel. This awareness must ensure that all involved understand that it is essential that all rules, technical requirements, and procedures must be followed, verbatim. This necessitates the training of all stakeholders in the repair process including the engineer, the welder, the supervisor, and the inspector. Overlooking any one requirement in a given repair specification will almost certainly result in problems and/or premature failure leading to a weld repair that is less than acceptable for long-term performance. There can be no substitute for a sound technical grasp of the issues involved in the repair, the exercise of engineering judgment in developing the repair procedure, the use of mockups to validate the repair procedure, and the provision of proper training to the welders tasked with executing the repair.

There are multiple documents available to engineers that permit familiarization with the challenges in welding, heat treating, and fabricating Grade 91 steel components. The relevant EPRI reports providing background are listed following the references at the end of this document. While the primary responsibility of the Engineer is to assemble and write a detailed technical specification, success cannot be ensured unless a comprehensive series of implementation procedures are assembled. These procedures should ensure that the repair process will be properly monitored before, during, and after completion. Engineering staff must take an active and progressive role in developing, coordinating, and transmitting the technical criteria specific to the weld repair procedure to the project supervision, craft labor, and inspection personnel.

For qualification of welders, in addition to a welding procedure specification (WPS), it is highly recommended that an additional mockup test that includes the actual variables specified in the actual repair(s) be carried out. The welding requirements for a specific repair that may need to be assessed for a given scenario and welder include (but are not necessarily limited to) welding out-of-position, welding in restricted/tight spaces, and welding with Ni-base

consumables. Guidelines are provided by AWS B2.1 for special weld tests such as mockups [37]. It should be noted that the NRC has specific guidance for the qualification of welders in situations of limited accessibility [38]. A welder with little experience with Grade 91 steel may incorrectly assume that welding this alloy is not different from welding other carbon or CrMo low-alloy steels. This misconception will lead to problems and can only be avoided by the proper training, which emphasizes that attention to detail is mandatory with regard to maintenance of preheat, observance of limits on the interpass temperature, use of proper fill technique, control of bead overlap, effective control of PWHT (if applicable), and complete and accurate documentation and monitoring of all aspects of the weld repair.

Supervision must be aware of the technical requirements necessary for satisfactory repair of Grade 91 steel and implement these specific criteria, as outlined by the engineer. Additionally, supervision must be able to properly and effectively communicate with the welder and/or craft labor employed in the repair process—that is, speak their language. Guidelines for certification of welding supervisors are highlighted in [39].



## Section 7: Repair Roadmap

Figure 7-1 presents an overview of the weld repair process. The sections that follow outline the key decision-making processes that should be followed when damage is detected in an in-service component. Good engineering practice for repair should always begin with an investigation into the extent of and the cause of the damage present. When a proper root cause analysis is not completed it is difficult if not impossible to judge the risk of repeat fractures.

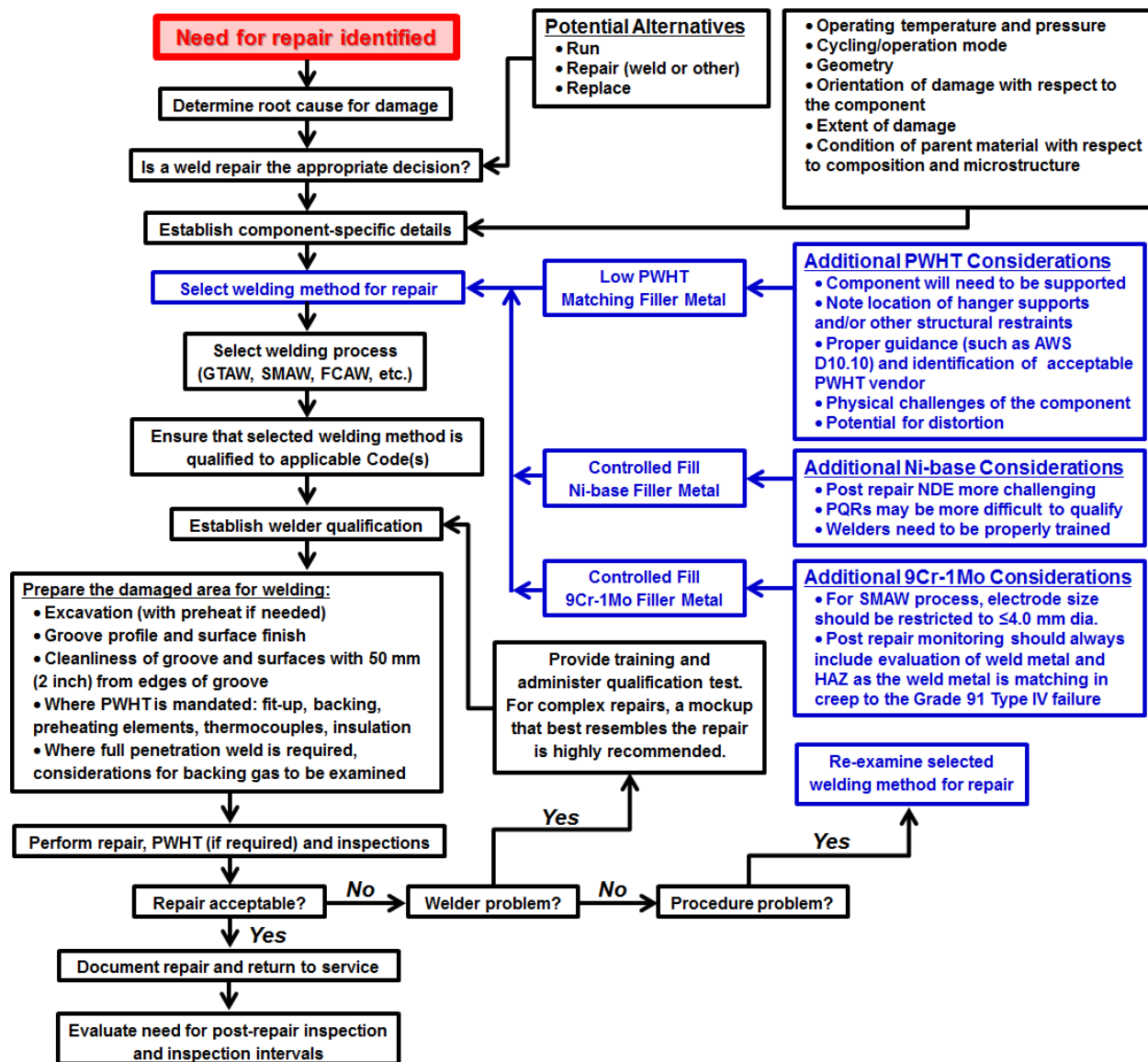


Figure 7-1  
Weld Repair Roadmap



## Section 8: Root Cause Analysis

Damage in Grade 91 components may arise from a variety of factors and operating conditions. Proper identification of damage, failure mode(s), and other details is critical to the selection of the proper weld repair technique for a given component. A general summary derived from extensive plant experience with Grade 91 steel components indicates that problems requiring repair and remediation may be associated with the following:

### **Design – issues include:**

- Use of heavy section Weldolet-type connections
- Use of flat end caps for closure on headers
- Use of fabricated fittings with severe stress/strain concentrations and without balanced reinforcement as opposed to requiring forged fittings with well-blended connections
- Ensuring supports are effective in reducing systems loads
- Requirement for “cold spring” to minimize thermal stresses
- Proper design of dissimilar metal welds or welds joining dissimilar steels
- Application of weld efficiency factors for welds operating in the creep range

### **Operation – issues include:**

- Identifying sustained temperatures above design
- Determining presence of high systems loads (often linked to incorrect support design or performance), and conducting forensic analysis of piping system behavior anomalies
- Identifying significant thermal cycles (tracking of transients should consider relatively low stress events that occur often as well as higher stress but less frequent events)

**Fabrication – issues include:**

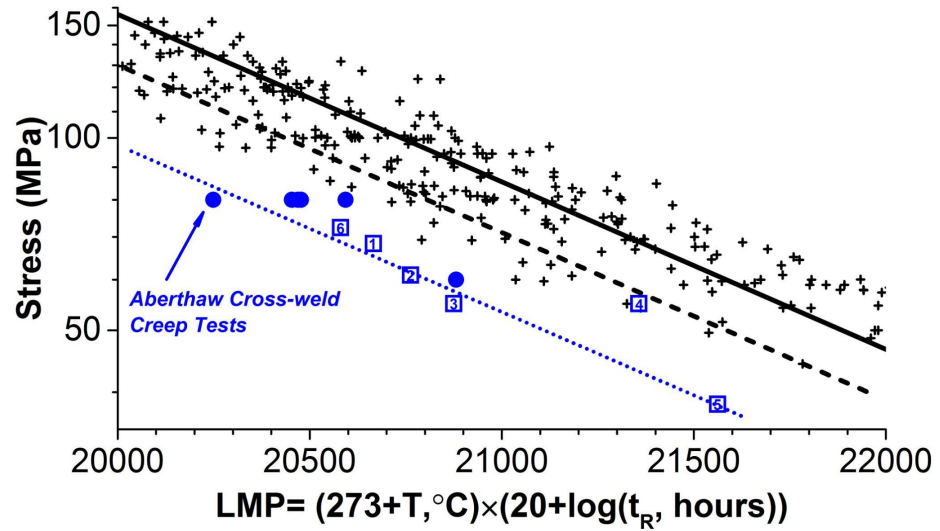
- Ensuring adequate control of alloy composition
- Lack of control and monitoring of component preheat, interpass, and heat treatment including peak temperature, hold time, and/or cooling rate
- Lack of planning for and control of the timing of tempering treatments
- Lack of planning for and control of the timing and execution of post-weld heat treatment

**Construction – issues include:**

- Use of temporary welded attachments
- Lack of control of weld consumables and adequate quality assurance
- Use of seam welded components when the specified seamless components are not readily available
- Application of adequate techniques for repair and remediation
- Overall quality assurance
- Documentation of work actually performed

It is important, both for the dispositioning of defects and for the overall assessment of the condition of the component, that the mechanism responsible for the damage be properly identified and, if possible, that the root cause of the damage be determined. It should be emphasized that a root cause analysis is significantly more than simply identifying the damage mechanism. Thus, root cause analysis should establish the reasons for the accelerated damage so that appropriate remedial action can be undertaken to minimize the risk of future problems.

Recent root cause analyses [40, 41] of cracking in a Grade 91 steel header have shown that composition and processing variables are linked to low creep ductility in base metal and weld HAZs. The observed in-service component cracking is not simply a “one off” anomaly. Examination of failures in other Grade 91 welded components [25, 26] indicates a trend where an increasing number of failures of Grade 91 welds are occurring in times below that expected based on previous analysis (see Figure 8-1). The trend in the reduced creep ductility in Grade 91 steel and the link to very low HAZ creep life may be characteristic of a significant number of in-service components.



Note the shift in behavior to a regime below the minimum (mean-20%) and the known database of cross-weld failures in the heat-affected zone of Grade 91 steel.

Figure 8-1

Analysis of Cross-Weld Behavior Using a Larson Miller Parameter Relationship ( $C = 20$ ) for Cross-Weld Tests Performed in Recent Work (Blue Data Points Labeled Barrels 1, 2, 4) and Published Failures [25, 26]





## Section 9: Assessment of the Base Metal Condition

It is very important that the condition of the parent material be established, regardless of whether the repair is required in virgin, unaffected base metal or in a weldment. The properties of CSEF steels are critically dependent on factors that include control of steel-making, composition, processing, and heat treatment [42, 43]. Moreover, lack of correct control of these factors can severely compromise strength, ductility, or both. In addition, degradation due to accelerated creep damage has been linked to different factors, including the formation of new phases; coarsening or dissolution of carbides; recovery of the dislocation substructure; and the nucleation, growth, and linking of microvoids [44-47]. These effects have been shown to control the ultimate behavior and performance of the weld repair, as detailed in Appendix G for weld repairs made using 9Cr-1Mo filler metal (E8015-B8). Research has shown that it is important to properly establish the condition and properties of the parent material. This evaluation should include review of metallurgical condition and risk factors, characterization of damage, and application of the EPRI-developed Grade 91 Life Ranking Estimator [48].





## Section 10: Selection of the Welding Process

The selection of the appropriate welding process and the development of a detailed procedure are a function of the size of excavation, the access to skilled labor, the orientation of the required weld repair, the cost of the repair, and the constraints of time. For single-sided, full penetration welds, it is always preferred to fabricate the weld root and hot passes using the GTAW process. The performance of welds made using the SMAW process or the FCAW process has been evaluated in consideration of the potential for achieving improved productivity. As compared to the SMAW process, the FCAW process has been shown to provide a ~50% increase in productivity [49], but this improved productivity should be weighed against other considerations specific to the FCAW process, as detailed in [50]. Some of these considerations include, but are not limited to, the added complexity from shielding gas, wire feed systems, added scaffolding to support the additional weight of the welding equipment, and additional consumable items such as tips, drive rolls, and liners. Each repair situation must include review of the background and skill level of the welding personnel in order to make an effective process selection decision.





## Section 11: Excavation of Defects

The methodology for damage removal from base material is straightforward, since the extent of damage will dictate the required amount of material to be removed. For any scenario where material is being excavated, the static and dynamic load(s) of the component(s) must be considered. It may be necessary to add additional supports prior to the repair process to ensure that the component does not move or distort and create additional issues during machining or weld repair. During repair and PWHT, it is advised to isolate the weldment from any external loading. The restraints must be adequate to remove any long-range loading arising from the balance of the adjoining pipework system. Unless this is achieved the weld will be subjected to loading and creep damage either during welding or PWHT (where specified) or both. Specifically with regard to PWHT, the restraint needs to be released in a controlled manner to allow for thermal expansion as the PWHT region is brought up to the specified temperature. Unless this is achieved, bending stresses will build up between the restraint points, again subjecting the repair weld region to loading and creep damage during the PWHT procedure.

Excavation of damage in weldments is less straightforward. For the hypothetical damage scenario shown in Figure 11-1, there are at least four approaches for the excavation of damage, depending on the assumptions that are made:

1. For base material that may exhibit a difference in metallurgical risk factors, it may be appropriate to locally excavate the damage, as shown in Figure 11-2. In uniaxial creep tests, damage has preferentially developed in the base metal HAZ as opposed to the HAZ developed in the weld metal and depicted in Figure 11-3. However, it must be mentioned that any local excavation consistent with that shown in Figure 11-2 has a risk for failure in the weld metal HAZ if the existing weld metal exhibits specific risk factors such as:
  - Improper PWHT (i.e., low hardness values in the weld metal)
  - Mn+Ni content > 1.5 weight percent
2. For base material that is of the same parent heat on either side of the weldment, it is advisable to consider a partial repair (Figure 11-4) as opposed to a minor repair. Although weldment geometry, design, service stresses, and other factors dictate the formation and rate of accumulation of damage, it is reasonable to make a simple assumption that for a given component, the extent of the damage is likely to be similar on either side of the weldment. Because of this, the conservative approach would be to remove the HAZ on each side of the weld.

3. Should a full penetration repair weld be considered, there are several issues that need to be evaluated:
  - a. It is not recommended to make a weldment to the geometry shown in Figure 11-5. An aligned HAZ exhibits an inherently low tolerance to damage and may result in catastrophic failure of the repair weld under service conditions. The performance of the weld repair using this type of geometry will be no better than the performance of the original weld it is replacing. For a full penetration weld, it is recommended to consider the machining of a “step” as shown in Figure 11-6 to increase the damage tolerance of the repair weld. Details of the dimensions associated with a weld “step” will be published by EPRI in the near future.
  - b. When possible, avoid a full penetration weld so as to prevent any susceptibility to stress corrosion cracking at the root or in the HAZ at the inside diameter of the repair weld and so as to reduce the potential for metal shavings and debris to enter the system. In general, it is recommended to have a remaining thickness near the root of approximately 0.20 inches (5.0 mm).
  - c. When it is not possible to retain a small land for the repair weld, a full penetration weld is recommended whereby the root and hot passes are made using the GTAW process. In these cases, the back side of the open void shall be purged with an argon purge gas to protect the interior portion of the initial root pass welds. The balance of the fill passes can be made as directed in previous sections.

Suitable methods for defect removal include grinding, machining, and use of arc-gouging. The use of arc-gouging will create a HAZ in the material, and it is therefore recommended that this HAZ be removed in its entirety prior to conducting the weld repair. All grinding and air-arc gouging shall be further shaped and trimmed to remove all oxides and form a uniform contour so that weld metal can be adequately applied to the full depth of the defect/crack and blend into the apparent base metal. The arc-gouge HAZ must be completely removed by mechanical means such as grinding or machining. Hardness measurements during the removal of the HAZ created by arc-gouging by grinding or other means can be utilized to provide confirmation that it has been entirely removed.

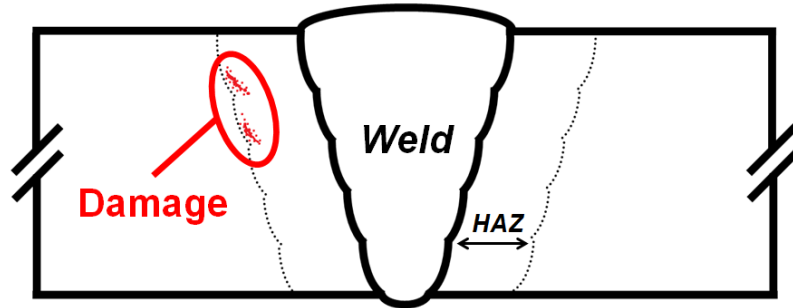


Figure 11-1  
Hypothetical Scenario for Inspection and Identification of Damage in a Welded Grade 91 Steel Component

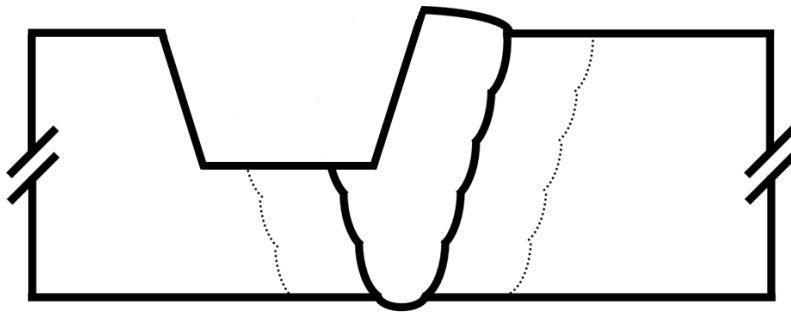


Figure 11-2  
"Minor" Excavation of Damage Scenario Identified in Figure 11-1

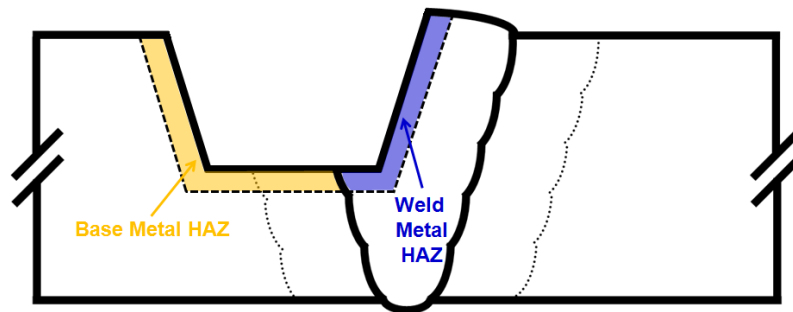


Figure 11-3  
Heat-Affected Zone Regions Created from a "Minor" Weld Repair

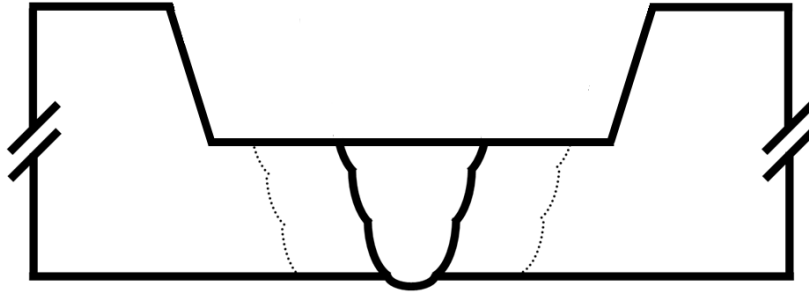


Figure 11-4  
*"Partial" Excavation of Damage Scenario Identified in Figure 11-1*

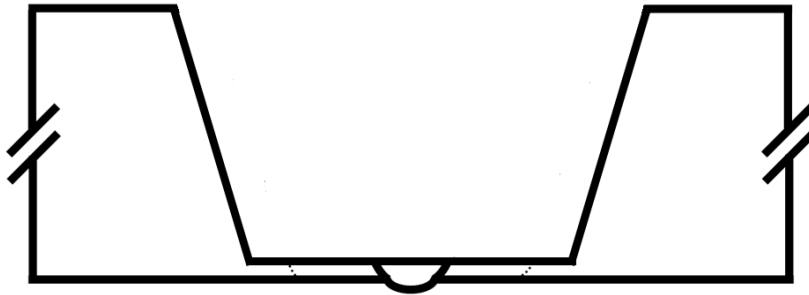


Figure 11-5  
*"Full" Excavation of Damage Scenario Identified in Figure 11-1*

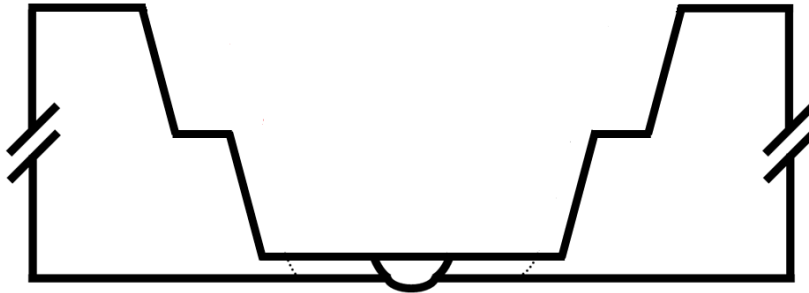


Figure 11-6  
*"Stepped Full" Excavation of Damage Scenario Identified in Figure 11-1*

## Section 12: Geometry of the Weld Repair Excavation

Final geometry of the excavated region for weld repair should not contain sharp corners. Round and/or contoured transitions should be mandated to eliminate the possibility of introducing internal stress risers. Additionally, there are several critical aspects to the geometry of the weld repair excavation, as supported by the information provided in Appendix I:

1. Bevel angle, as exhibited by dimension “ $\alpha$ ” in Figure 12-1. Selection of a given bevel angle for the excavation should be primarily dictated by the amount of access required for the welder to make an acceptable repair weld. It must be noted that there is an observed tradeoff in performance for unnecessarily large bevel angles. It has been shown that as the bevel is increased to a standard value of  $37.5^\circ$  (such as for tube-to-tube butt welds), the performance will decrease by at least a factor of 2 as compared to similar welds made with a bevel of  $10^\circ$ . Thus, a reasonable attempt should be made to both satisfy the welder and maximize the long-term performance of the repair.
2. The radius, as shown by dimension “R” in Figure 12-1, should be specified to a 0.0625 inch (1.6 mm) minimum to reduce the risk of lack of fusion (LOF) defects. Ensuring a smooth transition between the flat and bevel decreases the likelihood that a defect results from the welding process in this region. Multiple weldments have demonstrated, therefore, that a 0.0625 inch (1.6 mm) radius is sufficient to prevent LOF in this region. This value should be regarded as an absolute minimum and can be process dependent. For high deposition welding processes, such as FCAW, the radius may need to be increased to fully prevent LOF.
3. Complete removal of the HAZ, as exhibited by dimension “w” in Figure 12-1. Note that this dimension is a function of the measured distance from the fusion line. The strength of the filler metal likely may play an additional role in sizing this dimension. It is therefore recommended that the removal of the HAZ be at least 0.40 inch (10 mm) from the fusion line.
4. The bead overlap near the face or cap of the weldment, as identified by the dimension “S” in Figure 12-1, has been an important criterion in nuclear temper bead construction and is defined in ASME B&PV Section IX QW-462.12. As it pertains to high-temperature performance (defined here as  $>1000^\circ\text{F}$ ,  $538^\circ\text{C}$ ), the “S” dimension is not critical to component

performance. In general, it may be specified to perform an additional layer of reinforcement that will be removed by grinding to ensure a level of tempering at the cap/face of the weld repair. A good general practice for completing any weld is to avoid placing the final weld bead on the edge of the weld cap. Wherever possible, the cap bead progression should proceed from the edges toward the center of the excavation.

5. Depth of material removal, as shown by dimension “D” in Figure 12-1, will be dictated by the extent of the damage. It is not suggested to remove excessive material or additional material aside from what is identified by a suitable NDE method or destructive evaluation (a boat or plug sample, for instance). To ensure complete removal of defects, it is recommended that a liquid penetrant or magnetic particle test be performed prior to weld repair. Magnetic particle examination is always preferred over liquid penetrant examination when possible.

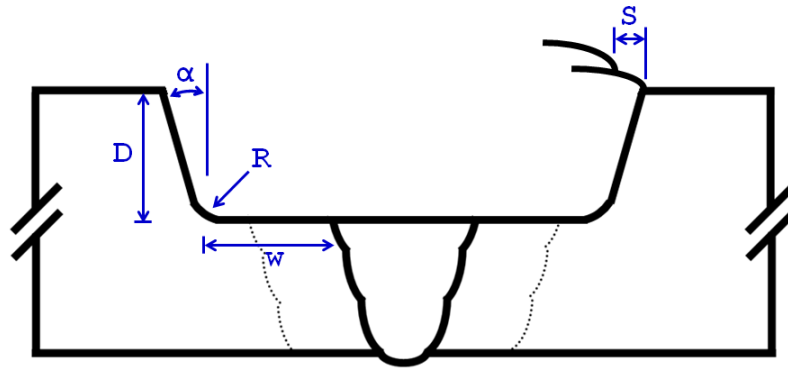


Figure 12-1  
Critical Dimensions for Excavation and Weld Repair of Welded Grade 91 Steel  
Components, Partial Repair Excavation Shown



## Section 13: Fill Technique

Key aspects regarding the fill technique, regardless of the proposed weld repair procedure, are defined by Figures 13-1 and 13-2. In general, to maintain an appropriate heat input, it is recommended to weld the excavation using a “controlled fill” technique. In this technique, the first layer in contact with the excavation can be identical or smaller in diameter than the fill passes. The bead-to-bead overlap should be ~50% or greater. The fill passes should be deposited working from the bevel toward the center of the excavation with a minimum overlap of 25% and ideally 50%. This method not only helps promote tempering of ferritic filler materials, but helps to control distortion and is common in the welding of CrMo steam turbine casings [29]. As a rule of thumb, if the welder aims for the toe of the previously deposited weld bead, an overlap of at least 40% will be achieved.

Figure 13-3 provides further information regarding the fill sequence in the weld plane of travel (i.e., the plane that is into the page in Figures 13-1 and 13-2) to minimize distortion. Additional recommendations, specific to the filler material, are as follows:

1. In ferritic filler materials, an electrode size of 3/32 inch (2.5 mm) has been shown to be acceptable for use by the welder and deposit of the first layer. It is generally recommended to restrict subsequent electrode size to 1/8 inch (3.2 mm) electrode for the subsequent controlled fill passes. Although the recommendation provided here is to utilize a 3/32 inch (2.5 mm) electrode for the first-layer controlled overlap beads, acceptable qualifications have been demonstrated utilizing 1/8 inch (3.2 mm) for the first-layer controlled overlap. For the fill passes, the diameter of the electrode shall be restricted to  $\leq 5/32$  inch (4.0 mm), and it is recommended to utilize a 1/8 inch (3.2 mm) electrode for control of heat input and material deposition.
2. In nickel base filler metals, an electrode size of 3/32 inch (2.5 mm) has proven difficult to utilize, especially in the case of EPRI P87 [34]. To improve the weldability, it is generally recommended that any butter layer be performed with 1/8 inch (3.2 mm) diameter electrode. Additionally, it is acceptable to utilize 5/32 inch (4.0 mm) diameter electrode, provided the welder has demonstrated the proper skill level to utilize the larger diameter electrode without introducing defects.
3. Regardless of electrode size or weld repair method, bead-to-bead overlap should be ~50%. This is particularly important to prevent introducing welding defects.

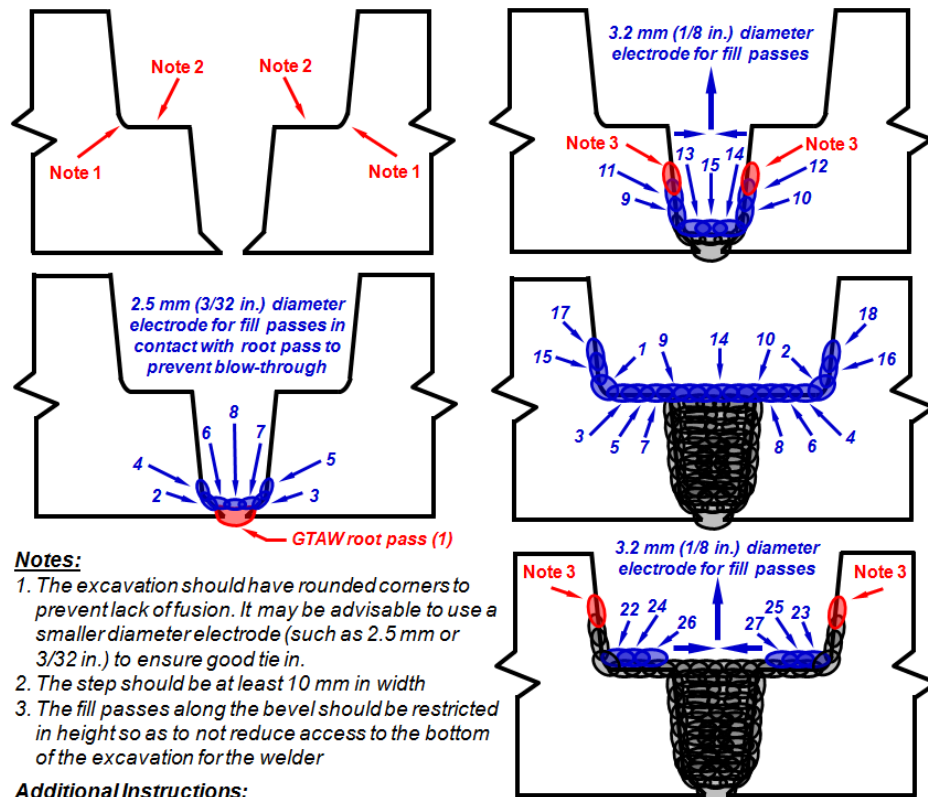


Figure 13-1  
Controlled Fill Technique for Weld Repair of Grade 91 Steel Components, as  
Shown for a Full Repair Scenario in Base Material or Welded Grade 91 Steel  
Component

**Notes:**

1. The excavation should have rounded corners to prevent lack of fusion. It may be advisable to use a smaller diameter electrode (such as 2.5 mm or 3/32 in.) to ensure good tie in.
2. The step should be machined at least 10 mm beyond the fusion line of the original weld
3. The fill passes along the bevel should be restricted in height so as to not reduce access to the bottom of the excavation for the welder

**Additional Instructions:**

- The fill passes should be conducted working "outside-in", whereby the fill passes are first deposited on either side of the excavation and additional fill passes are deposited welding towards the center of excavation
- 50% overlap is recommended for all welding passes either in contact with the bevel or fill
- Stringer beads only are recommended for all welding passes either in contact with the bevel or fill
- A 2.5 mm (3/32 in.) diameter electrode may be utilized for the weld passes in contact with the bevel but is not mandated nor required for acceptable performance

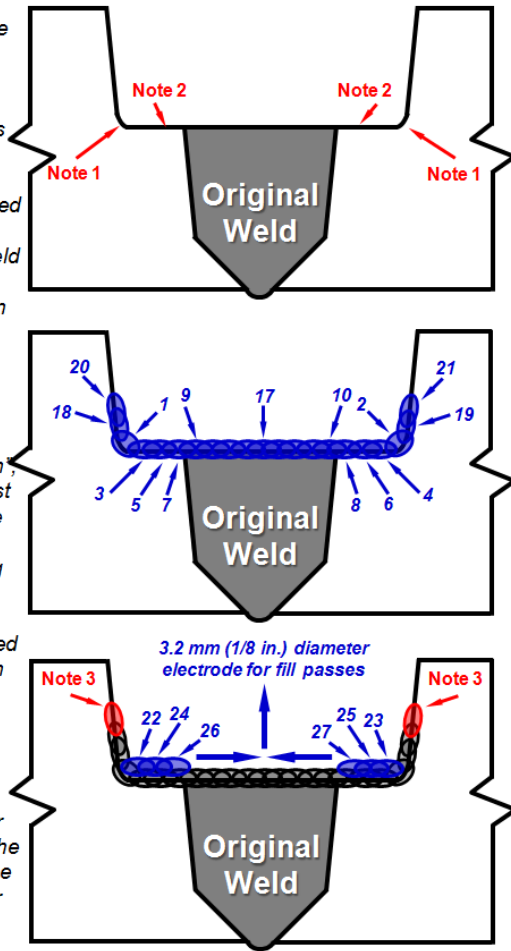


Figure 13-2

Controlled Fill Technique for Weld Repair of Grade 91 Steel Components, as Shown for a Partial Repair Scenario in Base Material or Welded Grade 91 Steel Component

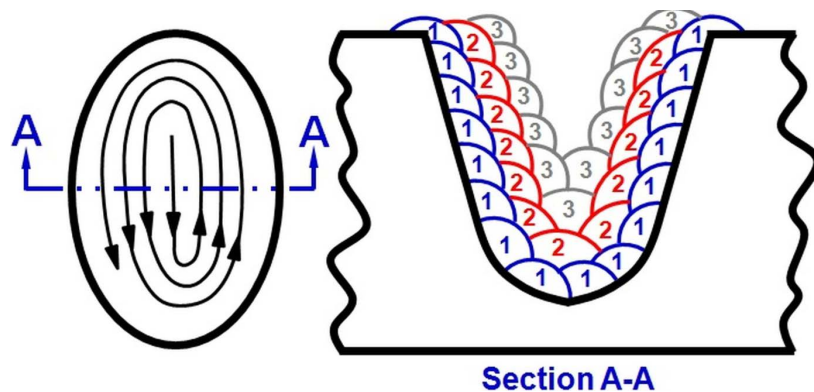


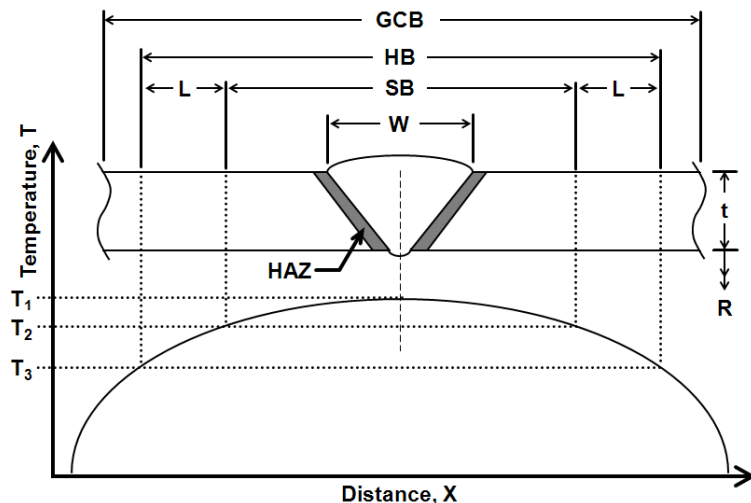
Figure 13-3

Example of Bead Sequencing for a "Boat" Shaped Excavation to Minimize Distortion [29]



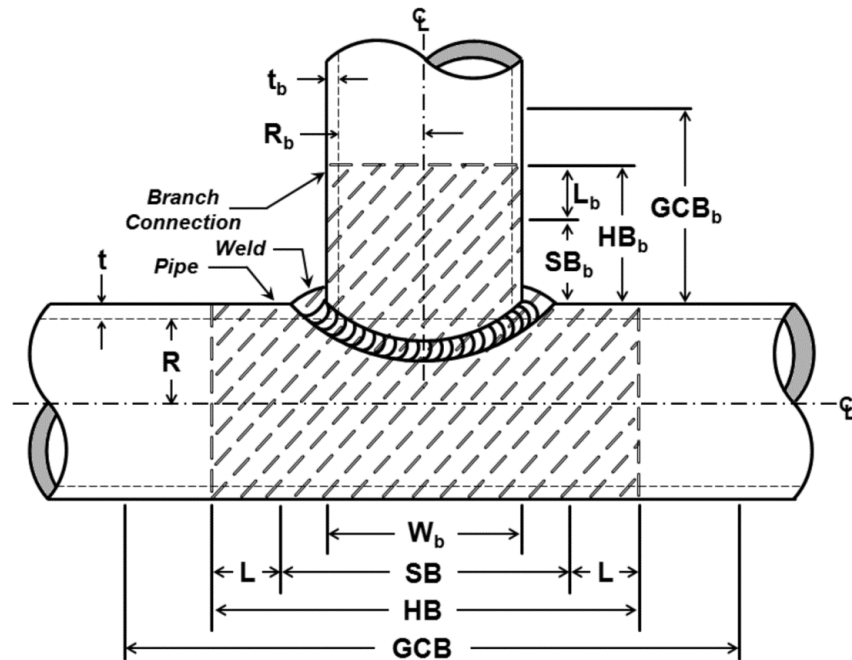
## Section 14: Post-Weld Heat Treatment Guidance (Where Applicable)

With regard to PWHT practice, monitoring, and thermal gradients, AWS D10.10, *Recommended Practices for Local Heating of Welds in Piping and Tubing*, provides guidance on the number and placement of thermocouples [32]. The common terms and definitions are outlined and depicted in Figures 14-1 and 14-2. Although not published at the time of this publication, a new AWS standard D10.22 [51] will be published to provide specific and additional instructions to AWS D10.10.



|       |                                                                                                                                                                                                                                                    |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $T_1$ | Maximum required soak band temperature                                                                                                                                                                                                             |
| $T_2$ | Minimum required soak band temperature                                                                                                                                                                                                             |
| $T_3$ | Minimum required percentage of $T_2$                                                                                                                                                                                                               |
| GCB   | Gradient control band (minimum width of insulation and/or gradient heat source)                                                                                                                                                                    |
| HB    | Heated band (width of heat source)                                                                                                                                                                                                                 |
| SB    | Soak band (width of the volume of material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as $W$ plus a multiple $t$ on each side of the weld). |
| $W$   | Width of butt or attachment weld                                                                                                                                                                                                                   |
| HAZ   | Heat affected zone                                                                                                                                                                                                                                 |
| $L$   | Minimum distance over which the temperature may drop to a percentage of that at the edge of the soak band                                                                                                                                          |
| $t$   | Nominal thickness of piping, branch connection, nozzle neck, or attachment                                                                                                                                                                         |
| $R$   | Inside radius of piping, branch connection, or nozzle neck                                                                                                                                                                                         |

Figure 14-1  
Image and Description of Post-Weld Heat Treatment Terms Outlined in  
AWS D10.10 for a Tube-to-Tube or Pipe-to-Pipe Connection [27, 32]



|                       |                                                                                                                                                                                                                                                                                              |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| GCB, GCB <sub>b</sub> | Gradient control band (minimum width of insulation and/or gradient heat source)                                                                                                                                                                                                              |
| HB, HB <sub>b</sub>   | Heated band (width of heat source), shown as shaded area                                                                                                                                                                                                                                     |
| SB                    | Soak band on pipe (width of the volume of material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as $W_b$ plus a multiple $t$ on each side of the weld attaching the branch connection). |
| SB <sub>b</sub>       | Soak band on branch connection. The minimum width is typically specified as a multiple $t_b$ beyond the widest width of the weld attaching the branch connection                                                                                                                             |
| $W_b$                 | Widest width of weld attaching the branch connection to the pipe                                                                                                                                                                                                                             |
| HAZ                   | Heat affected zone                                                                                                                                                                                                                                                                           |
| $L, L_b$              | Minimum distance over which the temperature may drop to one half of that at the edge of the soak band                                                                                                                                                                                        |
| $t, t_b$              | Nominal thickness of pipe or branch connection                                                                                                                                                                                                                                               |
| $R, R_b$              | Inside radius of pipe or branch connection                                                                                                                                                                                                                                                   |

Figure 14-2

Local 360° Band PWHT Practice for Branch Connection to Pipe Attachment Weld [27, 32]

If a PWHT is specified for a weld repair, the procedure must be reviewed and approved prior to implementation. The procedure should include thermocouples (monitor and control), how the repair will be wrapped, the number of heat blankets, and the pertinent calculations including the soak band, heat band, gradient heat band widths, and so on. All PWHT activities should be monitored/inspected by inspectors or engineers having prior experience with heat treatment protocols for Grade 91 steel and/or other CSEF steels.

Past approaches used to control and monitor Grade 11 or 22 steel components during PWHT are not adequate for Grade 91 applications. The use of AWS D10.10 alone will not ensure proper PWHT, a point highlighted by [52]:

Recognizing that temperature monitoring has inherent errors that may approach as much as 1.5% of the soak temperature (0.75% from errors of the thermocouple wire, and 0.75% from errors in the recording device), in the case of the CSEF steels this may create as much as a  $1375^{\circ}\text{F}$  ( $746^{\circ}\text{C}$ )  $\times 1.5\% = 20^{\circ}\text{F}$  ( $11^{\circ}\text{C}$ ) variation from actual temperature. Adding this possible error to the total expected through wall temperature gradient (when using an AWS D10.10 procedure), means that when using a  $75^{\circ}\text{F}$  ( $42^{\circ}\text{C}$ ) temperature range for PWHT, the ID temperature could be as much as  $65^{\circ}\text{F}$  ( $36^{\circ}\text{C}$ ) below the hottest part of the OD temperature. Leaving a minimal  $10^{\circ}\text{F}$  ( $6^{\circ}\text{C}$ ) tolerance for controlling temperature. AWS D10.10 therefore has extreme difficulty in controlling heat treatments on the CSEF steels that require total temperature variations within the soak band of  $75^{\circ}\text{F}$  ( $42^{\circ}\text{C}$ ).

To alleviate the inadequate guidance within AWS D10.10, the authors in [52] suggested two remedies to increase the potential for proper PWHT. These are detailed in Table 14-1.

Table 14-1

Comparison of AWS D10.10 Requirements to Best Practice Guidance in [52] for PWHT

| Scenario                                       | AWS D10.10 Requirements                                                                 | 1                              | 2                                                                       |                       |
|------------------------------------------------|-----------------------------------------------------------------------------------------|--------------------------------|-------------------------------------------------------------------------|-----------------------|
| Objective                                      |                                                                                         | Increase the heated band width | Change from a soak band width scenario to a control band width scenario |                       |
| Control band width                             | 3t                                                                                      | 3t                             | 12.8t                                                                   | 19.2t                 |
| Heated band width                              | 20 inches<br>(508 mm)                                                                   | 49 inches<br>(1245 mm)         | 20 inches<br>(508 mm)                                                   | 28 inches<br>(711 mm) |
| Gradient control band width                    | 30 inches<br>(762 mm)                                                                   | 60 inches<br>(1524 mm)         | 30 inches<br>(762 mm)                                                   | 38 inches<br>(965 mm) |
| Reduction in through-wall temperature gradient | 0%<br>(Observed through-wall gradient was $52^{\circ}\text{F}$ , $29^{\circ}\text{C}$ ) | 40%                            | 40%                                                                     | 60%                   |

**Note:** In the presented scenario, the measurements are specific to a 14 inch (356 mm) outside diameter and 1.25 inch (31.75 mm) wall pipe.

There are many additional requirements that must be considered during PWHT. The most widely utilized form of PWHT is the use of ceramic bead resistance heating pads. Additional precautions must be taken since soft material, identified away from the weld metal and HAZ, has been attributed to areas where ceramic bead resistance heating pads without proper control were utilized for preheat and PWHT operations. Furthermore, detailed EPRI research and other independent assessment have arrived at a unified position regarding other salient details for performing PWHT [53-55]. These are as follows:

- The pads must be properly sized and wrapped onto the parts without gaps or slackness.
- The pads should never overlap.
- The gaps between heating pads should be minimized.
- In addition to the thermocouple layout detailed in AWS D10.10, it is recommended to have at least one thermocouple installed under each stress relief heating pad to verify that the material under the pad has not exceed the lower critical temperature.
- Thermocouples under pads must also be insulated so they measure the metal temperature and not the pad temperature.
- A single control thermocouple should not control multiple heaters, as uniform heating will be difficult over the desired PWHT area.
- Monitoring or control thermocouples should be located underneath the pads in the location of the expected highest temperature.
- Use of multiple control zones for joints with dissimilar thickness transitions.
- Many companies specify redundancy in these control thermocouples in the event one becomes unattached during PWHT.
- Where access to the ID is possible, monitoring should be mandated. Single point monitoring is unacceptable.
- Excessively high ramp rates during PWHT (that is, where there is large thickness transition as in a pipe to a valve or fitting) can lead to a dwell above the lower critical temperature and result in soft regions.

Regardless of the method for heating, the importance of proper thermocouple control is critical. Factors such as placement, number of thermocouples, and redundancy cannot be overemphasized. In addition to the through-wall gradients that are inevitable during PWHT, added consideration should be given to temperature distributions in complex shapes, dissimilar thickness, and chimney/position effects. As the complexity of the component geometry increases, so does the need for increased emphasis on planning, execution, monitoring, and control of heat treatment.

A variety of devices are available for measuring and monitoring temperature while the welding operation is in progress. For preheat and interpass temperature measurements, instantaneous devices such as temperature-indicating crayons, contact pyrometers, or direct reading thermocouples (analog or digital) are satisfactory. All devices should be calibrated or have some means of verifying their ability to accurately measure temperature within the desired temperature range. Crayons are generally not recommended above 400°F (200°C); monitoring of temperatures above this threshold should be conducted by a contact thermocouple. It is never acceptable to make or take readings using a method that would result in contamination of the weld groove. Because of their ability to provide continuous monitoring and data storage, thermocouples using chart recorders or data acquisition systems are preferable over instantaneous measuring devices for both preheat and PWHT operations. Temperature-indicating crayons, contact pyrometers, and direct reading thermocouples with instantaneous readouts are not acceptable for PWHT operations. Only continuously recorded temperature measurement devices are acceptable for PWHT.





## Section 15: Nondestructive Evaluation of the Weld Repair

In all cases, visual inspection should be performed after each weld pass. This visual inspection should check compliance with the defined procedure and identify issues regarding weld bead shape, position, and so on.

### **Weld Repairs Made Using 9Cr-1Mo or 9Cr-1Mo-VNbN Consumables**

It is desirable for welds to also be inspected at several stages in the welding sequence to check for cracks or linear indications. In many instances, it is best practice to inspect a weld repair following three specific milestones:

- Completion of the root and/or hot passes, generally conducted using magnetic particle inspection
- 50% completion of the repair weld, generally conducted using magnetic particle inspection
- 100% completion of the repair weld, conducted using magnetic particle inspection and 100% volumetric inspection

In weld repair scenarios where access is limited or welding is primarily being conducted out-of-position, it may be advisable to include additional inspection through the repair process. In instances where the repair procedure includes PWHT, it should be noted that codes of construction often require that for Grade 91 steel (P No. 15E), NDE be conducted after PWHT. In such cases, it is advisable to conduct preliminary informational NDE before PWHT to screen the weld and make remediations if necessary. The acceptance NDE would then be performed following the PWHT. **This will allow corrections to be made without the consequence of additional PWHT cycles.** The specific criteria should be checked with the code of construction.

It is always recommended to inspect the completed weld repair prior to service exposure, using an appropriate nondestructive evaluation technique. Volumetric NDE examination allows the end-user to identify potential defects that may propagate when placed under load prior to conducting a hydrotest and/or under service conditions. This technique should be sufficiently sensitive to identify the relative size and extent of welding defects; such examination is critical to the assessment of defect tolerance for low-temperature operations such as initial firing, cycling (especially cold starts), and/or hydrotesting. Assessment of the fracture toughness behavior of the ferritic filler materials in the as-welded, service-aged, and/or PWHT condition has been evaluated. Based on the analysis, a minimum critical flaw size of ~0.10 inch (3 mm) should be identified by the selected NDE method.

### **Weld Repairs Made Using Nickel Base Consumables**

These welds are not suitable for nondestructive testing using magnetic particle methods or by ultrasonic methods. However, the primary concerns for defects will be linked to lack of fusion or inclusion type defects. The presence of these defects should be assessed by means of post-repair volumetric inspection using a qualified radiographic technique; welds must pass applicable acceptance tests.

## Section 16: Post-Repair Testing

NBIC NB-23 requires that all repairs to pressure-retaining items shall be verified by examination or test. Liquid pressure testing, also known as hydro-testing, is widely used for this purpose. NB-23, Part 3, 4.4.1, a), 3) defers that the metal temperature at the time of test be in accordance with the original code of construction. The original codes of construction require that the metal and test medium temperatures should be the same at the time of the test. The equilibrium temperature should be such that the pressure-containing material is at a level where it is resistant to low-temperature fracture. It is highly recommended that the water be heated to a temperature as recommended in the 2013 Edition of the NBIC Part 3, Table 4.4.2 [2] to prevent risk of low-temperature fracture for full penetration or near full penetration repair welds. For reference, this table is reprinted here as Table 16-1.

Table 16-1

*Guidance for Minimum Hydro-Test Water Temperature for a Given Component Thickness [2]*

| Minimum Liquid Temperature for Pressure Testing |    | Thickness (t) of Pressure-Retaining Object <sup>1</sup> |                   |
|-------------------------------------------------|----|---------------------------------------------------------|-------------------|
| °F                                              | °C | inches                                                  | mm                |
| 60                                              | 15 | $t \leq 0.5$                                            | $t \leq 13$       |
| 70                                              | 20 | $0.5 < t \leq 1$                                        | $13 < t \leq 25$  |
| 85                                              | 29 | $1 < t \leq 2$                                          | $25 < t \leq 50$  |
| 100                                             | 38 | $2 < t \leq 4$                                          | $50 < t \leq 100$ |
| 110                                             | 43 | $t > 4$                                                 | $t > 100$         |

<sup>1</sup>Thickest section of the pressure-retaining object

If the ambient temperature, hence the metal temperature prior to initiating hydro-test, is below the minimum liquid temperature limits, it is recommended to warm the test liquid beyond minimum temperatures so that the equilibrium metal and liquid temperature is achieved above the required minimum liquid temperature. Additional allowance should be applied to further warm the test medium temperature to allow for cooling in low ambient temperature environments. The temperatures should be above minimum values for the entire duration of the test.

The NBIC does not restrict post-repair testing to only liquid pressure tests. Alternate testing methods are recognized in NBIC, Part 3, 4.4.1 and are useful to consider when liquid pressure testing is not practical, isolation is difficult to achieve, or the situation may include components not set up for a full liquid pressure test. Alternate testing options may require concurrence of the Inspector. It is recommended that the Owner/User include input from the Inspector as early in the process as possible, preferably during the repair planning stage.



## Section 17: Post-Repair Inspection Intervals

Post-repair inspection is not considered a single event. Regular re-inspection of in-service repairs in Grade 91 welds is recommended to monitor the stability of the repairs. A recommended base re-inspection interval is every other planned major outage or six years, whichever is less. The Owner/User may expand or compress the re-inspection interval based on trend results from previous inspections.

In the event a weld repair is performed where the material condition is degrading over time or incomplete removal of the defect was performed, periodic monitoring should be conducted based on a risk-based inspection program. It is mandated that a post-repair inspection be performed at the nearest opportunity, whether that be a planned outage or a purposeful inspection interval.





## Section 18: Avoidance of Stress Corrosion Cracking

To mitigate the risk of stress corrosion cracking after weld repair, several steps can be taken. These are outlined as follows and are dependent on the selection of the weld repair method and extent of excavation.

1. For weld repairs that will be performed using a minor or partial repair excavation, the effect of stress corrosion cracking is of most concern with respect to the OD of the weld repair. For these weld repairs, the OD of the weld repair (including the weld, HAZ, and at least 25 mm beyond the fusion line of the weld) should be coated with a water-resistant coating to prevent the occurrence of stress corrosion cracking. It is highly recommended that the weldment be properly protected from all moisture or preserved “dry” prior to unit startup, especially where the piping is directly exposed to the environment, such as in some combined cycle power plants.
2. For weld repairs that must be made using a full penetration weld, it is recommended that the weldment be made using the matching B9 consumables and low PWHT weld repair method. Weld repair methods that undergo a lower temperature PWHT are not susceptible to SCC following the PWHT.
3. For weld repairs that are full penetration, but a land is left in the weldment, it is recommended that the land be at least 0.20 inch (5 mm) thick to avoid retransforming the base material and creating a HAZ that is exposed to the ID surface. Furthermore, it is recommended that a smaller diameter electrode (such as a 3/32 inch, 2.5 mm) be used to ensure that the HAZ does not extend to the ID.





## Section 19: Conclusions

It is clear that the technical details for “best practice” regarding welding of low-alloy bainitic steels do not apply directly to welding of tempered martensitic steel. Thus, repair techniques commonplace for “conventional” low-alloy steels are not directly relevant for repairs on Grade 91 steels. Furthermore, technical definition of the best-option repair in Grade 91 steel components is not a one-size-fits-all approach. Thus, for specific repair scenarios, it must be determined whether it is appropriate to perform a weld repair, replace the component, or perform a weld repair and establish a specified life management plan. Approaches for well-engineered weld designs have been outlined for a variety of considerations. With regard to the repair of specific materials and components, it has been shown that a given requirement for repair is specific to the material, component, and operating conditions. Data generated in a series of EPRI reports [3-24] highlight this assertion with respect to the weld repair of CSEF steel Grade 91. The data and figures provided in this document highlight options and recommendations that must be considered for any weld repair in Grade 91 (with or without PWHT). In general, the following recommendations can be made:

1. For minor or partial repairs, there are three recommended welding procedures.
2. For full section weld repairs, there are three recommended welding procedures and the specification of a damage-tolerant design, as highlighted in Figure 11-6 and shown as a “step.”

The difficulty in the volumetric detection of in-service creep damage in Grade 91 steel [6, 56] has highlighted the benefit of using damage-tolerant weld designs. The remediation of damage identified in Grade 91 offers an opportunity for remediation of an intolerant weld design through introduction of a properly designed excavation (i.e., a “step” weld design) to promote damage tolerance in an otherwise damage-intolerant material.





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Appendix A: Filler Metal Compositions, as  
Listed in ASME B&PV Code  
Section IIC and Code Cases  
2833 and 2734  
[34, 35, 57]

| Type                         | 9Cr-1Mo     |                   | 9Cr-1Mo-VNbN |                   | Ni-base                    |                         |                         |                       |                      |
|------------------------------|-------------|-------------------|--------------|-------------------|----------------------------|-------------------------|-------------------------|-----------------------|----------------------|
| Product Form                 | Solid Wire  | Covered Electrode | Solid Wire   | Covered Electrode | Solid Wire                 | Covered Electrode       | Covered Electrode       | Solid Wire            | Covered Electrode    |
| AWS Designation (Trade Name) | ER80S-B8    | E8015-B8          | ER90S-B9     | E9015-B9          | ERNiCr-3 (Filler Metal 82) | ENiCrFe-3 (INCONEL 182) | ENiCrFe-2 (INCO-WELD A) | ERNiFeCr-4 (EPRI P87) | ENiFeCr-4 (EPRI P87) |
| ASME Specification           | SFA-5.23    | SFA-5.5           | SFA-5.23     | SFA-5.5           | SFA-5.14                   | SFA-5.11                | SFA-5.11                | N/A                   |                      |
| Carbon                       | 0.12 (max)  | 0.05-0.10         | 0.08-0.13    | 0.08-0.13         | 0.10 (max)                 | 0.10 (max)              | 0.10 (max)              | 0.08-0.14             |                      |
| Manganese                    | 1.2 (max)   | 1.0 (max)         | 1.20 (max)   | 1.20 (max)        | 2.5-3.5                    | 5.0-9.5                 | 1.0-3.5                 | 1.2-1.8               |                      |
| Phosphorus                   | 0.030 (max) | 0.030 (max)       | 0.010 (max)  | 0.01 (max)        | 0.03 (max)                 | 0.03 (max)              | 0.03 (max)              | 0.01 (max)            |                      |
| Sulfur                       | 0.030 (max) | 0.030 (max)       | 0.010 (max)  | 0.01 (max)        | 0.015 (max)                | 0.015 (max)             | 0.02 (max)              | 0.01 (max)            |                      |
| Silicon                      | 0.80 (max)  | 0.90 (max)        | 0.80 (max)   | 0.30 (max)        | 0.50 (max)                 | 1.0 (max)               | 0.75 (max)              | 0.05-0.50             |                      |
| Chromium                     | 8.00-10.00  | 8.0-10.5          | 8.0-10.5     | 8.0-10.5          | 18.0-22.0                  | 13.0-17.0               | 13.0-17.0               | 8.5-9.5               |                      |
| Molybdenum                   | 0.80-1.20   | 0.85-1.20         | 0.85-1.10    | 0.85-1.20         |                            |                         | 0.5-2.5                 | 1.8-2.2               |                      |
| Iron                         |             |                   |              |                   | 3.0 (max)                  | 10.0 (max)              | 12.0 (max)              | 38-42                 |                      |
| Vanadium                     |             |                   | 0.15-0.25    | 0.15-0.30         |                            |                         |                         |                       |                      |
| Niobium                      |             |                   | 0.02-0.10    | 0.02-0.10         | 2.0-3.0 (Nb+Ta)            | 1.0-2.5 (Nb+Ta)         | 0.5-3.0 (Nb+Ta)         | 0.90-1.40             |                      |
| Nitrogen                     |             |                   | 0.02-0.07    | 0.02-0.07         |                            |                         |                         | 0.2 (max)             |                      |
| Nickel                       |             | 0.40 (max)        | 0.80 (max)   | 0.80 (max)        | 67.0 (min)                 | 59.0 (min)              | 62.0 (min)              | 54 (max)              |                      |
| Aluminum                     |             |                   | 0.04         | 0.04 (max)        |                            |                         |                         | 0.10-0.20             |                      |
| Titanium                     |             |                   |              |                   | 0.75 (max)                 | 1.0 (max)               |                         | 0.05 (max)            |                      |
| Boron                        |             |                   |              |                   |                            |                         |                         | 0.0005-0.002          |                      |
| Copper                       | 0.35 (max)  |                   | 0.25 (max)   | 0.25 (max)        | 0.50 (max)                 | 0.50 (max)              | 0.50 (max)              | 0.25 (max)            |                      |
| Cobalt                       |             |                   |              |                   | 0.12 (max)                 | 0.12 (max)              | 0.12 (max)              |                       |                      |

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Appendix B: Common Base Metal  
Compositions for Grade 91  
Product Forms as Listed in  
ASME B&PV Code  
Section IIA [36]

| Product Form   | ASME SA-182 | ASME SA-213 | ASME SA-217 | ASME SA-234 | ASME SA-335  | ASME SA-336  | ASME SA-387   |                  |
|----------------|-------------|-------------|-------------|-------------|--------------|--------------|---------------|------------------|
|                | Forging     | Tubing      | Casting     | Fittings    | Piping       | Forging      | Plate         |                  |
|                |             |             |             |             |              |              | Heat Analysis | Product Analysis |
| Marking Symbol | F91         | T91         | C12A        | WP91        | P91          | F91          | Grade 91      | Grade 91         |
| Carbon         | 0.08-0.12   | 0.07-0.14   | 0.08-0.12   | 0.08-0.12   | 0.08-0.12    | 0.08-0.12    | 0.08-0.12     | 0.06-0.15        |
| Manganese      | 0.30-0.60   | 0.30-0.60   | 0.30-0.60   | 0.30-0.60   | 0.30-0.60    | 0.30-0.60    | 0.30-0.60     | 0.25-0.66        |
| Phosphorus     | 0.020 (max) | 0.020 (max) | 0.030 (max) | 0.020 (max) | 0.020 (max.) | 0.025 (max.) | 0.020 (max.)  | 0.025 (max.)     |
| Sulfur         | 0.010 (max) | 0.010 (max) | 0.010 (max) | 0.010 (max) | 0.010 (max.) | 0.025 (max.) | 0.010 (max.)  | 0.012 (max.)     |
| Silicon        | 0.20-0.50   | 0.20-0.50   | 0.20-0.50   | 0.20-0.50   | 0.20-0.50    | 0.20-0.50    | 0.20-0.50     | 0.18-0.56        |
| Chromium       | 8.0-9.5     | 8.0-9.5     | 8.0-9.50    | 8.0-9.5     | 8.0-9.5      | 8.0-9.5      | 8.0-9.5       | 7.90-9.6         |
| Molybdenum     | 0.85-1.05   | 0.85-1.05   | 0.85-1.05   | 0.85-1.05   | 0.85-1.05    | 0.85-1.05    | 0.85-1.05     | 0.80-1.10        |
| Vanadium       | 0.18-0.25   | 0.18-0.25   | 0.18-0.25   | 0.18-0.25   | 0.18-0.25    | 0.18-0.25    | 0.18-0.25     | 0.16-0.27        |
| Niobium        | 0.06-0.10   | 0.06-0.10   | 0.06-0.10   | 0.06-0.10   | 0.06-0.10    | 0.06-0.10    | 0.06-0.10     | 0.05-0.11        |
| Nitrogen       | 0.03-0.07   | 0.030-0.070 | 0.030-0.070 | 0.03-0.07   | 0.030-0.070  | 0.030-0.070  | 0.030-0.070   | 0.025-0.080      |
| Nickel         | 0.40 (max)  | 0.40 (max)  | 0.40 (max)  | 0.40 (max)  | 0.40 (max.)  | 0.40 (max.)  | 0.40 (max.)   | 0.43 (max.)      |
| Aluminum       | 0.02 (max)  | 0.02 (max)  | 0.02 (max)  | 0.02 (max)  | 0.02 (max.)  | 0.02 (max.)  | 0.02 (max.)   | 0.02 (max.)      |
| Titanium       | 0.01 (max)  | 0.01 (max)  | 0.01 (max)  | 0.01 (max)  | 0.01 (max)   | 0.01 (max)   | 0.01 (max)    | 0.01 (max)       |
| Zirconium      | 0.01 (max)  | 0.01 (max)  | 0.01 (max)  | 0.01 (max)  | 0.01 (max)   | 0.01 (max)   | 0.01 (max)    | 0.01 (max)       |



## Appendix C: Exemplar Filler Metal Procurement Form

## Procurement Specification Guideline for Grade 91 (Ref. AWS A5.01-08)

### I. General

|                                     |                    |            |                      |                       |
|-------------------------------------|--------------------|------------|----------------------|-----------------------|
| [Suggested Procurement Detail Form] | [Table A2]         | [Table A1] | [Table A4]           | [Table A3]            |
| A. Quantity                         |                    |            |                      |                       |
| B. AWS Specification                | A5.28              | A5.5       | A5.23                | A5.29                 |
| C. AWS Classification               | ER90S-B91          | E9015-B91  | EB91                 | E91T1-B91             |
| D. Supplemental Designators         | N/A                | H4         | N/A                  | H4                    |
| E. Diameter                         |                    |            |                      |                       |
| F. Length                           |                    |            |                      |                       |
| G. Unit Package Type and Weight     |                    |            |                      |                       |
| 1. Carton                           |                    |            |                      |                       |
| 2. Can                              |                    |            |                      |                       |
| 3. Other                            | 11 lbs. (5kg) Tube |            | 55 lbs. (25 kg) Coil | 33 lbs. (15 kg) Spool |

### II. Certification and Testing

|                       |    |    |    |    |
|-----------------------|----|----|----|----|
| A. Lot Classification | S1 | C1 | C1 | T1 |
| B. Level of Testing   | H  | K  | H  | K  |

### III. Other Requirements

|                                  |                                        |                            |                                        |                                       |
|----------------------------------|----------------------------------------|----------------------------|----------------------------------------|---------------------------------------|
| A. Imprinting/Marking            | Heat No. and Classification, Both Ends | Lot No. and Classification | Label with Heat No. and Classification | Label with Lot No. and Classification |
| B. Stamping or Tagging           | Stamp or Tag                           | Stamp                      | Label                                  | Label                                 |
| C. Report Tensile/Yield Strength | N/A                                    | Yes                        | N/A                                    | Yes                                   |
| D. PWHT: 760°C, 2 hrs. min.      | N/A                                    | Yes                        | N/A                                    | Yes                                   |
| E. Report Toughness @ Temp.      | N/A                                    | Yes @ 68°F                 | N/A                                    | Yes @ 68°F                            |
| F. X-Factor (Bruscati Number)    | < 15                                   | < 15                       | < 15                                   | < 25                                  |
| G. Mn/S > 50                     | Yes                                    | Yes                        | Yes                                    | Yes                                   |
| H. N/Al > 2                      | Yes                                    | Yes                        | Yes                                    | Yes                                   |
| G. CMTR or "3.1" Required        | Yes                                    | Yes                        | Yes                                    | Yes                                   |

#### Notes:

- The -B91 classification designation is pending, but going through the approval cycle at AWS. Until the specifications are printed, a -B9 designation should be used.
- The EPRI recommended composition is as follows:

|                                     |                               |                |                |
|-------------------------------------|-------------------------------|----------------|----------------|
| C: 0.08-0.13%                       | Cr: 8.5-9.5%                  | Cu: <0.25%     | Mn: 1.20% max. |
| Ni: 0.80% max.                      | N <sub>2</sub> : 0.040-0.070% | Si: 0.20-0.50% | Mo: 0.85-1.20% |
| Ti: 0.010 max                       | Nb: 0.02-0.10%                | V: 0.15-0.30%  | Al: < 0.04%    |
| P: <0.010% (Note for FCAW: <0.020%) |                               | S: <0.010%     | Other: <0.50%  |
| As: <0.008                          | Sn: <0.005                    | Sb: <0.003     | Ni+Mn < 1.0%   |

- Mechanical Properties:

|                           |                          |
|---------------------------|--------------------------|
| Ultimate Tensile Strength | 85 ksi (586 MPa) minimum |
| Yield Strength            | 60 ksi (414 MPa) minimum |
| Elongation (2 inches)     | 20% minimum              |



## Appendix D: Evaluation of the Hardenability of Filler Metal E8015-B8 (9Cr-1Mo)

To evaluate the hardenability of Grade 91 HAZ and applied filler metals, large hardness maps were made through a consideration portion of the Grade 91 HAZ and deposited filler metal. A representative hardness map is shown in Figure D-1A for a controlled fill procedure using E8015-B8 filler metal. The hardness map was developed using a Vickers indenter, 500 g load, and 0.25 mm spacing between indents and measures 1 inch<sup>2</sup> (25 mm<sup>2</sup>), resulting in a total of 10,000 individual indents for each hardness map. The parameters described here meet guidelines provided in a peer-reviewed journal paper that examined the variables associated with making Vickers hardness measurements and mapping in Grade 91 steel [58].

The hardness map data was post-processed to provide color hardness maps and statistical comparisons in the form of box plots. Unless noted, the color hardness maps utilized the same scale, whereby specific hardness ranges were assigned a color as follows:

- HV > 440 → Black
- 440 < HV < 400 → Red with cross hashes
- 400 < HV < 360 → Orange with diagonal hash lines
- 360 < HV < 320 → Yellow
- 320 < HV < 280 → Green
- 280 < HV < 240 → Light Blue
- 240 < HV < 200 → Blue
- HV < 200 → White

The hardenability of as-deposited (no PWHT or aging) E8015-B8 is provided in Figure D-1B and in comparison to E9015-B9 (no PWHT or aging) in Figure D-1C in the form of a color hardness map. In this visual evaluation, the as-deposited E9015-B9 filler metal clearly exhibits a higher overall hardness that is reinforced in the box plot analysis in Figure D-2 and tabulated results in Table D-1.

In addition to the reduction in hardenability of E8015-B8 filler metal in the as-welded condition, the hardness was observed to decay following a simulated service condition (SSC) of 1112°F (600°C)/10 hours, Figure D-3B. The reduction in hardness values is shown in the box plot comparison in Figure D-4 and in Table D-2.

A Holloman and Jaffe Parameter (HJP) comparison [59] for the 1112°F (600°C)/10 hours to lower temperatures and longer times can be made using the following relationship:

$$\text{HJP} = (T + 273) \times (C + \log_{10}(t))/1000$$

T = Tempering temperature in °C

t = Holding time in hours

C = HJP constant (in this study, a value of 22 was utilized)

It can be expected that for an application temperature  $\geq 538^{\circ}\text{C}$  (1000°F), the maximum hardness values in an as-deposited E8015-B8 repair weld would decay to a hardness value  $<290 \text{ HV } 0.5$  in a time  $<500$  hours. Clearly, and as illustrated in Figure D-5, this time would be considerably less for higher application temperatures. The  $290 \text{ HV } 0.5$  value can be converted in Hardness Brinell (HB) using the following relationship from [60]:

$$\text{HB} = 0.859 \times \text{HV} + 21.11$$

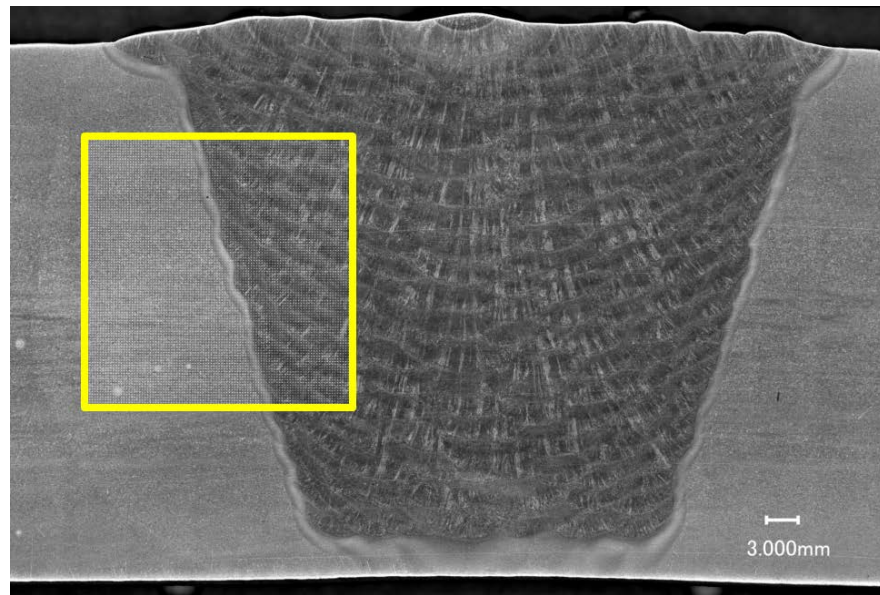
Using this relationship, the  $290 \text{ HV } 0.5$  threshold achieved for the range of time and temperature parameters in Figure D-5 yield a value of 270 HB. Using a similar approach for the Grade 91 HAZ, it can be shown that the values decay to  $<380 \text{ HV } 0.5$  ( $<350 \text{ HB}$ ), a reduction that is nearly 100 HV less than in the as-welded condition.

The data provided in this appendix support several key conclusions regarding the weld repair of Grade 91 steel, including the following:

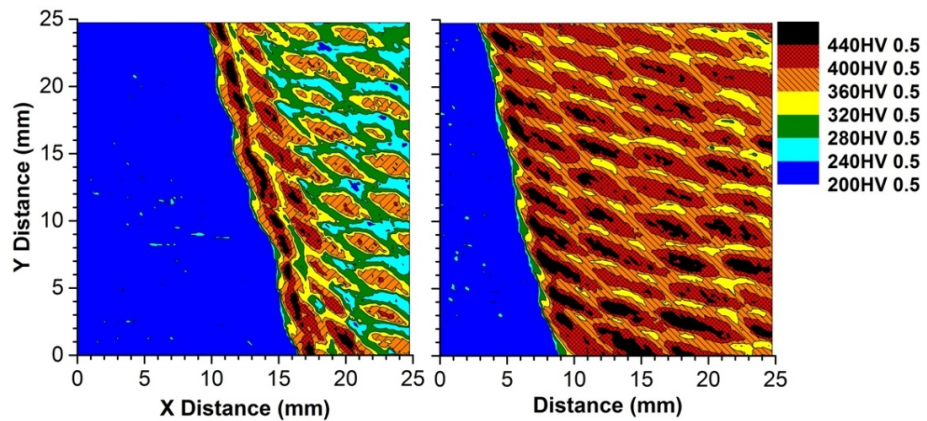
1. E8015-B8 and its similar 9Cr-1Mo consumables are less hardenable than E9015-B9 and its similar 9Cr-1Mo-VNbN consumables.
2. E8015-B8 and its similar 9Cr-1Mo consumables can be expected to temper in service conditions typical of Grade 91 steel components (nominally  $>1000^{\circ}\text{F}$ ,  $538^{\circ}\text{C}$ ).
3. The hardest regions in the Grade 91 HAZ, typically associated with the CGHAZ, temper under simulated service conditions by  $\sim 100 \text{ HV}$  from the peak values measured in the as-welded condition.

Finally, it should be emphasized that in the original Oak Ridge National Laboratory and its consortium of  $\sim 40$  industrial partners, the use of E8015-B8 filler metal and its parent consumables was evaluated in cross-weld creep. Some of these results are detailed in [61] and also in various ASME B&PV Research Reports such as in [62]. In this work, it was never suggested that a 9Cr-1Mo was unacceptable for use in the welding of Grade 91 components. By the time Grade

91 steel was widely implemented in the early 1990s, consumable manufacturers had ample time to develop a mature supply industry of consumables that were directly matching to the Grade 91 steel composition (i.e., E9015-B9 or similar).



A.



B.

C.

Figure D-1

A: Macro Image of Hardness Map in a Simulated, Through-Thickness Weld Repair Using a Controlled Fill Procedure and E8015-B8 Filler Metal; B: Color Hardness Map for Controlled Fill Procedure and E8015-B8 Filler Metal, As-Welded Condition; C: Color Hardness Map for Controlled Fill Procedure and E9015-B9 Filler Metal, As-Welded Condition

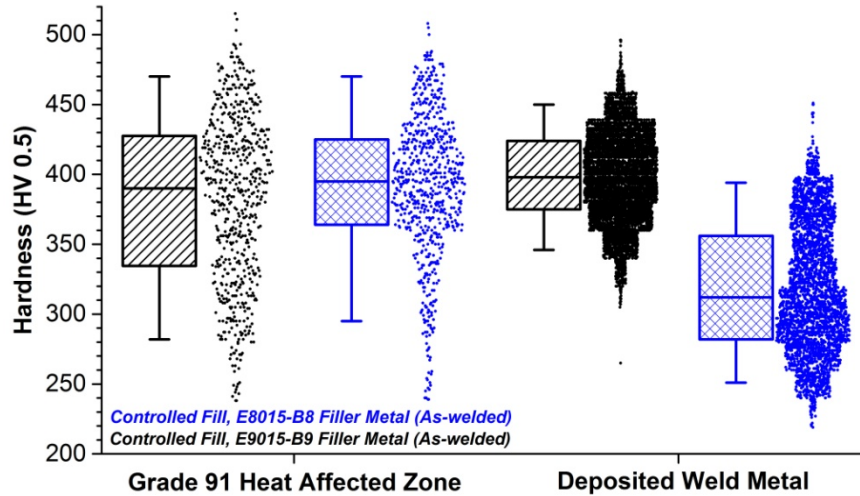


Figure D-2  
Box Plot Comparison of Hardness Values in the As-Welded Condition and for Specific Regions (Grade 91 Heat-Affected Zone and Weld Metal) for Two Welding Procedures: Controlled Fill Procedure and E8015-B8 Filler Metal (Blue) and Controlled Fill Procedure and E9015-B9 Filler Metal (Black)

Table D-1  
Comparison of Statistically Relevant Hardness Values in the As-Welded Condition and for Specific Regions (Grade 91 Heat-Affected Zone and Weld Metal) for Two Welding Procedures: Controlled Fill Procedure and E8015-B8 Filler Metal (Blue) and Controlled Fill Procedure and E9015-B9 Filler Metal (Black)

| Filler Metal            | Diameter          | Hardness Values (HV 0.5) <sup>A</sup> |        |                          |                             |                             |                             |
|-------------------------|-------------------|---------------------------------------|--------|--------------------------|-----------------------------|-----------------------------|-----------------------------|
|                         |                   | 1 <sup>st</sup> Quartile              | Median | 3 <sup>rd</sup> Quartile | 90 <sup>th</sup> Percentile | 95 <sup>th</sup> Percentile | 99 <sup>th</sup> Percentile |
| E9015-B9 (9Cr-1Mo-VNbN) | 1/8 inch (3.2 mm) | 375                                   | 398    | 424                      | 440                         | 450                         | 464                         |
| E8015-B8 (9Cr-1Mo)      |                   | 282                                   | 312    | 356                      | 385                         | 394                         | 412                         |

<sup>A</sup>For interpretation of this table, and as an example, when examining the 3<sup>rd</sup> Quartile, 75% of the hardness values were below this stated value.

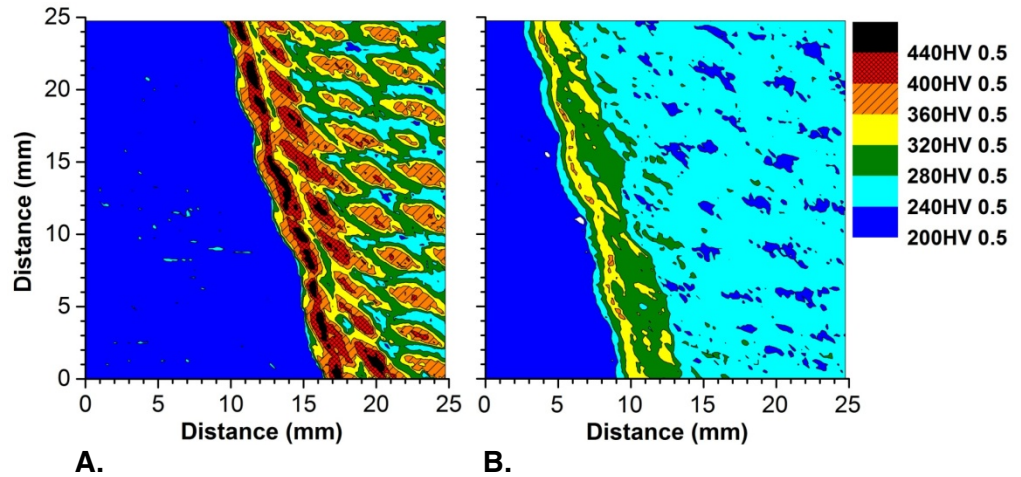


Figure D-3

A: Color Hardness Map for Controlled Fill Procedure and E8015-B8 Filler Metal, As-Welded Condition; B: Color Hardness Map for Controlled Fill Procedure and E8015-B8 Filler Metal, Simulated Service Condition (1112°F, 600°C/2 Hours)

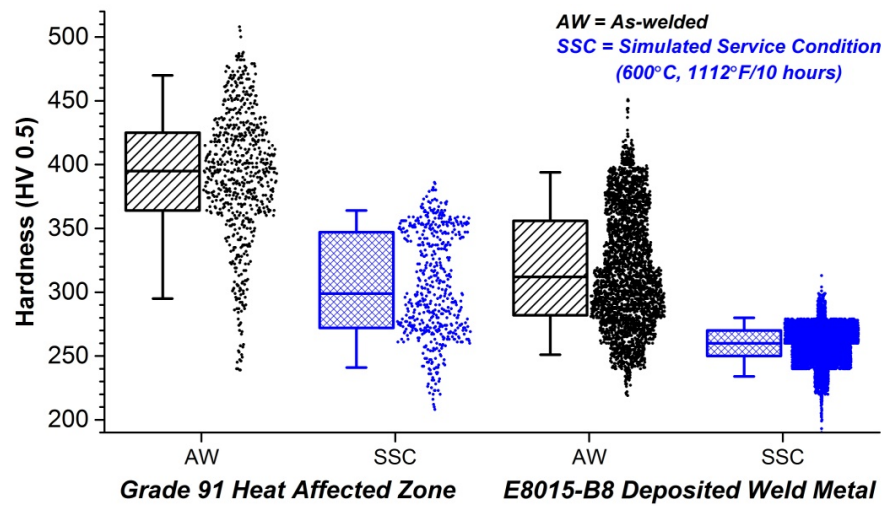


Figure D-4

Box Plot Comparison of Hardness Values in the As-Welded Condition and for Specific Regions (Grade 91 Heat-Affected Zone and Weld Metal) for Two Welding Procedures: Controlled Fill Procedure and E8015-B8 Filler Metal (Blue) and Controlled Fill Procedure and E9015-B9 Filler Metal (Black)

Table D-2

Comparison of Statistically Relevant Hardness Values for the Grade 91 Heat-Affected Zone and E8015-B8 Weld Metal and in the As-Welded (Black) and Simulated Service Condition (Blue)

| Constituent or Filler Metal                       | Hardness Values (HV 0.5) <sup>A</sup> |        |                          |                             |                             |                             |
|---------------------------------------------------|---------------------------------------|--------|--------------------------|-----------------------------|-----------------------------|-----------------------------|
|                                                   | 1 <sup>st</sup> Quartile              | Median | 3 <sup>rd</sup> Quartile | 90 <sup>th</sup> Percentile | 95 <sup>th</sup> Percentile | 99 <sup>th</sup> Percentile |
| Grade 91 HAZ, As-welded                           | 364                                   | 395    | 425                      | 458                         | 470                         | 485                         |
| Grade 91 HAZ, SSC <sup>1</sup>                    | 272                                   | 299    | 347                      | 359                         | 364                         | 380                         |
| E8015-B8 <sup>B</sup> (9Cr-1Mo), As-welded        | 282                                   | 312    | 356                      | 385                         | 394                         | 412                         |
| E8015-B8 <sup>B</sup> (9Cr-1Mo), SSC <sup>1</sup> | 250                                   | 260    | 270                      | 276                         | 280                         | 288                         |

<sup>1</sup>SSC = Simulated Service Condition, 1112°F (600°C)/10 hours

<sup>A</sup>For interpretation of this table, and as an example, when examining the 3<sup>rd</sup> Quartile, 75% of the hardness values were below this stated value

<sup>B</sup>1/8 inch (3.2 mm) diameter electrode

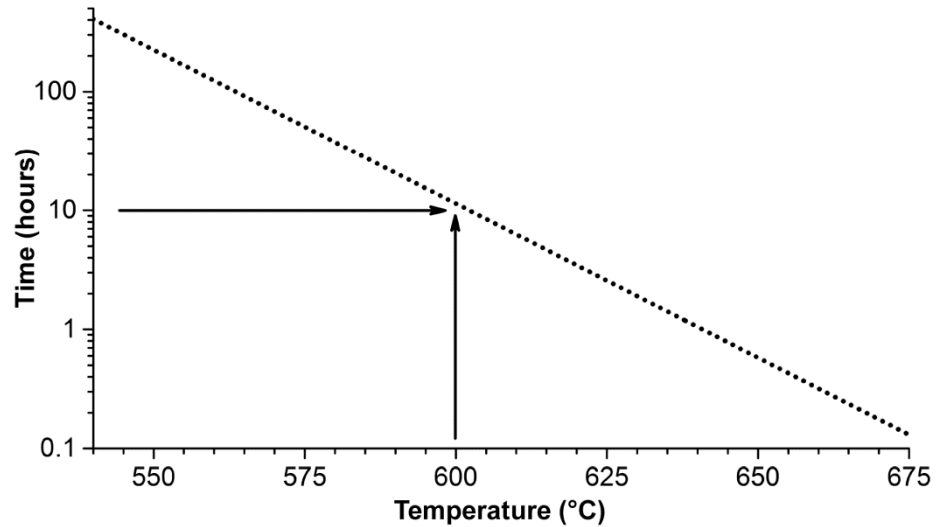


Figure D-5

Extrapolation of the Simulated Service Condition (Indicated by Arrows) to Lower Temperatures/Longer Times and Higher Temperatures/Shorter Times Using the Holloman-Jaffe Parameter Relationship [60]



## Appendix E: Evaluation of the Hardenability of Filler Metal E9015-B9 (9Cr-1Mo-VNbN) in the As-Welded and Low PWHT (675°C, 1250°F/ 2 Hours) Condition

To evaluate the hardenability of Grade 91 HAZ and applied filler metals, large hardness maps were made through a consideration portion of the Grade 91 HAZ and deposited filler metal. A representative hardness map is shown in Figure E-1A for a controlled fill procedure using E9015-B9 filler metal. The hardness map was developed using a Vickers indenter, 500 g load, and 0.25 mm spacing between indents and measures 1 inch<sup>2</sup> (25 mm<sup>2</sup>), resulting in a total of 10,000 individual indents for each hardness map. The parameters described here meet guidelines provided in a peer-reviewed journal paper that examined the variables associated with making Vickers hardness measurements and mapping in Grade 91 steel [58].

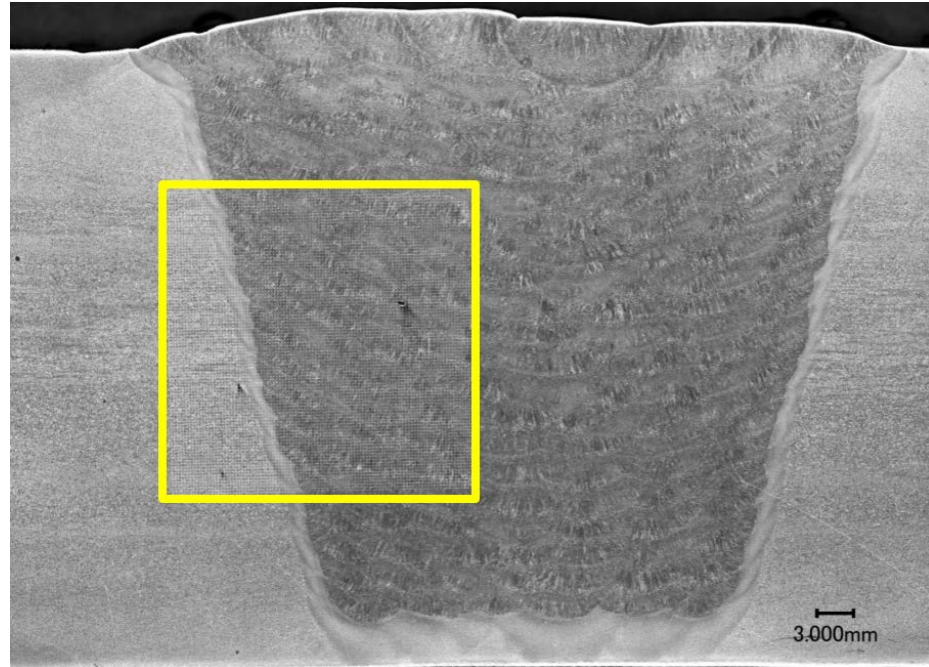
The hardness map data was post-processed to provide color hardness maps and statistical comparisons in the form of box plots. Unless noted, the color hardness maps utilized the same scale, whereby specific hardness ranges were assigned a color as follows:

- HV > 440 → Black
- 440 < HV < 400 → Red with cross hashes
- 400 < HV < 360 → Orange with diagonal hash lines
- 360 < HV < 320 → Yellow
- 320 < HV < 280 → Green
- 280 < HV < 240 → Light Blue
- 240 < HV < 200 → Blue
- HV < 200 → White

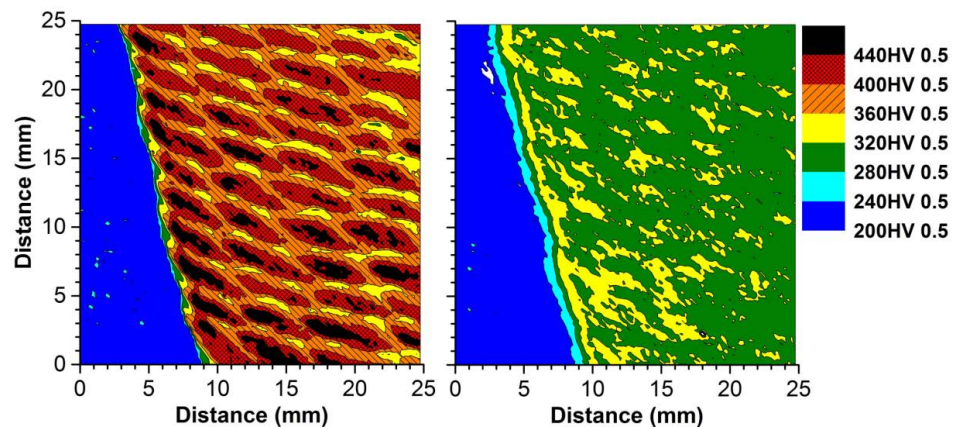
The hardenability of as-deposited (no PWHT or aging) E9015-B9 is provided in Figure E-1B and in comparison to E9015-B9 (Low PWHT of 1250°F, 675°C/2 hours) in Figure E-1C in the form of a color hardness map. In this visual evaluation, the as-deposited E9015-B9 filler metal clearly exhibits a higher overall hardness that is reinforced in the box plot analysis in Figure E-2 and tabulated results in Table E-1.

The data provided in this appendix support several key conclusions in the weld repair of Grade 91 steel, including the following:

1. Following a Low PWHT Condition (1250°F, 675°C/2 hours), the maximum hardness values in the Grade 91 HAZ are reduced to a value <350 HV 0.5 (322 HB).
2. Following a Low PWHT Condition (1250°F, 675°C/2 hours), the maximum hardness values in the E9015-B9 weld metal are reduced to a value <335 HV 0.5 (310 HB).



**A.**



**B.**

**C.**

*Figure E-1*

*A: Macro Image of Hardness Map in a Simulated, Through-Thickness Weld Repair Using a Controlled Fill Procedure and E8015-B8 Filler Metal; B: Color Hardness Map for Controlled Fill Procedure and E9015-B9 Filler Metal, As-Welded Condition; C: Color Hardness Map for Controlled Fill Procedure and E9015-B9 Filler Metal, Low PWHT Condition (1250°F, 675°C/2 Hours)*

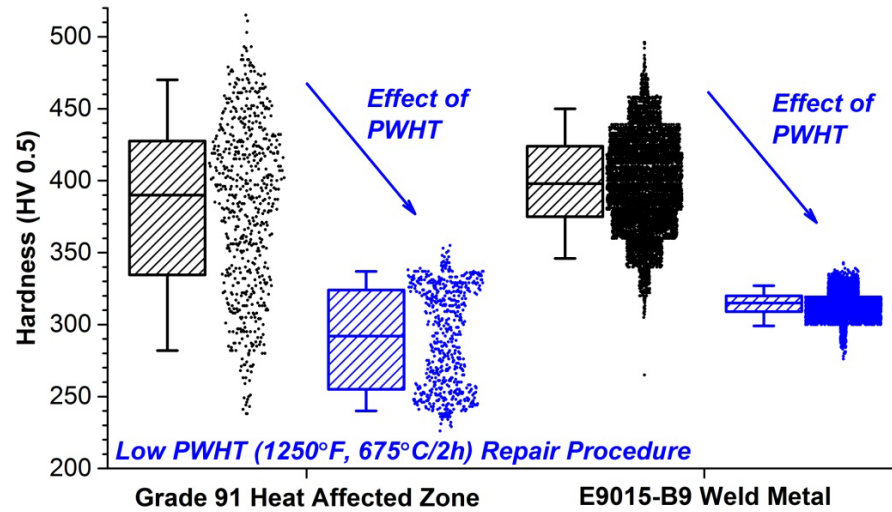


Figure E-2

Box Plot Comparison of Hardness Values for a Controlled Fill Welding Procedure in the Grade 91 Heat-Affected Zone and in the E9015-B9 Weld Metal and for Two Conditions: As-Welded (Black) and in the Low PWHT Condition (Blue, 1250°F, 675°C/2 Hours)

Table E-1

Comparison of Statistically Relevant Hardness Values for a Controlled Fill Welding Procedure in the Grade 91 Heat-Affected Zone and in the E9015-B9 Weld Metal and for Two Conditions: As-Welded and in the Low PWHT Condition (1250°F, 675°C/2 Hours)

| Filler Metal                       | Hardness Values (HV 0.5) <sup>A</sup> |        |                          |                             |                             |                             |
|------------------------------------|---------------------------------------|--------|--------------------------|-----------------------------|-----------------------------|-----------------------------|
|                                    | 1 <sup>st</sup> Quartile              | Median | 3 <sup>rd</sup> Quartile | 90 <sup>th</sup> Percentile | 95 <sup>th</sup> Percentile | 99 <sup>th</sup> Percentile |
| Grade 91 HAZ, As-welded            | 335                                   | 390    | 428                      | 457                         | 470                         | 490                         |
| Grade 91 HAZ, Low PWHT             | 255                                   | 292    | 324                      | 334                         | 337                         | 347                         |
| E9015-B9, As-welded (9Cr-1Mo-VNbN) | 375                                   | 398    | 424                      | 440                         | 450                         | 464                         |
| E9015-B9, Low PWHT (9Cr-1Mo-VNbN)  | 309                                   | 315    | 320                      | 324                         | 327                         | 332                         |

<sup>A</sup>For interpretation of this table, and as an example, when examining the 3<sup>rd</sup> Quartile, 75% of the hardness values were below this stated value



## Appendix F: Performance of Through-Thickness Weld Repairs in Grade 91 Steel

Cross-weld creep tests have been performed for a number of weld repair exemplars. In this appendix, there are two critical variables that are examined and support the alternative welding procedures proposed in this document:

1. Base metal condition
  - a. Ex-service, highly variable Grade 91 steel (variable with regard to hardness and microstructure). This material is identified in Table F-1 as “Poor Gr. 91.”
  - b. Renormalized and tempered ex-service Grade 91 steel in its ideal state. This material is identified in Table F-1 as “Optimum Gr. 91.”
  - c. Ex-service Grade 91 steel. A detailed history of this material, including the manufacturing, service conditions, and subsequent removal from the plant is provided in [40, 41]. This material is identified in Table F-1 as “Ex-service Gr. 91 Forging.”
2. A number of different welding procedures that were applied to the different parent material conditions. The combinations investigated were as follows:
  - a. **Normal Procedure:** the welding procedure was performed with no specific guidance beyond normal “good practice” detailed in [27]. Welders utilized proper-sized electrode for given layers; 3.2 mm (1/8 inch) in the root and 4.0 mm (5/32 inch) for remaining fill.
  - b. **Method A:** this procedure utilized a three-layer technique in accordance with [66, 67], where the electrode size was increased for each of the butter layers. Thus, the electrode diameters were as follows: layer 1 used 2.5 mm (3/32 inch), layer 2 used 3.2 mm (1/8 inch), and layer 3 used 4.0 mm (5/32 inch). The fill passes were performed using 4.0 mm (5/32 inch) electrodes.
  - c. **Method B:** this procedure utilized a two-layer technique in accordance with [68, 69], where the electrode size was increased for each of the butter layers: 2.5 mm (3/32 inch), 4.0 mm (5/32 inch). The fill was performed using 4.0 mm (5/32 inch) electrode.

- d. **Method C:** this procedure utilized a two-layer technique in accordance with [69], where the electrode size was increased for each of the butter layers: 2.5 mm (3/32 inch) – 3.2 mm (1/8 inch). The fill was performed using 3.2 mm (1/8 inch) electrode.
- e. **Controlled Fill:** this procedure is as defined in this report in the section “Fill Technique” and as outlined in Table 4-1 and in [18, 70].

Each of the weldments identified in Table F-1 was creep tested at a standard test condition of 1157°F (625°C) and 11.6 ksi (80 MPa) using feature-type specimens. Details of the specimens and testing have been detailed in previous documents [15-18]. In some cases, additional creep tests were performed at either 1112°F (600°C) and 11.6 ksi (80 MPa) or 1157°F (625°C) and 8.7 ksi (60 MPa) [63]. These selected test conditions are important, as they have been utilized in past research to duplicate the premature, HAZ failure mode that has been widely documented in Grade 91 steel and is often identified as Type IV cracking.

The use of feature-type specimens in the assessment of the weld repair performance was critical, as these larger tests contained a significant portion of the weldment within the gauge length. An assembled database of HAZ failures in Grade 91 cross-weld failures [48, 64] is provided in Figure F-1. In this plot, there are ~300 individual test results with shown low-ductility HAZ failures. These results have been described using a stress versus Larson-Miller Parameter (LMP) [65] approach. The relationship used is as follows:

$$\text{LMP} = (T + 273) \times (C + \log_{10}(t))/1000$$

T = Tempering temperature in °C

t = Holding time in hours

C = LMP constant (in this study, a value of 20 was utilized)

The results of the present cross-weld creep tests are included in Figures F-2A, F-3A, and F-4A. These results indicate that the performance of the welding procedures examined with regard to creep strength can be summarized as follows:

- The welds made using the E9015-B9 procedure followed by Low PWHT exhibited creep lives close to the mean of the EPRI Grade 91 steel database for HAZ fractures in cross-weld tests.
- The welds made using the Ni-base Controlled Fill procedure showed performance that was in between the mean-20% and mean of the EPRI Grade 91 steel database for HAZ fractures in cross-weld tests.
- The welds made using the E8015-B8 Controlled Fill procedure displayed strength that was consistently at the mean-20% of the EPRI Grade 91 steel database for HAZ fractures in cross-weld tests. This observation is discussed in detail in Appendix G.

Each of the cross-weld creep failures occurred in the HAZ with low overall ductility. An image of a representative failure for each of the repair weld procedures is shown in Figures F-2B, F-3B, and F-4B. In most cases, the failure location was clearly removed from the fusion line and in a region commonly identified as the fine-grained HAZ (FGHAZ).

The influence of the welding procedure on cross-weld creep behavior exhibited only a second-order effect. However, it was clear that while the failures were partially dependent on the strength of the filler material, there was no apparent influence of PWHT. For the tested weld procedures, gross defects that may have altered the results of the study were not documented in any of the as-deposited weld metal nor along the fusion line with the parent material. Based on the results presented here, the following conclusions can be made:

1. **PWHT is not required to impart acceptable strength or performance in Grade 91 steel weldments.** The purpose of PWHT in the context of Grade 91 steel repair welds will only alter the material properties in the HAZ and/or weld metal with respect to hardness, Charpy impact toughness strength, and welding residual stress. It must be emphasized that hardness and Charpy impact toughness tests are not true engineering design parameters. Hardness is often utilized to provide some indication of strength, either in tensile or creep. While hardness can be directly equated to yield or tensile strength, it is only empirically related to creep strength where substantial databases have been developed. Charpy impact toughness is only empirically related to the actual design criterion for fracture toughness (i.e.,  $K_{Ic}$  or  $J_{Ic}$ ), and such relationships have not been well-established for Grade 91 steel weldment performance.
2. **The performance of the weld procedure with respect to strength is only partially controlled by the strength of the selected filler material.** For through-thickness (defined here as >90% of thickness) repairs, the use of E8015-B8 filler metal provided results that were consistently at the minimum of the Grade 91 HAZ database when the Grade 91 parent material exhibited mean behavior. It should be emphasized that in the original Oak Ridge National Laboratory and its consortium of ~40 industrial partners, the use of E8015-B8 filler metal was evaluated in cross-weld creep in weldments that underwent PWHT. Some of these results are detailed in [61] and also in various ASME B&PV Research Reports such as in [62]. In this work, it was never suggested that a 9Cr-1Mo consumable was unacceptable for use in the welding of Grade 91 components, and similar behavior as reported here was noted. The influence of the Grade 91 parent material condition on performance of E8015-B8 weldments is discussed in detail in Appendix G.
3. **The performance of the three proposed alternative weld repair methods can be expected to achieve the performance of the original weld.** This is an important conclusion, since in Grade 91 steel weldments—because failure occurs in the HAZ and is a function of the base material condition—a repair weld cannot be expected to exceed the performance of the original weld without some alteration in design (i.e., introduction of a step).

Although the data presented in this appendix are related to the performance of through-thickness repairs made with a single, uniform bevel, it is recommended that any repair be designed with a step as shown in Figure 12-1. The important of the step design on creep performance and the geometric considerations associated with step weld profiles are addressed in detail in Appendix G.

Table F-1

*Summary of the Through-Thickness Repair Welds in Grade 91 Steel*

| Weldment | Base Metal Condition      | Filler Metal | Repair Technique     | PWHT                   |
|----------|---------------------------|--------------|----------------------|------------------------|
| 2A       | Poor Gr. 91               | E9015-B9     | Normal Best Practice | 675°C<br>(1250°F)/2hrs |
| 2B       | Optimum Gr. 91            |              |                      |                        |
| 7C       | Ex-service Gr. 91 Forging |              | Controlled Fill      |                        |
| 5A       | Poor Gr. 91               | E8015-B8     | Method B             | None                   |
| 5B       | Optimum Gr. 91            |              | Controlled Fill      |                        |
| 8C       | Ex-service Gr. 91 Forging |              |                      |                        |
| 9A       | Poor Gr. 91               | EPRI P87     | Method C             |                        |
| 10A      |                           | ENiCrFe-2    | Method A             |                        |
| 9B       | Optimum Gr. 91            | EPRI P87     | Method C             |                        |
| 10B      |                           | ENiCrFe-2    | Method A             |                        |
| 9C       | Ex-service Gr. 91 Forging | EPRI P87     | Controlled Fill      |                        |

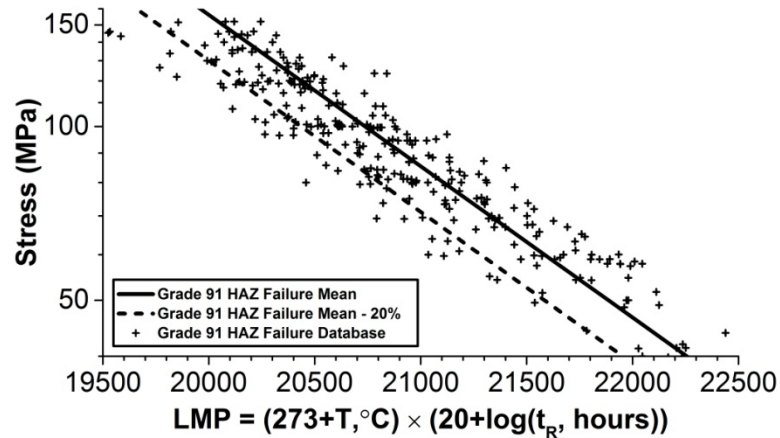
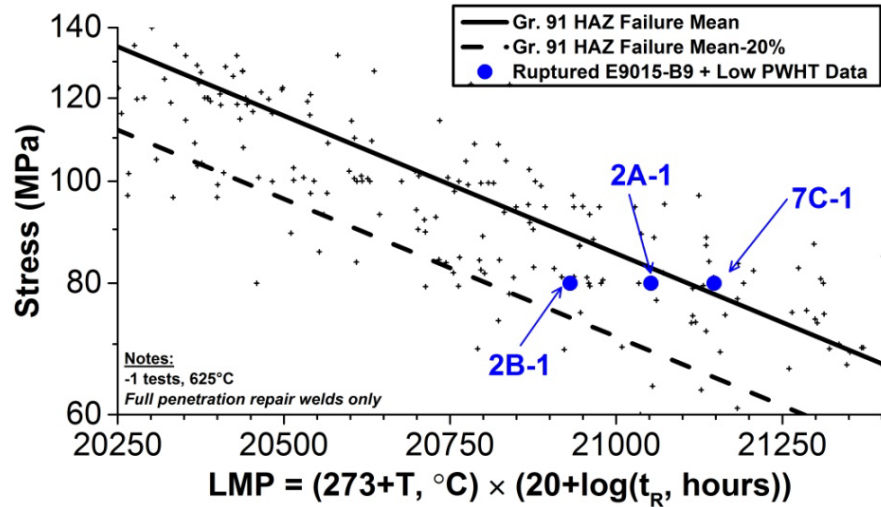
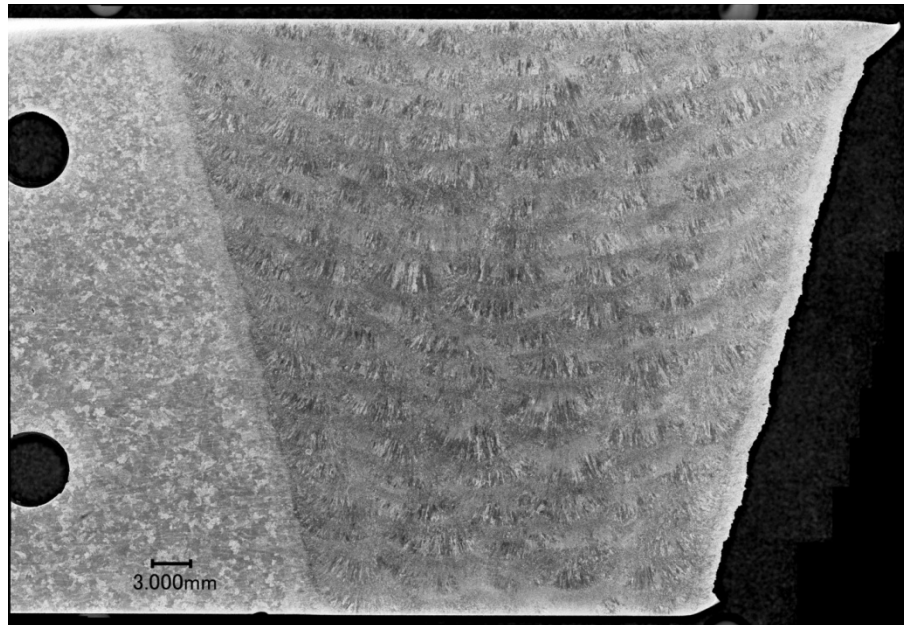


Figure F-1

*Larson Miller Parameter (LMP) Comparison for Reported HAZ Failures in Cross-Weld Creep Tests in Grade 91 Steel. This database was used for comparison of the performance of simulated repair welds made in Grade 91 steel.*



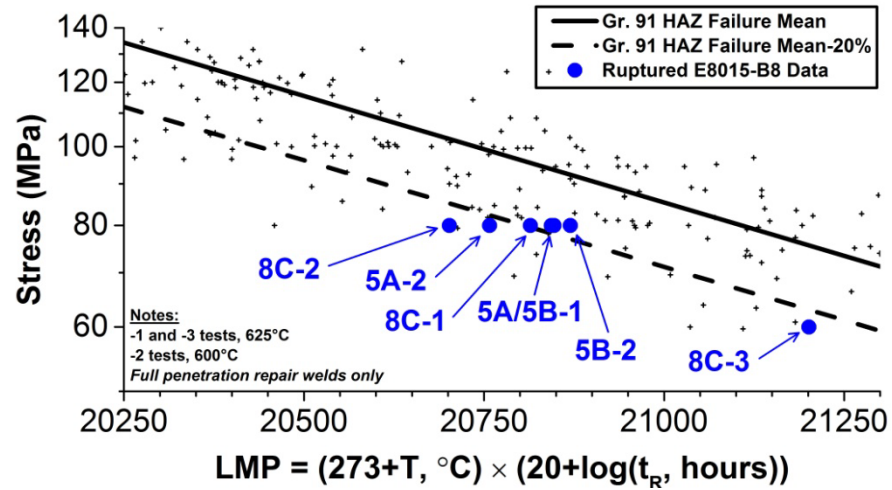
A.



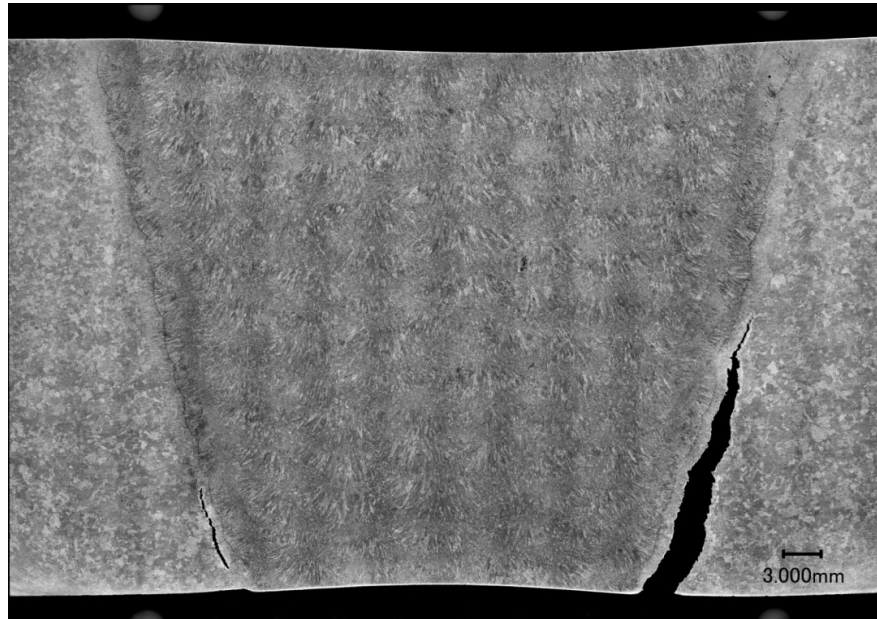
B.

Figure F-2

A: Larson Miller Parameter Comparison for Phase 1 and Phase 2 Repair Welds Made with E9015-B9 Filler Metal and Given a PWHT Below the Normally Recommended Minimum (PWHT Performed at 1250°F, 675°C/2 Hours);  
B: Representative Image of the HAZ Creep Failure Associated with the Sample Made with the E9015-B9 Filler Metal and Given a PWHT Below the Normally Recommended Minimum (PWHT Performed at 1250°F, 675°C/2 Hours), Weld 7C-1 Shown, Vilella's Reagent



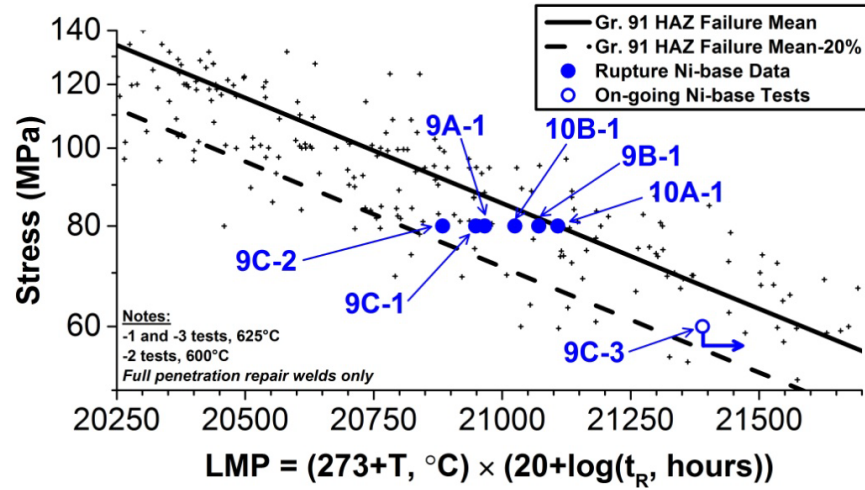
A.



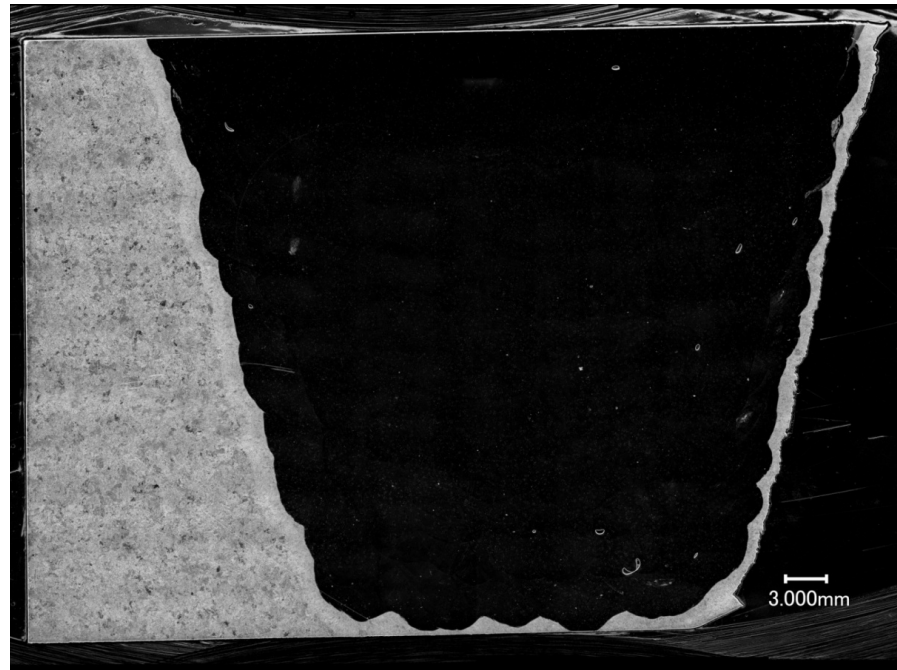
B.

Figure F-3

A: Larson Miller Parameter Comparison for the Creep Tests on Phase 1 and Phase 2 Repair Welds Made with E8015-B8 Filler Metal and No PWHT;  
B: Representative Image of the HAZ Failure Associated with the E8015-B8 Repair Welds in Phase 1 and Phase 2 (Weld 8C-1 Shown), Vilella's Reagent



A.



B.

Figure F-4

A: Larson Miller Parameter Comparison for Creep Test Results for Phase 1 and Phase 2 Repair Welds Made with Ni-base Filler Metal and No PWHT;  
B: Representative Image of the HAZ Failure Associated with the Ni-Base Repair Welds in Phase 1 and Phase 2 (Weld 9C-1 Shown), Vilella's Reagent





## Appendix G: Performance of Weld Repairs Using E8015-B8 Filler Metal and Importance of the Grade 91 Parent Material Condition

The performance of the repair welds made using the E8015-B8 consumables was consistent. The creep performance was in agreement with the mean-20% bound for Grade 91 HAZ failures in typical welds. The behavior can be explained by consideration of the results presented in Figure G-1. This observation is only true for Grade 91 parent material that exhibits acceptable damage tolerance and creep strength. The measured creep life in Weldments 5A, 5B, and 8C from Appendix F all achieved the minimum of the cross-weld scatter-band. These observations are consistent with the fact that the strength of the B8 weld metal matches that of the fine-grained region of the Grade 91 HAZ. As shown in Figure G-1, the creep lives for simulated fine-grained microstructures, consistent with the documented weak-zone in the Grade 91 HAZ produced when peak temperatures are near to the  $A_3$  temperature and  $\sim 900^\circ\text{C}$  ( $1652^\circ\text{F}$ ), are in excellent agreement with the mean-20% line for test stresses  $\leq 100\text{ MPa}$  (14.5 ksi). This is significant, because in agreement with the reported results [13], it is clear that HAZ failures consistent with service failures can be reproduced in Grade 91 steel weldments when the temperature is  $\leq 625^\circ\text{C}$  ( $1157^\circ\text{F}$ ) and the test stress is  $\leq 100\text{ MPa}$  (14.5 ksi).

For repair welds made in poor Grade 91 steel that has poor damage susceptibility, the behavior is different. In these cases the creep behavior of welds is below expected minimum life. Thus, for base metal that is creep damage susceptible, a large reduction in cross-weld performance has been observed. In these scenarios the performance of the weld repair will be directly related to the poor damage susceptibility of the Grade 91 steel base metal. This is an important distinction that is highlighted in Figure G-2. Whereas damage was documented in both the Grade 91 HAZ and E8015-B8 filler metal for tests in Weldments 5A, 5B, and 8C, there was no damage identified in the E8015-B8 filler metal for tests in Weldment 11C. The vastly reduced performance in Weldment 11C was directly a function of the poor damage tolerance in this particular heat of

material. Details of the factors affecting the metallurgical risk behavior of Grade 91 steels have been presented previously [42]. The following conclusions can be made regarding the performance of repair welds made using E8015-B8 consumables in Grade 91 steel:

1. The use of E8015-B8 in the weld repair of aged, service-exposed Grade 91 components is similar to the approach investigated by the CEGB, TWI, and EWI in the weld repair of Grades 11, 12, 22, and CrMoV using “-L” grade consumables such as E7018-B2L and E8018-B3L to better match the strength of the aged material. This approach was designed to allow for a weld material that readily tempered in service and better accommodated the relaxation of welding residual stresses with high creep ductility.
2. Where the strength and/or damage tolerance of Grade 91 steel meets mean behavior, through-thickness repair welds made with E8015-B8 filler metal will meet the minimum of the scatter band for Grade 91 HAZ failures. Damage may be found in the Grade 91 HAZ, E8015-B8 filler metal, or both.
3. Where the strength and/or damage tolerance of Grade 91 steel is at or below minimum behavior, the performance of the through-thickness repair welds made with E8015-B8 filler metal is likely to be entirely controlled by the condition of the Grade 91 parent material and can be expected to fail in the Grade 91 HAZ.

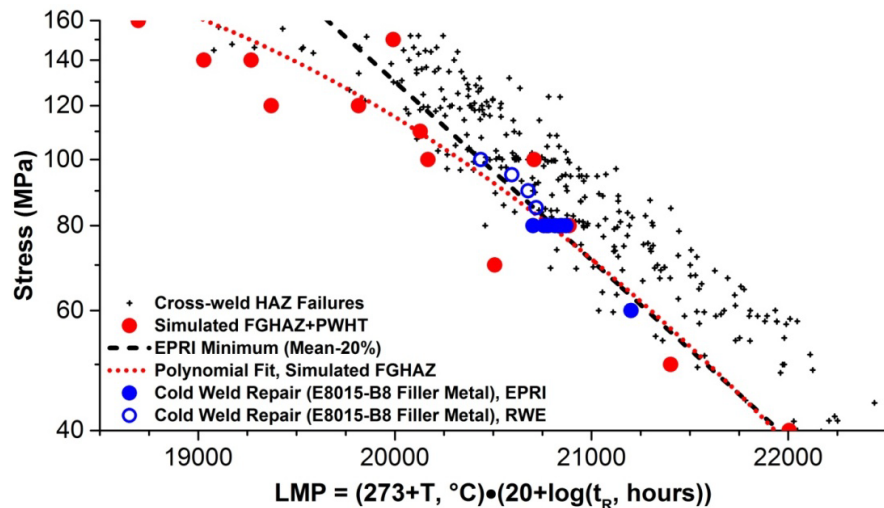
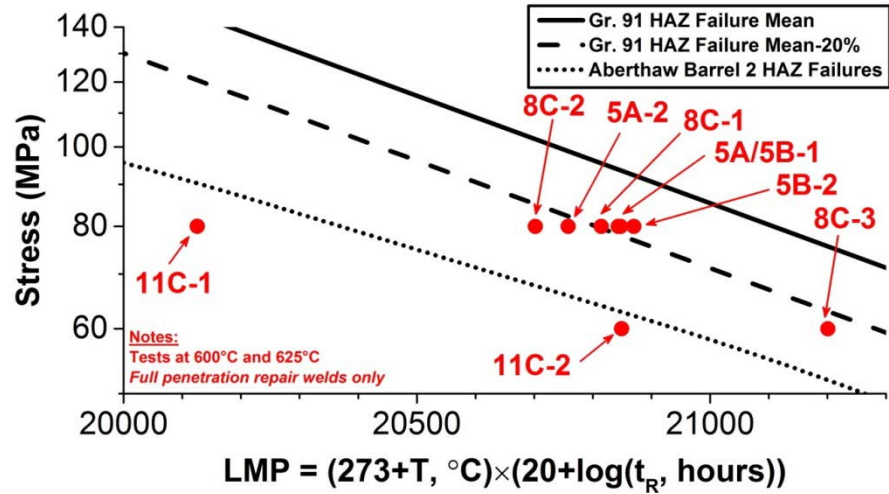


Figure G-1

Comparison of Weldments 5A and 5B (E8015-B8 and Method B, Closed Blue Circles) to Published Data (RWE) for E8015-B8 “Cold” Weld Repairs in Grade 91 Steel (Open Blue Circles) [71] and to Simulated FGHAZ+PWHT in Grade 91 Steel (Red Circles and Red Dotted Line Fit) [72, 73]



**Note:** Welds 5A/5B were made in Sample 8, Weld 8C was made in Tee Piece 1, and the results obtained are at the minimum in the database of typical cross-weld creep failures. Weld 11C was made between Barrel 1 and Barrel 2; failures were in the HAZ of Barrel 2. The dotted line for the performance of HAZ failures in Aberthaw Barrel 2 was made from tests detailed in [22].

Figure G-2

*Larson Miller Parameter Comparison for Phase 1 and Phase 2 Repair Welds Made with E8015-B8 Filler Metal and in Three Grade 91 Parent Materials*





## Appendix H: Effect of the Weld Repair Quality on Performance

A comparison was made for three welding procedures using the same heat of parent material [16]. In each case the filler metal (E9015-B9) was utilized for the following:

- **Low PWHT Procedure:** the welding procedure was performed with no specific guidance beyond normal “good practice” detailed in [27]. Welders utilized proper-sized electrode for given layers: 3.2 mm (1/8 inch) in the root and 4.0 mm (5/32 inch) for remaining fill. A Low PWHT was applied with a nominal temperature of 675C, 1250°F/2 hours.
- **Method A:** this procedure utilized a three-layer technique in accordance with [65, 66], where the electrode size was increased for each of the butter layers. Thus, the electrode diameters were as follows: layer 1 used 2.5 mm (3/32 inch), layer 2 used 3.2 mm (1/8 inch), and layer 3 used 4.0 mm (5/32 inch). The fill passes were performed using 4.0 mm (5/32 inch) electrodes.
- **Poor Practice Method A:** this procedure was similar to Method A but the welders were asked to not control overlap and also “stack” the fill passes through the fill. Whereas in Method A, the target bead-to-bead overlap was on the order of 50%, the overlap in Method A was ~<25% and the stacking of the deposited filler metal created a preferentially weak region in the center of the as-deposited weldment.

Each of these weldments was creep tested using feature-type specimens at a standard test condition of 1157°F (625°C) and 11.6 ksi (80 MPa). The experiments and the results obtained have been detailed previously [15-18]. The test conditions selected are important, as they have been utilized in past research to duplicate the premature, HAZ failure mode that has been widely documented in Grade 91 steel and is often identified as Type IV cracking. The use of feature-type specimens in the assessment of the weld repair performance was critical, as these larger tests contained a significant portion of the weldment within the

gauge length. An assembled database of HAZ failures in Grade 91 cross-weld failures [48, 63] is provided in Figure F-1. The results of ~300 individual failures have been described using a stress versus Larson-Miller Parameter (LMP) [65] approach. The relationship used is as follows:

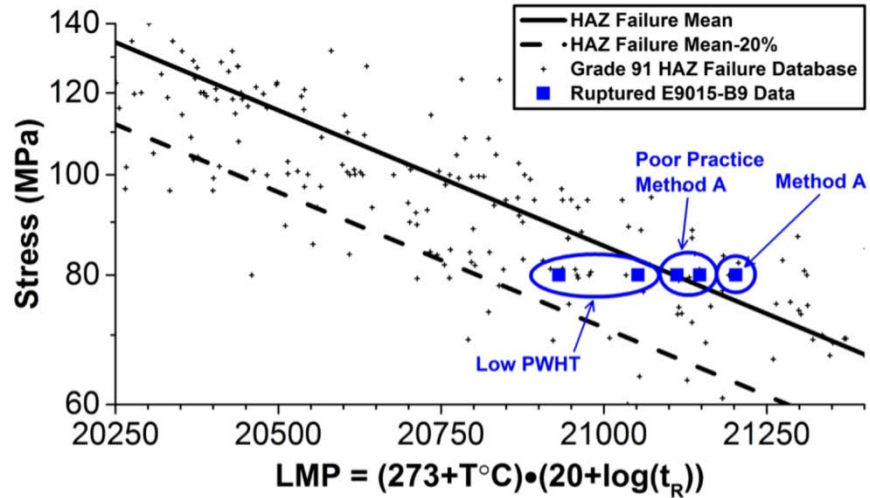
$$\text{LMP} = (T + 273) \times (C + \log_{10}(t))/1000$$

T = Tempering temperature in °C

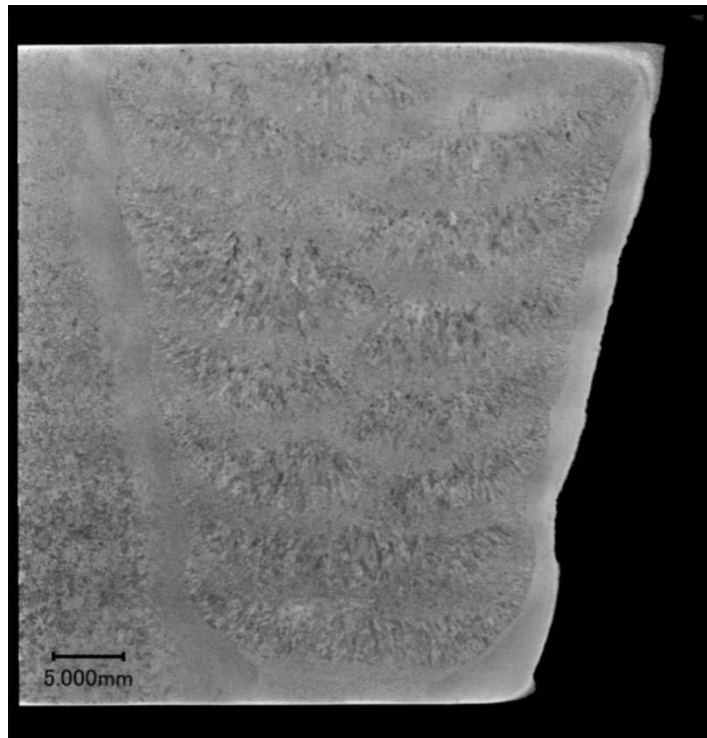
t = Holding time in hours

C = LMP constant (in this study, a value of 20 was utilized)

The results of this study are provided in Figure H-1 as a comparison to the performance of HAZ failures in typical Grade 91 welds. Although there was some variation in the rupture life in the weld repair tests, all failures were documented in the Grade 91 HAZ. This was an important observation since the parent material that was utilized in this study was the same heat of Grade 91 steel. Furthermore, there did not appear to be a significant reduction in the performance when comparing the Poor Practice technique to the other two scenarios. This result can be rationalized by the fact that the introduction of any welding thermal cycle in Grade 91 steel fundamentally alters the performance parent material (i.e., creation of a HAZ). Even the most well-controlled repair procedure cannot change the properties or behavior of the Grade 91 steel HAZ, as the damage tolerance and performance of the HAZ is primarily controlled by the condition of the Grade 91 parent material. Thus, the primary goal of any weld repair procedure in Grade 91 should be to prevent the introduction of gross defects from the welding process that may result in premature failure in the weld or fusion line. The other important criterion in the performance of the weld repair, the strength of the selected filler metal, has been previously discussed in Appendix F.



A.



B.

**Note:** The low PWHT repair welds were made using a best practice welding procedure and given a PWHT at 1250°F (675°C) for 2 hours. The Method A repair weld was made using a three-layer technique described in previous sections. For the Poor Practice Method A repair weld, the overlap for beads within a layer and layer to layer was uncontrolled and in general <25% (normal good practice states a 50% overlap).

Figure H-1

A: Comparison of Performance for Selected Phase 1 Grade 91 Repair Welds Made with E9015-B9 Filler Metal to Database of Grade HAZ Failures;  
B: Representative HAZ Failure in Grade 91 Steel





## Appendix I: Effect of Geometry on the Performance of Weld Repairs in Grade 91 Steel

While strength is one consideration for any weld repair, less emphasis has traditionally been placed on damage tolerance. Additional testing and examining the extent of excavation has shown that repair welds in Grade 91 steel can be made more damage tolerant and less susceptible to catastrophic failure. An example of a representative failure in a Grade 91 HAZ is provided in Figure I-1A, and a catastrophic failure in a Grade 91 header end cap utilizing a similar geometry is shown in Figure I-1B. The concern in Grade 91 components is that components manufactured with a similar geometry (such as thick-section girth welds) may fail in a similar manner. This is especially true where welded Grade 91 components do not exhibit specific or inherent design features that promote damage in a specific location (such as a bending moment from poor design or maintenance and in welded construction of tees, wyes, or branches, where damage is primarily concentrated at the flanks of the component).

A well-engineered weld repair has the ability not only to exhibit an acceptable life but, more importantly, to provide a safer solution as compared to the traditional fabrication methods. To meet this standard, it is proposed that through-thickness and partial penetration repair welds be designed with a “step” to impart added damage tolerance in the performance of the weld repair that is not inherent to a typically manufactured weld such as the behavior shown in Figure I-1A.

The effect of manufacturing a step in the performance of a repair weld made in Grade 91 steel is shown schematically in Figure I-2. It has been shown that an optimized geometry can improve the performance of the weld repair. There are two primary contributors on performance that can be optimized in the weld geometry, including the width of the step (identified in Figure 12-1 as the “w” dimension) and the bevel angle (identified in Figure 12-1 as the “ $\alpha$ ” dimension).

The effect of the width of the step on performance has been examined for a wide range of conditions including welds with multiple steps (Figure I-3) and in single step, partial repair welds (Figures I-4 to I-6). The stated, minimum step width of 0.40 inch (10 mm) has been validated in the failed tests shown in these figures. In Figure I-3, a double step configuration examination was investigated for a weld made in Grade 91 steel using E9015-B9 filler metal and a conventional heat treatment. This result shows two key features:

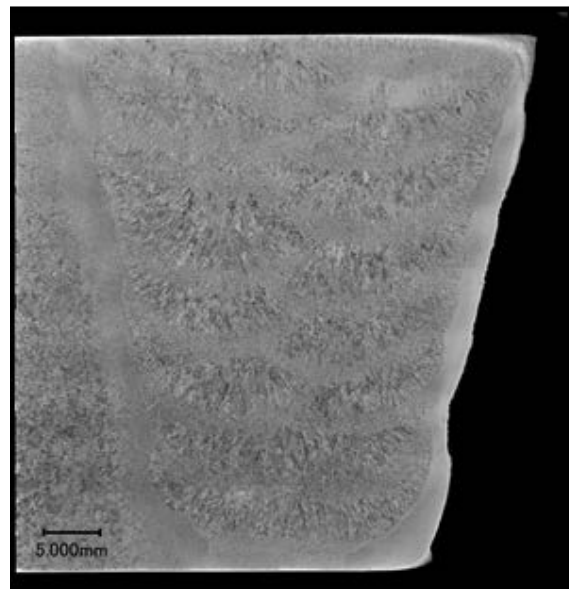
1. The initial failure along the two, offset HAZs in the upper and middle step was allowed to connect because of a relatively narrow step width. The HAZ crack “jumped” because the narrow land was unable to support the applied load.
2. Although the damage in the upper and middle step was allowed to connect, the width of the lower step was sufficient to support the applied load, if even for a relatively short time. The connected, HAZ crack was forced to propagate through more ductile parent material and away from the weldment altogether. In a Grade 91 component in an actual plant, this behavior would be manifested as a “leak before break” or more easily detected during an outage using conventional inspection techniques.

Where the step width is insufficient, such as in Figure I-4, the behavior is markedly similar to the behavior shown in Figure I-1A. The failure of the partial repair weld shown in Figure I-4 is clearly a function of the narrow step that was machined across the original girth weld that was repaired. For slightly wider steps, as shown in Figures I-5 and I-6, the initial damage in the upper step is forced to propagate through more ductile Grade 91 parent material.

The effect of the bevel angle on performance has been investigated for both matching weldments in Grade 91 steel using conventional welding approaches (E9015-B9 filler metal and PWHT within the allowable range specified by ASME B&PV Section I), as seen in Figure I-7 and in repair welds in Figure I-8. The observation of increased performance with a bevel that is more normal (i.e., closer to 0°) to the pipe or tube axis has been further interrogated using FEA in other references [74]. As shown in Figure I-7, the influence of the bevel on performance becomes notable for applied test stresses  $\leq 11.6$  ksi (80 MPa). In the circled data points for tests conducted at test conditions of 1157°F (625°C) and 11.6 ksi (80 MPa), the difference in the time to rupture for a 10° and 35° bevel was 6,243 versus 2,869 hours, respectively (a factor of 2.2).

The following conclusions can be made regarding the optimization of welding geometry on performance of weld repairs made in Grade 91 steel:

1. In the weld repair of component girth welds, the repair should be offset with a “step” whenever possible to prevent the propagation of damage through the constrained, weak and aligned region in a given Grade 91 HAZ.
2. If a step is utilized in the weld repair of a Grade 91 component, the width should be machined to a minimum of 0.40 inch (10 mm) in width.
3. The bevel should be optimized to consider the ability of the welder and also to optimize performance in the long term. To promote better access for the welding of thick-section components it is desirable to machine the component with a larger bevel. However, the performance of Grade 91 weldments with such large bevel angles has been documented to be less than that of similar parent material machined with bevel angles more normal to the parent material tube/pipe axis.



A.



B.

**Note:** There is a relative lack of plastic deformation at both surfaces and near uniform crack front in Image A. These observations indicate the relative brittle nature of the failure, a function of the constraint of the parent material and weld metal as well as the concentration of damage in a very narrow region in the Grade 91 HAZ. These features of the failure cannot be altered by the welding process, no matter the level of control that is implemented.

*Figure I-1*

*A: Grade 91 HAZ Failure in Ex-service Girth Weld; B: An Example of a Catastrophic Failure in a Grade 91 Component Where a Header End Cap was Ejected into a Parking Lot at a UK Power Station, and as Detailed in [25]. The welded end-cap was manufactured using a typical, single bevel as shown in Figure I-1A.*

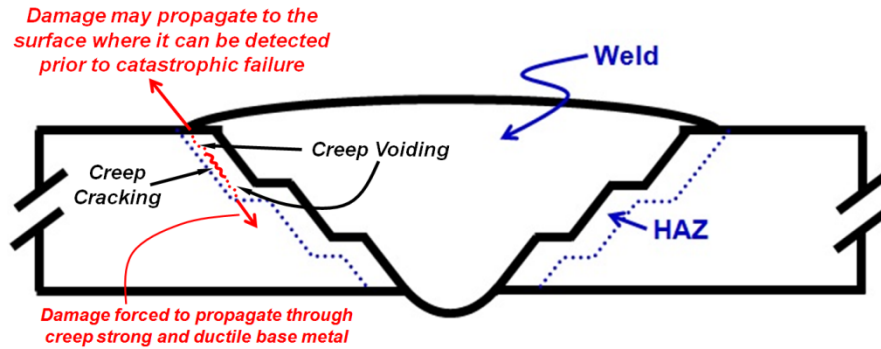
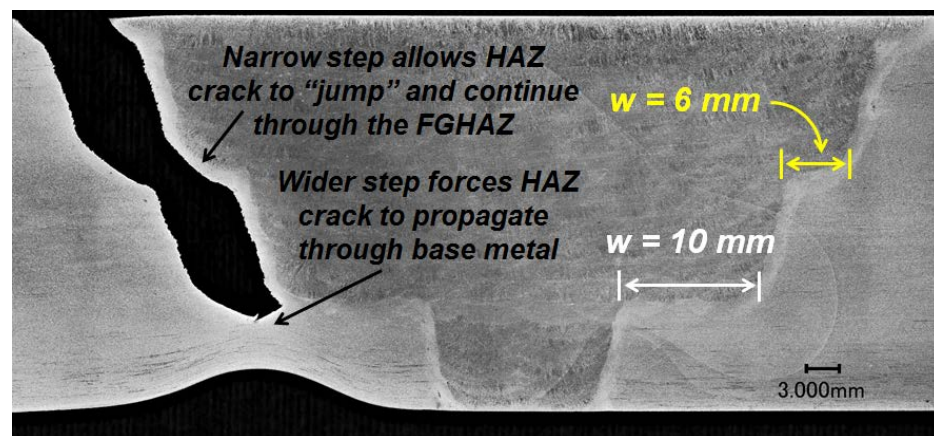
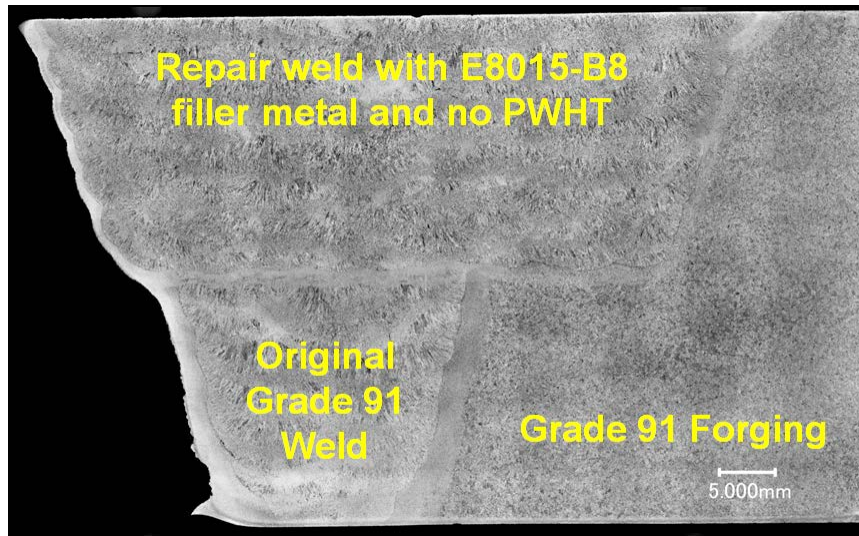


Figure I-2  
Schematic Drawing That Depicts the Concept for Manufacturing Grade 91 Similar, Dissimilar, and Repair Welds with Steps in the Geometry



**Note:** In this examination, the 6 mm wide step was insufficient to prevent damage in the HAZ from connecting through the thickness. However, the 10 mm wide step was of sufficient width to force the HAZ crack through the Grade 91 parent material.

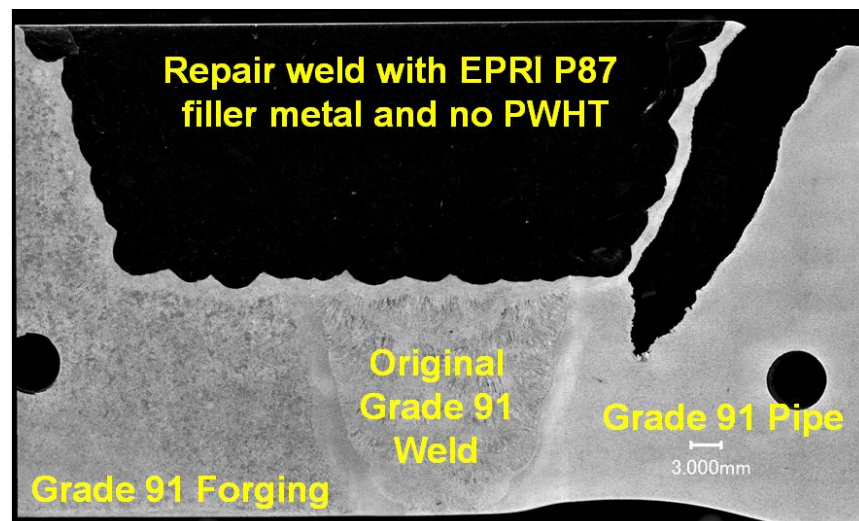
Figure I-3  
Results for Examination of the "w" Dimension (Step Width) on Performance of Through-Thickness and Partial Repair Welds in Grade 91 Steel



**Note:** In this examination, the step on the left side of the repair weld was insufficient to prevent damage in the HAZ from connecting through the thickness. However, the 10 mm wide step on the left side of the repair weld was of sufficient width to force the HAZ crack through the Grade 91 parent material.

*Figure I-4*

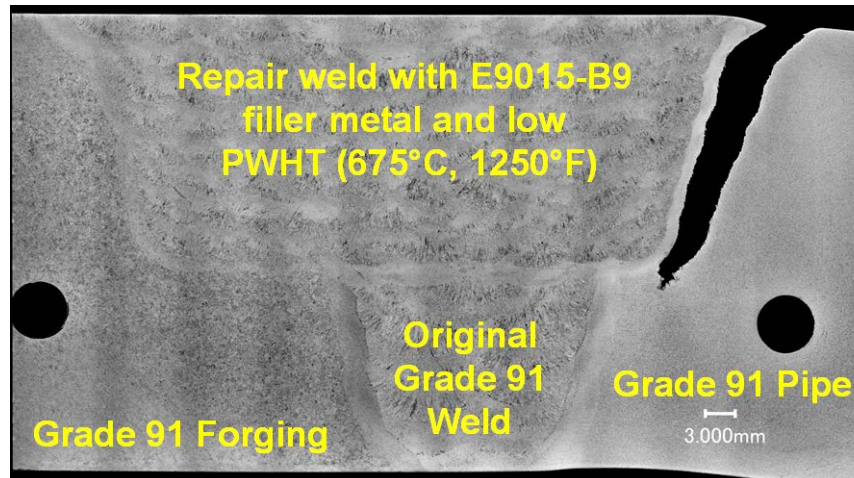
*An Example of a Partial Repair Weld (Made with Controlled Fill Procedure, E8015-B8 Filler Metal, and No PWHT) Where a Step of Insufficient Width Did Not Drive Cracking Through the Grade 91 Parent Material and Away from the HAZ of the Original Weld*



**Note:** In this examination, the step on the left side of the repair weld was sufficient to prevent damage in the HAZ from connecting through the thickness. Additionally, the 10 mm wide step on the left side of the repair weld was of sufficient width to force the HAZ crack through the Grade 91 parent material.

*Figure I-5*

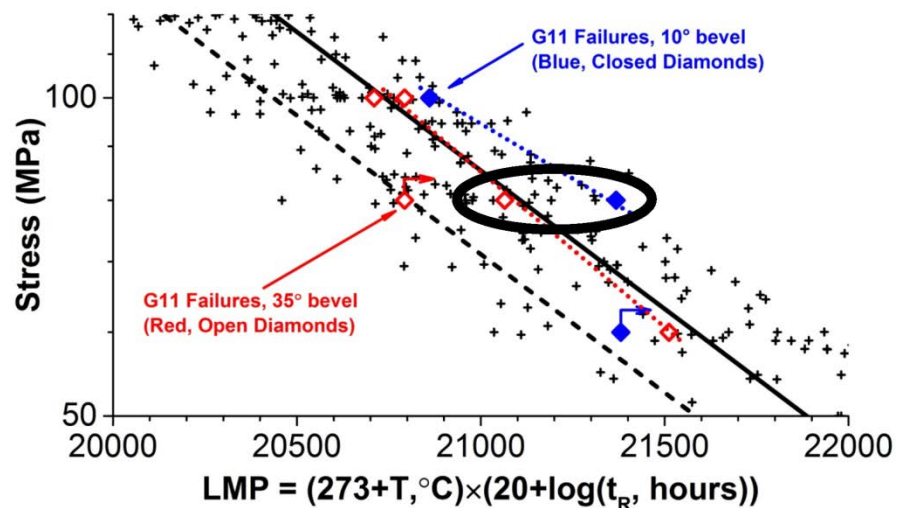
*An Example of a Partial Repair Weld (Made with Controlled Fill Procedure, EPRI P87 Filler Metal, and No PWHT) Where a Step of Sufficient Width Drove Cracking Through the Grade 91 Parent Material and Away from the HAZ of the Original Weld*



**Note:** In this examination, the step on the left side of the repair weld was sufficient to prevent damage in the HAZ from connecting through the thickness. Additionally, the 10 mm wide step on the left side of the repair weld was of sufficient width to force the HAZ crack through the Grade 91 parent material.

Figure I-6

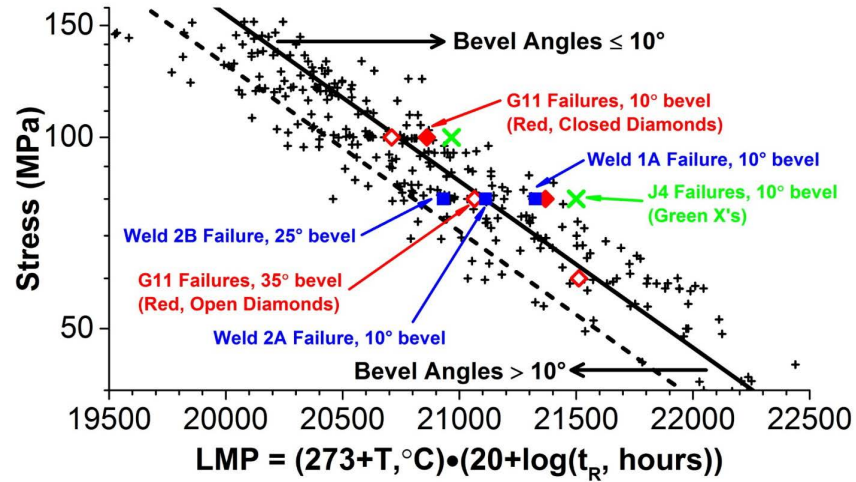
An Example of a Partial Repair Weld (Made with Controlled Fill Procedure, E9015-B9 Filler Metal, and Low PWHT) Where a Step of Sufficient Width Drove Cracking Through the Grade 91 Parent Material and Away from the HAZ of the Original Weld



**Note:** In this examination, welds were made in the same heat of Grade 91 parent material, using the SMAW process and same heat of E9015-B9 weld metal. These welds were given the same PWHT. At a test stress of  $\leq 80$  MPa, the effect of the bevel angle becomes more pronounced. For a 10° bevel, the time to rupture was  $>2X$  that for the 35° bevel.

Figure I-7

Results for Examination of the "α" Dimension (Bevel Angle) on Performance of Through-Thickness Welds in Grade 91 Steel Made Using a Conventional Approach. Tests with arrows indicate ongoing test specimens.



**Note:** Regardless of the welding procedure, and at a test stress of  $\leq 80$  MPa, the effect of the bevel angle becomes more pronounced. For a  $10^\circ$  bevel, the time to rupture was  $>2X$  that for the  $25^\circ$  or  $35^\circ$  bevel.

Figure I-8

Results for Examination of the "a" Dimension (Bevel Angle) on Performance of Through-Thickness and Partial Repair Welds in Grade 91 Steel. Tests with arrows indicate ongoing test specimens.





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