Guideline for Welding P(T) 91

William F. Newell, Jr., PE*

1.0 ABSTRACT
Factors affecting use, development, and procurement of Modified Grade 91 welding consumables for heavy wall applications are the focus of this report. Differences in technical approach between domestic and European producers and users are provided, particularly in composition variances. Prior and current activities are highlighted as well as progress to date in obtaining suitable fabricated wires with acceptable mechanical and operational properties. The effects of composition, post weld heat treatment times and temperatures plus practical implementation factors as they relate to creep and toughness are examined. Availability and procurement considerations are also discussed. As we learn more about this alloy, it is becoming clear that *P(T)91 should not be treated as just another CrMo steel*. The alloy requires considerable care during joining to assure acceptable long term properties. (1)

2.0 INTRODUCTION (2-11)
Development of the Grade 91 or 9 chromium - 1 molybdenum steels microalloyed with vanadium, niobium(columbium) and controlled nitrogen is the result of research conducted at the Oak Ridge National Laboratory (ORNL) for the Clinch River Breeder Reactor and later carried out by Combustion Engineering and others during the late 1970's. However, the "super 9 chrome" alloys were initially evaluated for power boiler use between 1955 and 1960 at the Center for Metallurgical Research of Liege in Belgium. This early work resulted in a 9Cr-2Mo alloy with additions of niobium and vanadium. A parallel effort, but for different reasons, was conducted by the Timken Corporation (USA) concerning use of the alloy family for bearing applications.

The high temperature creep resistance of the generic 9Cr 2Mo alloy appeared ideal for increasing operating temperatures and efficiency plus reduction of wall thickness for many fossil fueled power applications. Électricité de France approved a product produced by Vallourec (France) named EM12 in 1964 for use in superheater and reheat superheater applications up to temperatures of 620^o C (1148^{o}F). Approval was based on creep rupture tests of 760,000 hours on nine commercial heats. As of 1978, test data up to 200,000 hours was available. EM12 was also a candidate in 1978 for steam generator components in the European Fast Breeder Program. Even though EM12 provides satisfactory service in superheater tubing, the duplex structure results in low impact strength thus limiting the material to use in thin sections. Over 9,000 tons of EM12 tubes have been installed, with many still in use on a world wide basis.

In the late 1960's, German steel makers developed a 12 Chrome steel grade for high temperature applications to compete with EM12. This material, X20CrMoV12 1, was commonly referred to as "X20". The primary advantage of the X20 material was its martensitic structure which permitted use in heavy sections or thick walled piping systems.

*W. F. Newell, Jr. is a Co-Founder of Euroweld, Ltd. and President of W. F. Newell & Associates, Inc.

The creep rupture strength above 520^{o}C (968^{o}F) proved inferior to the EM12, but even more important, X20 exhibited poor weldability due to of its elevated carbon content. Other competitive alloys such as the Swedish HT9 and Japanese HCM 9M were produced, but were not as widely used as EM12 or X20.

In 1974, a task force was initiated by the US Department of Energy (DOE) to select materials for the LMFBR (Liquid Metal Fast Breeder Reactor) Program. The Oak Ridge National Laboratory (ORNL), assisted by Combustion Engineering, initiated a program to develop a 9Cr-1Mo steel that included all of the advantages of the EM12 and X 20 alloys plus eliminated the disadvantages. The orginal service temperature called for this material to provide strength at 512^{0}C (970^{0}F) and toughness of 54J (40 ft-lbs) at room temperatue for selected liquid sodium coolant components.

Creep resistance, weldability and the ability to commercially produce the alloy were considerations. Toughness was the primary consideration. By 1980, over 100 base metal test heats had been formulated and tested. The resulting composition of the Modified 9Cr-1Mo (later T/P91) is shown in Table 2. Multiple refining operations in the steel making practice were found to be required to achieve the controlled composition.

Table 2. Summary of Heat Treatment and Mechanical Property Requirements for Modified 9Cr-1Mo Steels (13)

Product Form		Forging	Seamless Tubing	Wrought Piping Fittings	Seamless Pipe	Forging	Forged & Bored Pipe	Plate
ASME Section II-A Specification		SA182 F91	SA213 T91	SA234 WP91	SA335 P91	SA336 F91	SA369 FP91	SA387 Gr. 91
Tensile Strength,	KSI	≥85	≥85	≥85	≥85	85-110	≥85	85-110
	MPa	≥585	≥585	≥585	≥585	585-760	≥585	585-760
Min. Yield Strength,	KSI	60	60	60	60	60	60	60
	MPa	415	415	415	415	415	415	415
Min. Long. Elongation,	%	20	20	20	20	20	20	18
Min. Reduction of Area,	%	40	NR	NR	NR	NR	NR	NR
Max. Brinell Hardness		248	250	248	NR	NR	NR	NR
Normalizing Temp.,	°F	1900-2000	≥1900	1900-2000	≥1900	1900-2000	1900-2000	1900-2000
	°C	1040-1095	1040	1040-1095	1040	1040-1095	1040-1095	1040-1095
Min. Tempering Temp.,	°F	1350	1350	1350	1350	1350	1350	1350
	°C	730	730	730	730	730	730	730

NR - Not required by the specification.

The first set of Modified 9Cr-1Mo test tubes were installed in May 1980 in superheater sections of the TVA Kingston Unit 5 station, replacing TP321 stainless steel tubing.

Modified 9Cr-1Mo was recognized for tubing by ASTM as A213, Grade T91, in 1983. Use of the material for piping and headers was approved by ASTM (and ASME) as A/SA-335, Grade P91 in 1984. A European (German) equivalent is DIN 1.4903, Grade or Type X10 CrMo.V.Nb 91.

Figure 1. illustrates a comparison of wall thickness for various alloys for a given elevated temperature, pressure and European allowable strengths. Note that nearly a 2:1 reduction in wall thickness (61mm versus 132mm) is possible where Modified Grade 91 or P(T)91 (herein referred to as P91) is used in place of P22 material. The material provides an increase of 44 to 170% in allowable strength in the 510^{0}C (950^{0}F) to 593^{0}C (1100^{0}F) temperature range. The oxidation limit is also 38^{0}C (100^{0}F) above typical Grade 22 materials. Grade 91 also offers higher allowable strengths over type 304H up to 610^{0}c (1130^{0}F).

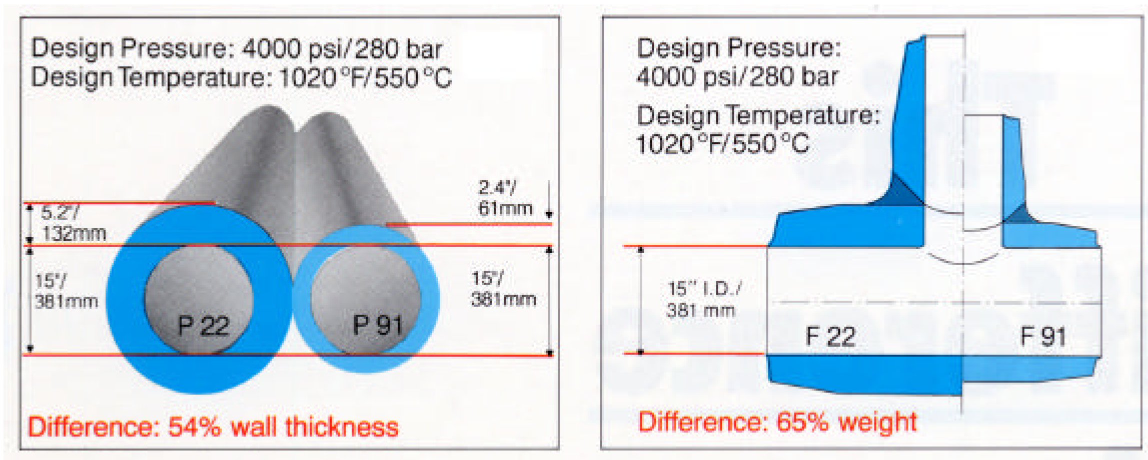

Figure 1. Comparison of Thickness and Weight using P(T)91 versus P(T)22.(38)

Thousands of tons of P91 materials are in use worldwide. Until about 1998, most installations or retrofits, however, have not been in the United States. Three major reasons were initially cited by domestic fabricators and end users for not using the P91 material:

1. The material is not readily available or is a special order (when the "ORNL Composition" is specified)
2. All welds require post weld heat treat, regardless of thickness or diameter
3. Installation and heat treatment of dissimilar weldments (e.g., P22 to P(T)91) can be complex in either shop or field applications.

Except for some selected Japanese variations, a consensus was observed concerning the base material, regardless of product form. The ORNL base metal composition was and is being produced and used in accordance with nationally recognized material specifications. Weld metal composition usage and specification, on the other hand, exhibit two distinctly different schools of thought: low nickel (0.4 max. per ORNL/CE) versus high nickel (~ 0.6 to 0.8 in Europe, plus tolerance for up to 0.5 silicon).

Currently, most of the consumables for welding P(T)91 components (hereafter referred to as P91) are produced overseas, due to greater use, and vary from the original ORNL recommendations. Increased levels of nickel and silicon or nickel + manganese limitations are observed over those in the ORNL specifications. Nickel is elevated to enhance toughness, but Ni+Mn limitations are utilized to ensure that the A_{C1} transformation temperature is maintained at a level sufficient to permit proper tempering. Minor increases in the silicon level are desired to ensure adequate deoxidization of the molten weld puddle. On a heat to heat basis, early European produced material occasionally fell within the AWS/ASME filler metal specifications for “B9” (Modified 9Cr-1Mo) classifications. Material required to meet the “ORNL” specification was usually a special order.

Today consumables meeting “B9” specifications (“ORNL”) are available from a variety of sources. Procurement of standard, commodity type consumables such as E7018, E308L-15 or ER316 is rather straightforward. However, when weld metal toughness, properties after post weld heat treatment, specified ferrite criteria, hardness, or other out-of-the-ordinary requirements are needed, communication between the purchaser and supplier becomes critical. This is especially the case with consumables for welding the 9CrMoV or P(T)91 materials. *P(T)91 should not be treated as just another CrMo steel.* The alloy requires considerable care during joining to assure acceptable long term properties. (1) Table 1. illustrates some of the major differences when compared with a traditional CrMo material.

Table 1. Comparison of Important Variables when Welding P(T) 22 versus P(T) 91.

Variable	Base Metal	
	P(T) 22	P(T) 91
Preheat	Always	Always !
PWHT	Sometimes (some code exemptions)	Always !
Normalize & Temper (after bending or cold working)	Sometimes	Always ! (> 18% strain)
Certified Material Test Report	Rarely (not normally required)	Always ! (PWHT < A_{C1})
Toughness Requirements	Rarely (not normally required)	Always !
Post Bake	Rarely (not normally required)	Always ! (except GTAW)
Cool < 100^0C before PWHT	No (not required)	Yes (pending further study)
Bead Sequence	Rarely (not normally required)	Always ! (interbead tempering needed)
Purge	No (not normally required)	Always ! (material will sugar)

3.0 BASE MATERIAL PROPERTIES

3.1 Base Metal Mechanical Properties (1,6,9,35,36)

Base metal material properties are directly influenced by the composition and subsequent heat treatment operations. Typical properties for selected P(T) 91 product forms are shown in Table 2. Comparison of P(T) 91 with P(T)22 and Type 304H austenitic stainless steel are provided for themal conductivity in Figure 2 and coefficient of linear expansion in Figure 3. Data on modulus of elasticity is shown in Figure 4. P(T)91 is becoming a material of choice because of its better thermal conductivity and lower coefficient of linear expansion.

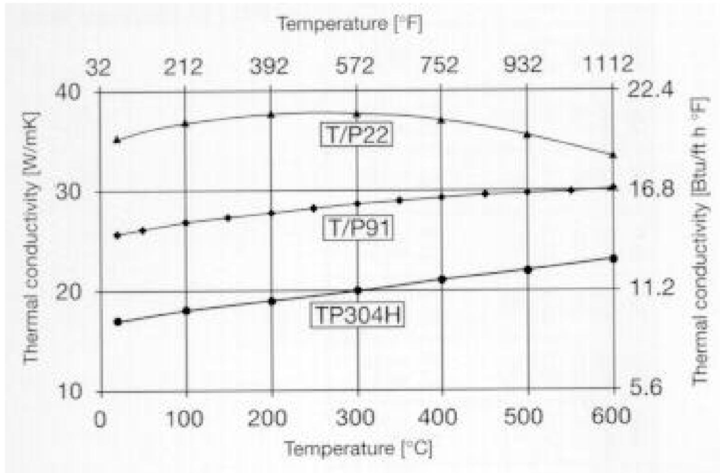

Figure 2. Thermal Conductivity among various alloys. (9)

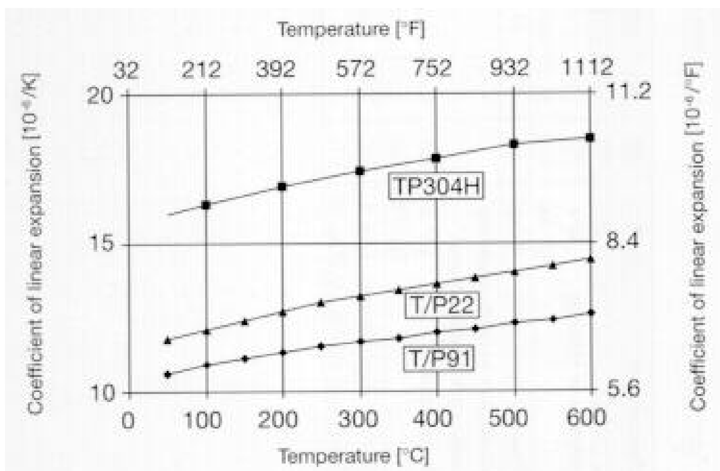

Figure 3. Mean coefficient of linear expansion comparison. (9)

Transformation Behavior

Because chemical composition may vary among heats of material, transformation temperatures will also vary. The A_{C1} (lower critical) typically ranges between 800^0C (1472^0F) and 830^0C (1526^0F), but values as low as 785^0C (1445^0F) have been observed. The A_{C3} (upper critical) has been found to range from 890^0C (1635^0F) to 940^0C (1725^0F). A continuous cooling temperature diagram for a selected P(T) 91 material is shown in Figure 5. Note that these values do NOT apply to weld metal.

This material is generally used in a normalized and tempered condition. Upon cooling from the austenitizing temperature to room temperature, the P(T) 91 structure transforms totally into martensite even with varying cooling rates. The maximum hardness of the martensite is characteristically less than 450 HV. The M_s (martensite start) temperature is normally around 400^0C (750^0F). The end of the martensite transformation, M_f, usually lies above 100^0C (210^0F) and will vary depending upon prior austenite grain size.

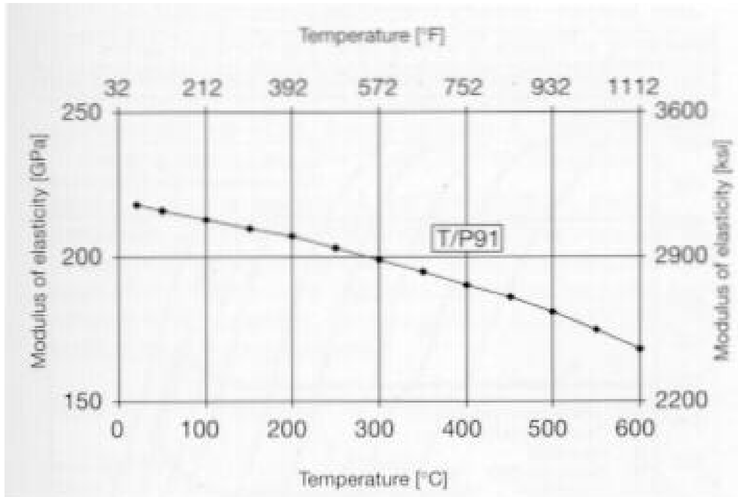

Figure 4. Modulus of elasticity versus temperature. (9)

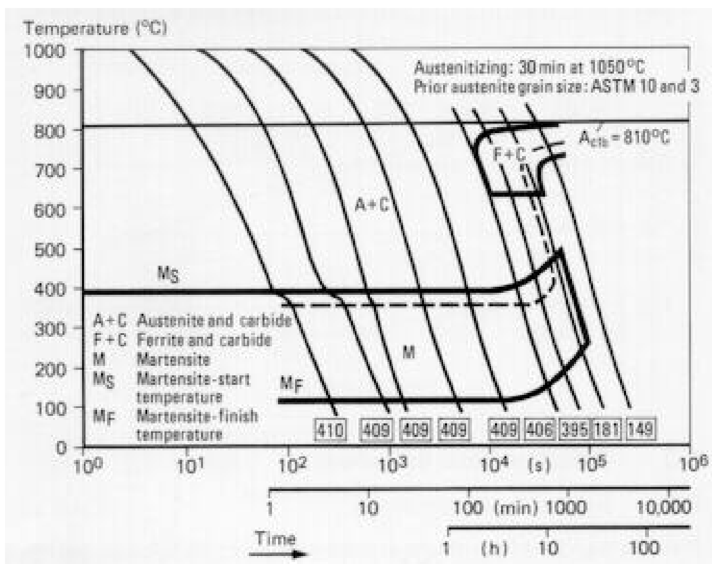

Figure 5. Continuous cooling transformation diagram for P(T) 91.

Heat Treatment

Heat treatment(s) of base material is selected to provide the best compromise between creep rupture strength, hardness and toughness. To achieve this compromize, material undergoes a quench and temper sequence. The material is typically normalized between 1040^{0}C (1900^{0}F) and 1080^{0}C (1980^{0}F) to dissolve most carbides without creating objectionable grain growth. The product form is then tempered between 750^{0}C (1380^{0}F) and 780^{0}C (1435^{0}F) to allow carbides to precipitate within the martensitic structure and soften the material. Yield strength, tensile strength and hardness will usually decrease while toughness increases as tempering temperatures approach the A_{C1}. Tempering above the A_{C1} results in increased strength and decreased toughness due to the formation of fresh martensite, but also significantly reduces creep rupture properties.

Microstructure

Heat treatments outlined herein will produce a structure of tempered martensite with preciptiation of $M_{23}C_6$ carbides and vanadium/niobium rich carbo-nitrides. These precipitates tend to improve creep rupture strength via precipitation hardening. The $M_{23}C_6$ carbides predominately stabilize the martensitic structure.

Welding & Forming

Welding of this material must be conducted with preheat and followed by post weld heat treatment (PWHT) to ensure that ductility has been restored in the weld metal and weld heat-affected zone. Adequate toughness must be present, even after PWHT, to ensure that the material will not be damaged in transit, during installation or shut down conditions. Experience over the last decade has shown that *where the base metal is subjected to cold bending strains over 18%, the material must be normalized and tempered.* One original equipment manufacturer performs a normalize and temper on all items that have seen cold bending and do so on the entire component. Localized normalizing and tempering has been found to be unacceptable. Normalizing and tempering may be the only way to completely eliminate the effects of a weld heat-affected zone.

Further, where thermal straitening is implemented, caution must be observed to not encroach on the lower critial (A_{C1}) temperature of the materal. If this is exceeded, the component must again be normalized and tempered. Some authorities make these additional heat treatments mandatory. (1)

3.2 Base Metal Composition

The composition of Modified 9Cr-1Mo base material in accordance with ASME/ASTM SA/A213, Grade T91, SA/A-335, Grade P91 or DIN 1.4903 Grade X10 CrMo.V.Nb 91 is provided in Table 3. The composition now used was derived from the ORNL program.

4.0 WELDMENT PROPERTIES

The weld deposit composition is designed to be as close as possible to the parent steel while maintaining mechanical properties and weldability. Early attempts to match base metal composition resulted in lower toughness when tempered within reasonable time and temperature cycles - typically 2 to 3 hours at 750 to 760^{0}C (1382-1400 ^{0}F).

Examples of typical properties at room temperature (RT) for P91 all weld metal versus weldments are provided in Table 4. In addition to tensile, yield strength and hardness, this material must provide creep resistance at elevated temperatures as well as exhibit reasonable toughness at RT. Simultaneously providing both optimum creep resistance and toughness is a challenge because measures for enhancing one property normally adversely affects the other.

Table 3. Comparison of "Grade 91 Modified" Weld Metal Compositions (13-17)

Element	P/T91 Steel ASME/ASTM	Gr. 91 AWS A5.28-96 ER90S-B9	Gr. 91 AWS A5.23-97 EB9	Gr. 91 AWS A5.5-96 E901X-B9	Gr. 91 BS EN 1599:1997 ECrMo91B	Gr. 91 EN 12070:1996 CrMo91**
Process	N/A	GTAW	SAW	SMAW	SMAW	GTAW
C	0.08/0.12	0.07/0.13	0.07/0.13	0.08/0.13	0.06/0.12	0.07/0.15
Mn	**0.30/0.60**	**1.25**	**1.25**	**1.25**	0.40/1.50*	0.4/1.5*
P	0.020	0.010	0.010	0.01	0.025	0.020
S	0.010	0.010	0.010	0.01	0.025	0.020
Si	**0.20/0.50**	**0.15/0.30**	**0.30**	**0.30**	0.60	0.6
Cr	8.00/9.50	8.00/9.50	8.00/10.00	8.00/10.50	8.0/10.5	8.0/10.5
Mo	0.85/1.05	0.80/1.10	0.80/1.10	0.85/1.20	0.80/1.20	0.80/1.20
Ni	**0.40**	**1.00**	**1.00**	**1.00**	0.40/1.00*	0.4/1.0*
V	0.18/0.25	0.15/0.25	0.15/0.25	0.15/0.30	0.15/0.30	0.15/0.30
N_2	0.03/0.07	0.03/0.07	0.03/0.07	0.02/0.07	0.02/0.07	0.02/0.07
Nb	0.06/0.10	0.02/0.10	0.02/0.10	0.02/0.10	0.03/0.10	0.03/0.10

Single values are maximums. * Ni + Mn < 1.5 ** Draft in Review.

Major differences between base metal and weld metal are highlighted in bold type.

Table 4. Typical Grade 91 All Weld Metal Mechanical Properties at Room Temperature.(2, 17-19)

Process	Deposit	Ultimate, MPa (Ksi)	Yield, 2% Mpa (Ksi)	Toughness, J(ft-lbs)	Hardness $HV_{.5}$
SMAW[1]	All Weld Metal	820 (120)	700 (102)	65 (47)	240[3]
	Weldment	698[5] (102)	N/A	54 (39)	N/A
GTAW[1]	All Weld Metal	750 (109)	660 (87)	147(109)	240[3]
	Weldment	703[5] (103)	N/A	199 (144)	N/A
FCAW Metal Core[3] 75Ar-25CO_2[4] 100% CO_2[4]	All Weld Metal	 850[6] (124) (116) (111)	 720[6] (105) (97) (92)	 32 (23) (23) (23)	 260[3] 246 246
	Weldment	N/A	N/A	N/A	N/A
SAW[3]	All Weld Metal	720[1] (105)	610[1] (89)	60 (44)	240[1]
	Weldment	657[4] (96)	N/A	54 (39)	N/A

Notes: 1. PWHT: 760°C/2hr 2. PWHT: 765°C/2hr 3. PWHT: 760°C/4hr
4. PWHT 760°C/2hr 5. Fracture in base metal. 6. PWHT: 755°C/3hr

4.1 Tensile Properties

Typical ultimate and yield strength, elongation, and hardness values for all weld metal and weldments with various welding processes used to join Grade 91 are illustrated in Table 4.

4.2 Creep Considerations (2-18)

Test results have shown that creep failure of welded joints in P91 steel welded with matching or near-matching weld metals occurs in the parent material. (9-12, 15-19) The reduction in transverse creep strength of P91 weldments is typically about 20%. However, *creep considerations do not characteristically become relavent until the operating temperature is greater than 1,050^{0}F (566^{0}C).*

Figure 6. illustrates stress-rupture properties for P91 base metal and representative weldments. A number of observations can be made:

- with the possible exception of very short duration tests, all the weldments lie below the average claimed by ORNL for P91 steel base metal
- in longer duration tests, weldment properties show increasing divergence from the P91 base metal
- all the weldments indicate similar behavior. It should be noted that failure location in cross-weld tests is normally at the outer boundary of the visible HAZ. This region is partially re-austenitized by re-heating within the intercritical temperature range during the welding thermal cycle where most of the carbon and nitrogen is precipitated from solution. Further recrystallization of the transformed microstructure during PWHT then produces a relatively soft martensite which lacks the carbo-nitride grain strengthening essential for creep resistance. This weakened zone where “Type IV” creep failure occurs is characteristic of all creep resisting CrMo steels. Figure 7. shows a typical hardness survey with a hardness almost 40HV below the base material average.

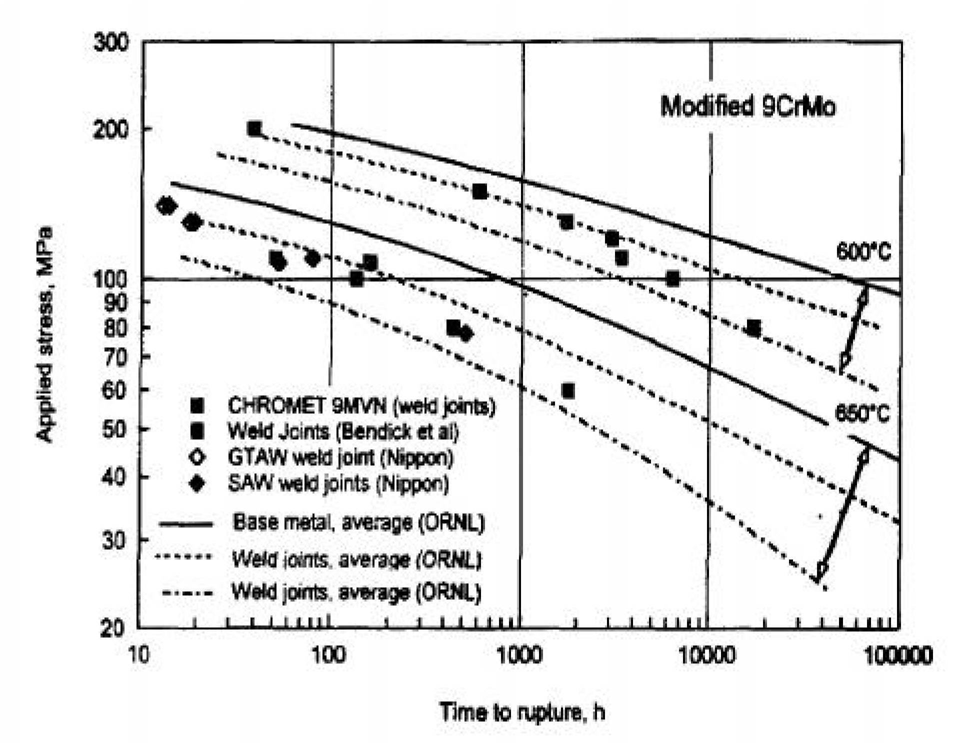

Figure 6. Creep Properties of Typical P91 Weldments. (16)

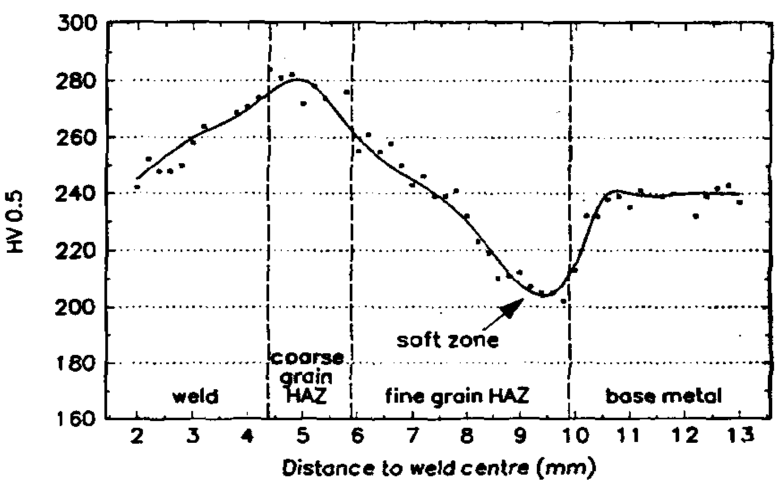

Figure 7. Representative Microhardness Across a P91 Weldment. (18)

Since Type IV failure is typical for cross-weld creep tests (except possibly for very high stress/short duration tests), the actual role of the weld metal creep performance could be considered as having little practical significance, except that it should perform at least as well as the HAZ region. Some authorities accept this observation. (11,16)

However, there are two other contrasting opinions concerning the influence of weld metal creep properties on the overall behavior of weldments or the possibility that weld metal behavior might be optimized in an attempt to delay the onset of Type IV failure:

- One proposal is that the weld metal should actually be weaker than the parent material and comparable with the type IV zone creep strength. (16)
- The alternative proposition is that the relatively wide weld zone should have a strength comparable to the base material so that less strain will be transferred to the narrow type IV zone and failure will therefore be delayed. (16)

Early work in the USA and recently discussed by Zhang, et al, (18) indicated that reducing niobium content to levels as low as 0.02 wt. % resulted in significantly tougher weld metal than the parent base metal (0.06 to 0.10 wt. %). Testing has also shown that a lower limit of 0.04 wt. % niobium is necessary to maintain satisfactory creep resistance. The accepted range is controlled to within 0.04 to 0.07 wt. %. (7,10,16)

Encouraging creep rupture results have been observed with reduced niobium levels, down to 0.025 to 0.03, from selected FCAW wires. The higher rupture stress of the FCAW weld metal is believed to be caused by the presence of residual titanium. Titanium forms stable carbonitrides like niobium, a positive influence was anticipated, and the intentional reduction of Nb was justified.

No previous reports highlighting the effects of Ti in P91 weld metal are available, but a similar level (200ppm Ti) was found to have no effect on 650°C rupture life in a low nitrogen 11%Cr rotor steel, and contrary to the weld metal here, fracture appearance transition temperature (FATT) was noticeably reduced. Early results suggest that this approach may even provide enhanced performance as shown in Figure 8.

Greater possible importance is the pick up of titanium into the weld metal which provides a further strong carbide former and provide more matrix strengthening. FCAW weld metals are generally about 5-10% stronger at ambient temperature than weld metals from SMAW and SAW processes and are similar to those of GTAW deposit after similar PWHT. The corresponding toughness is generally lower. To mitigate the effects of Ti pick-up (typically 0.02-0.04%Ti), the level of Nb is deliberately controlled to the minimum consistent with meeting weld metal specifications. A small proportion of this Nb is also derived from the rutile flux system.

It must also be cautioned that Grade 91 material is still susceptable to Type IV cracking, thus, it must be sized to properly accommodate performance in service. Both stress and operating temperature must be considered. There is general agreement that the failure mode of weldments is ultimately controlled by HAZ behavior, but currently there is no consensus as to the optimum choice of weld material properties to delay such failure and ultimately extend component life. This is particularly important where the design may consider longitudinal welds. In this case, some codes require derating the material an additional 20 to 40 percent to accommodate the elevated stresses associated with a longitudinal weld. Creep resistance behavior was generically categorized by EPRI (13-15), ORNL (20), Thyssen (2), and corroborated by others (16,25, 36, 38) as shown in Table 5.

Table 5. Grade 91 Weldment Performance Test Behavior. (2,3,10,11,13-16, 20, 25, 36, 38)

Temperature, ^{o}C (^{o}F)	Performance – Creep Results
550 (~960)	Base Metal, Weld and HAZ Have Comparable Properties
600 (~1050)	Base Metal and Weld Have Similar Properties; HAZ ~ 20% Less
650 (~1200)	Weld and HAZ Have Slightly Inferior Properties

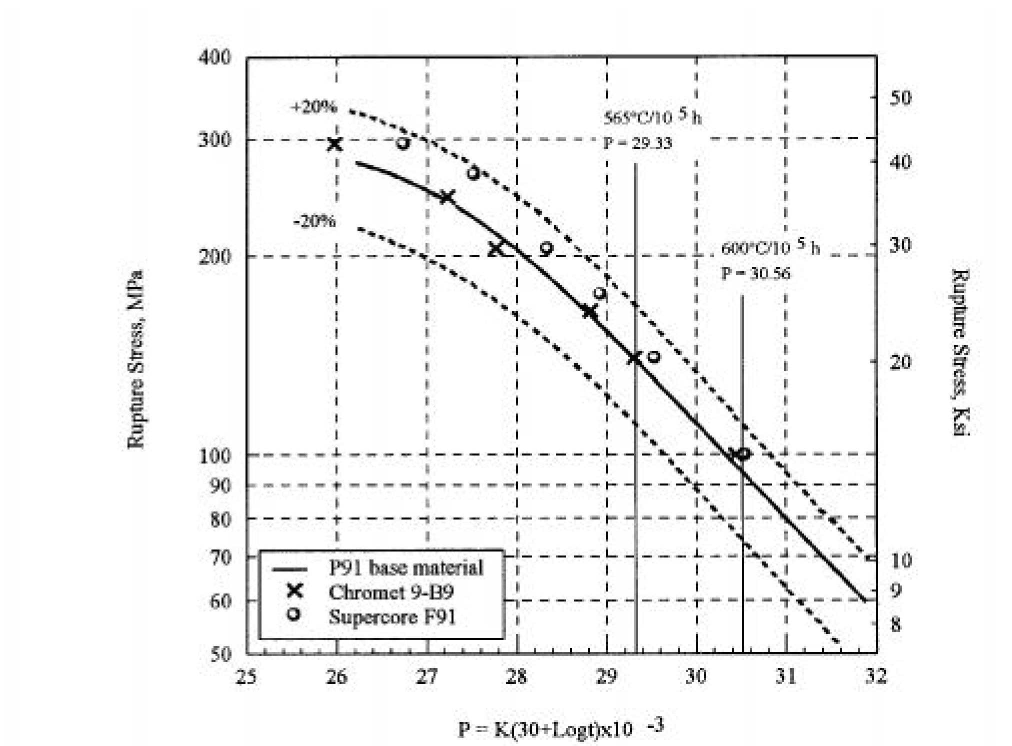

Figure 8. Larson-Miller plot of all-weld metal stress-rupture test results at 550-660°C for FCAW and SMAW (19)

4.3 Toughness Considerations

Four factors have a significant influence on weld metal toughness:

- Composition
- Post weld heat treatment time and temperature
- Welding process
- Microstructural effects (heat input, bead size, sequence and welding position)
- Toughness Testing Temperature

It has been argued that weld metal toughness is an irrelevant consideration for components which are designed to operate at temperatures in the range 500-600^{0}C (932-1112^{0}F) - far above the range at which any possible risk of fast brittle fracture could occur. However, there are situations where components might be pressurized or loaded at ambient temperatures during hydrostatic testing, construction, or start-up. To handle such conditions, most OEM's and fabricators consider that the weld metal should have a minimum toughness at + 20^0C (68^0F). The American Welding Society (AWS) filler metal specifications do not specify impact requirements for "-B9" filler metals, but the non-mandatory appendix to AWS A5.5-96 (covered electrodes) proposes that a suitable test criterion should be agreed upon between the purchaser and supplier. Conversely, the recently introduced European specification EN 1599: 1997 requires a minimum average of 47J (34.7 ft-lbs.) with a minimum single value of 38J at + 20^0C (28 ft-lbs @ 68^0F). These values coincide with some internal corporate specifications from those whom have imposed toughness criteria and required values in the range 20-50J at 20^0C (14.8-36.9 ft-lbs @ 68^0F) after PWHT. Determination of adequate toughness became an issue, particularly because of early work with the FCAW process.

Table 6. CTOD and K_Q values of *Supercore F91* weld metal. (19)

PWHT procedure	Test temperature, °C	CTOD, mm	K_Q, MPa m
760°C×2h+FC	20	0.021	75.10
		0.018	61.80
		0.030	76.79
	0	0.029	69.26
		0.021	55.75
		0.025	66.79

To answer the above question about the toughness of FCAW, a study was commissioned to calculate the maximum tolerable flaw sizes using critical assessment procedures set out in BS7910 (33,34). The model chosen was that of a fabricated header of 450mm (~18 in.) outside diameter and 50mm (~ 2 in.)wall thickness. The design conditions were 176 bar (2552 psi) at 580°C (1076^0F) with hydrotest conditions of 1.25 times design pressure at ambient temperature. This ensured that a comparison could be made between the FCAW and SMAW weld metals under similar conditions. (18,19)

To assess the worst toughness situation, the lowest measured CTOD value, namely δ_C = 0.018mm at 20°C, was used in the BS 7910 (33,34) calculations. The results indicate a maximum tolerable surface flaw size of 125mm in length and 12.5mm in depth for a longitudinal seam weld, i.e. equal to ¼ of the wall thickness. The results are shown in Table 6.

Comparing the above data with those achieved by other flux shielded processes, namely SMAW and SAW (2), the FCAW deposit, as expected, produced somewhat lower impact energy values. However, as illustrated by Figure 9, slightly higher PWHT temperature or longer soaking times are normally beneficial for improving impact toughness.

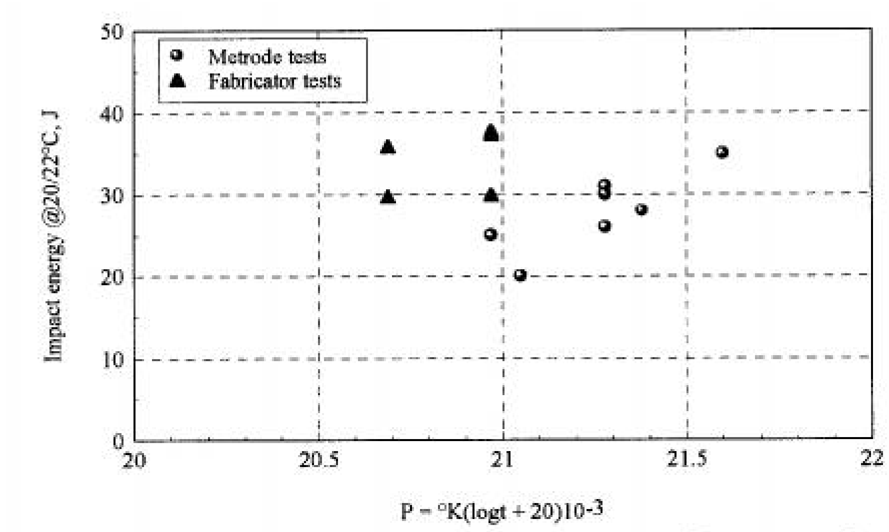

Figure 9. The effect of PWHT on *FCAW* weld metal toughness. (19)

4.3.1 Weld Metal Composition & Delta Ferrite

Various approaches to the weld metal composition have evolved since the original ORNL/CE project funding efforts from EPRI and others. Table 3 illustrates variations as they exist today between the USA and Europe. Although the Japanese will supply products that meet many of these compositions, they have modifications with increased tungsten additions, for example.

In general terms, those elements which are beneficial for improving creep performance are detrimental in terms of toughness, for example: Nb/Cb, V and to a lesser extent N and Si. A balanced composition or alloy that restricts delta ferrite formation but results in a fully martensitic microstructure helps to contribute both-optimum toughness and creep performance.

In the design of the flux cored wire, the deposit composition was aimed to be as close as possible to the requirements of the corresponding SMAW weld metal (e.g. AWS E9015-B9). The next revision of AWS A5.29 specification for low alloy flux cored wires will include this grade, and the expected classification for an all-positional wire will be E10XT1-B9. AWS specifications are ultimately included in Section II Part C of the ASME Boiler and Pressure Vessel Code. (32)

Table 7. presents the typical all-weld metal composition of a selected FCAW deposit. This composition is typical of a deposit made using welding grade Ar-20%CO_2 shielding gas. However, selected FCAW wires are formulated to work with either Ar plus15-25%CO_2 or 100%CO_2 shielding gases. Only minor changes in composition are typically observed.

Table 7 . Chemical composition of a typical FCAW weld metal.

Elements	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	N
wt%	0.10	0.8	0.3	0.010	0.015	9.5	0.6	1.0	0.03	0.20	0.05

To obtain a proper balance between fracture toughness, creep-rupture strength and resistance to long term embrittlement, the alloy composition and residual elements must be controlled to provide a single phase microstructure and avoid delta ferrite. The ORNL/CE programs found that by keeping the Chrome Equivalent (CE = Cr + 6Si + 4Mo + 1.5W + 11V + 5Cb + 9Ti + 12Al – 40C – 30N – 4Ni – 2Mn – 1Cu), as adjusted per their work, below 10, the tendency to form delta ferrite is reduced. This number is not absolute, but provides a good guideline since elevated delta ferrite in this material reduces its toughness. Even materials with a CE between 10 to 12 exhibited adequate toughness provided that the delta ferrite does not exceed five (5) percent.

Nickel

It is widely recognized that nickel can be useful for improving weld metal toughness. The addition of a controlled level of nickel is beneficial for two reasons. Nickel lowers the A_{C1} transformation temperature bringing this closer to the post weld heat treatment (PWHT) temperature and this improves the response to tempering. It also eliminates the possibility of residual delta ferrite being present which is undesirable because of its poor creep resistance and potentially adverse effect on toughness. However, excessive levels of nickel, exceeding 1% are also detrimental. The A_{C1} may be so low that PWHT at the top end of the temperature range could cause some austenite to form which in turn transforms to fresh untempered martensite on cooling. Most fabricators prefer to perform PWHT at least 50^{o}F (32^{0}C) below the transition temperature to allow room for minor temperature excursions. Excessive nickel also contributes to degradation of creep properties by changing the optimum long-term evolution of carbide precipitation during service. Nickel is therefore usually controlled in the range 0.4 - 1.0 wt.% in Europe.

The original ORNL work suggested a maximum of 0.4 wt.% was necessary to avoid complications with PWHT and the A_{C1} transformation temperatures while still achieving adequate tempering. Table 8 and Figure 6 compare transition temperature with nickel and manganese content. Recent work at ORNL examining the martensite start/finish temperatures has identified a potential and significant correlation of these temperatures to nickel content. Where nickel is elevated toward the upper end of the range, approximately 18% of the austenite may be retained at 204^{0}C (400^{0}F) and the M_f may actually be below room temperature! Many authorities recommended that you must allow the component to cool to ~100^{0}C (~200^{0}F) before PWHT to minimize the amount of retained austenite in the weldment. (20) It was shown by Santella, et al, that weld deposit specimens that were only cooled to 200C and had untempered martensite actually exhibited lower creep rates and relatively long rupture lives. These studies further suggest that nickel has the greatest effect in determining actual M_s and M_f temperatures. On the other hand, for typical base metals and low nickel bearing weld metal, the M_f is high enough in temperature that complete transformation should occur even when maintaining preheat temperatures around 200C (400F) after welding. (36)

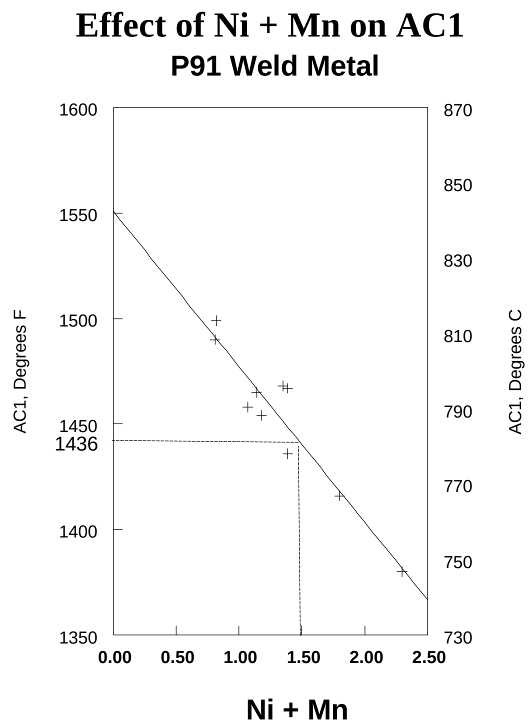

Figure 10. Effect of Ni+Mn on the A_{C1}.

Table 8. Calculated and measured lower critical temperatures (A_{C1}) as a function of Ni + Mn . (3,4,21)

Ni	Mn	Ni + Mn	$AC1_b$ ^0F [^0C]
0.3	0.51	0.81	1490 [807]*
0.33	0.49	0.82	1499 [816]
0.70	0.37	1.07	1458 [793]
0.71	0.43	1.14	1465 [796]
0.52	0.66	1.18	1454 [789]*
0.70	0.65	1.35	1468 [799]
0.63	0.76	1.39	1436 [778]*
0.79	0.60	1.39	1467 [797]
0.8	1.05	1.85	1416 [769]
1.0	1.3	2.3	1380 [749]

* ORNL Calculation

Variations in vanadium, carbon and nitrogen have been found to have smaller influences on toughness. Manganese is typically controlled at a higher level than the parent material to aid deoxidation and provide a sound weld deposit. However, some users, such as GEC- Alstom, limit Mn + Ni to 1.5% maximum as a safeguard against austenite reformation at the highest PWHT temperatures. Even with Ni + Mn levels consistantly at 1.5 wt.%, Figure 10 suggests that the lower critical temperature could be as low as 780^{0}C (1436^{0}F). Standard consumables are normally manufactured within this limit, but to ensure sufficient manganese for effective deoxidation, the nickel level is lowered to about 0.5 wt.%. However, the average toughness is usually somewhat lower. Toughness can be further reduced when users specify that both Mn and Ni in the weld metal must be in accordance with base metal limits. In order to be sure what effect the PWHT may have on the composition, the ACTUAL composition of the weld filler metal used should be known. Therefore, welding consumables should be procured with actual chemical compositions; e.g. Certified Material Test Reports (CMTR's) if domestic and/or an EN10204 3.1B certificate from Europe.

Silicon

What is unknown at this time is the effect of only having a minor portion of a weldment, such as the root and hot pass, at one composition or nickel level and the remainder of the weldment completed with another or lower nickel composition.

Silicon is an essential deoxidant required in both parent and weld metal. Combined with chromium, silicon may also contribute, to a minor degree, to the alloy's oxidation resistance. However, although some specifications have effectively the same range as P91 parent material (0.20 - 0.50%Si), a low level of silicon benefits weld metal toughness. The AWS specification limit of 0.30% is lower than the parent material and is perhaps too restrictive for certain consumables, particularly bare wires used with gas shielded processes. Chemical composition, particularly deoxidation tendency of the wire (Figure 11.), also has a significant effect on the welding operability of the GMAW process.(16) A silicon level of about 0.35 wt.% appears to be necessary for satisfactory operating behavior of the metal cored wire and up to 0.50 wt.% for FCAW wires. These silicon levels have not introduced any known problems in bare wires, SMAW or SAW used in Europe. In fact, silicon levels in bare wire between 0.3 and 0.35 actually aid deoxidation, wetting and manipulation of the puddle for GTAW. The proposed revision of AWS A5.29 to incorporate "-B9" FCAW, expands the silicon range up to 0.5 wt. percent to further enhance deoxidation.

Sulfur, Phosphorus & Residual Elements

Control of sulfur, phosphorous and residual elements is important. By observing the AWS "-B9" 0.010 maximum wt.% for sulfur and phosphorus, problems including crater cracking, maintenance of toughness after PWHT or other undesirable grain boundary effects can be avoided in SMAW, GTAW and SAW. It has been found that consumables exhibiting manganese to sulfur ratios greater than 50 provides one "rule of thumb", when combined with low phosphorous, to avoid crater cracking phenomena. By requiring low phosphorus levels, other elements in trace quantities that "come along for the ride" and that have been shown to be detrimental are also reduced. But, some sulfur (0.003 to 0.005 wt.%) and phosphorus (< 0.010 wt.%) are necessary to promote proper wetting action of the molten puddle where bare wire and gas shielding is used. Elevated levels of phosphorus up to 0.02 wt. % have been found to be permissible for FCAW wires because of the interaction of their slag formers and cooling rates on the deposited metal. Data also suggests that SMAW can normally tolerate this level of phosphorus (approved in European specifications). Where carbon and niobium (columbium) are both toward the upper end of their respective ranges, tolerance for phosphorus, sulfur and other trace elements is significantly reduced and may result in crater cracking, hot cracking or other undesirable grain boundary phenomena.

Many components fabricated for critical service (hydrocrackers, etc.) require strict control of residual elements to maintain resistance from temper embrittlement and elevated toughness of the material. Even though temper embrittlement criteria is not an issue for P91 consumables or most power piping, requiring that they meet an X Factor < 15, as calculated with the Bruscato Formula (or "X-Factor"; where, X = (10P+5Sb+4Sn+As)ppm/100, is a way to reduce or substantially minimize the presence of problematic constituants – primarily phosphorus and tin. By invoking this requirement, purity is maintained and tendancies that support hot cracking are reduced. The effect of selected chemical elements on creep resistance and toughness are summarized in Table 9.

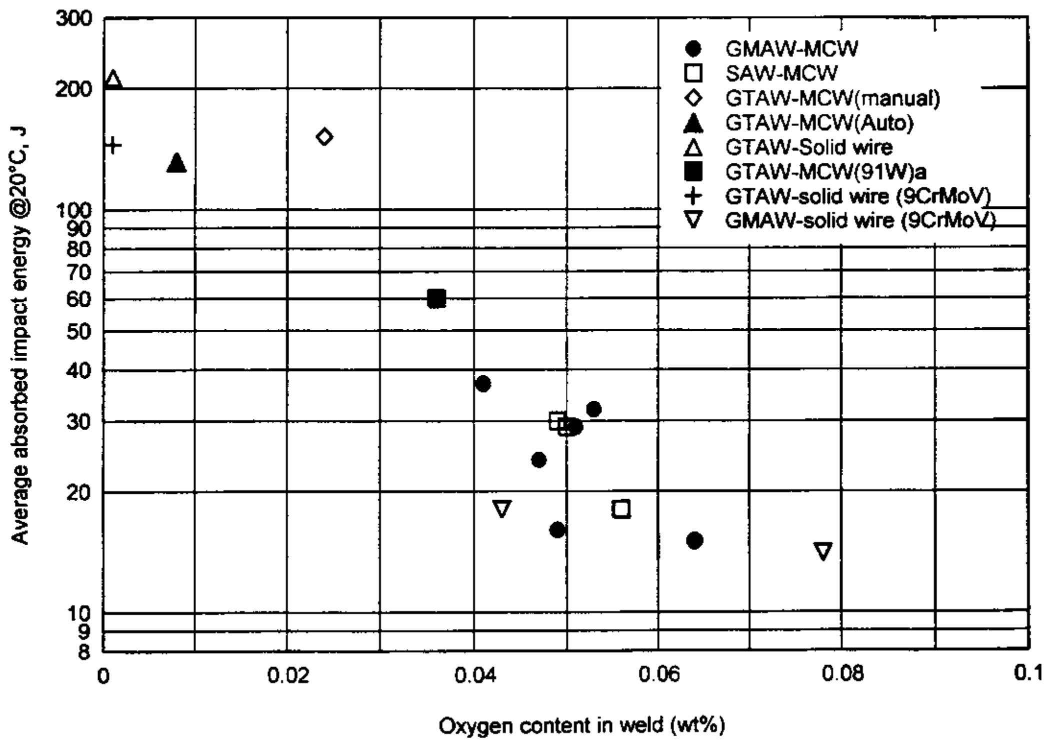

Figure 11. Effect of Oxygen Content on Toughness for Selected P91 Weldments. (16)

Table 9. Effect Summary of Individual Elements on P91 Weld Metal (2,3,6,13,16,20)

Element	Effect on Creep Resistance	Effect on Toughness	Notes
Ni 1.0max	CE believed that a negative effect on creep strength would be observed above 0.4 wt. percent.	Increases toughness. Europeans request up to 0.8 wt. % for increased toughness.	1,2
Mn 1.25max	None	Decreasing Mn will slightly improve toughness, but Mn is necessary for deoxidation of the molten weld pool. A minimum level of 0.40 wt. % is recommended.	1
Cr 8-10.5	Stated range required.	Variation within the range required for creep resistance result in little change.	
Mo 0.8-1.2	Stated range required.	N/A	
Si 0.15-0.30	N/A	As silicon decreases toughness increases. Silicon must remain above 0.15 wt. % to provide molten pool deoxidation and prevention of porosity. Preheat temperature to avoid cracking also increases with silicon content. Silicon therefore should be maintained as low as practically possible. Data suggests that levels between 0.20 and 0.50 wt. % are acceptable.	
Cb(Nb) 0.020-0.10	Minimal Cb(Nb) required to maintain creep properties.	Elevated Cb(Nb) significantly lowers toughness. 0.025 to 0.050 wt. % has been found to be acceptable.	3
V 0.15-0.30	Minimal levels required to Maintain creep properties.	Vanadium above 0.25 wt. % significantly lowers toughness.	
N 0.02-0.07	Minimal levels required to form carbonitrides to enhance creep properties.	High nitrogen levels lower toughness via formation of nitrides with other elements such as aluminum.	
Al	N/A	Limitations imposed in “-B9” specifications to avoid formation of toughness lowering nitrides.	
C 0.08-0.13	A minimum of 0.08 wt.% is required to achieve adequate creep strength.	Lower carbon can significantly increase toughness.	3

Notes:

1. CE concerns about elevated nickel content have not been verified. The widespread use and success of the higher nickel versions by the Europeans suggest that such concerns have not been validated.
2. Austenite forming elements Ni and Mn must be adjusted to ensure that the AC1 temperature is not below the PWHT temperature. Failure to do so may promote austenite formation which can lead to untempered martensite during cooling and result in lower creep properties. Therefore, as nickel is increased, manganese may have to decrease. Ni + Mn less than 1.5 is a guideline followed by European users.
3. Where carbon and niobium are both toward the upper end of their respective ranges, tolerance for phosphorus, sulfur and other trace elements is significantly reduced and may result in crater cracking, hot cracking or other undesirable grain boundary phenomena.
4. Chemistry range shown for each element is maximum and will vary depending on product form.

4.3.2 Preheat and Postweld Heat Treat

Application of elevated preheat and PWHT, including interpass temperature controls, are absolutely necessary with Grade 91 weldments, regardless of diameter or thickness. The literature suggests that 200°C (~ 400°F) is adequate for preheating P91 weldments. Fabricators typically aim for 250°C (~ 500°F) but will go as low as 150°C (~ 300°F), for root and hot pass layers only, thin-walled components or where GTAW is utilized. (8,22)

Interpass temperatures normally are restricted to 300 to 350°C (600-700°F). Field operations rarely have problems with interpass temperature limitations on heavy sections. Shop operations using SAW typically will exceed interpass temperatures and require cooling between passes. 350°C (700°F) appears to the upper practical temperature because of bead shape control limitations.

- **PWHT is one of the single most important factors in producing satisfactory weldments in P(T)91 materials. The PWHT methodology and implementation must be verified to ensure that the weldments are ACTUALLY receiving PWHT at the proper temperature. Additional thermocouples or qualification testing may be required.**

Proper tempering of the martensitic microstructure is essential for obtaining reasonable levels of toughness. In practice this involves selecting both an appropriate temperature and time. The AWS specification for consumable classification requires PWHT of 730-760°C (1346-1400 °F) for 1 hour. This time requirement is inadequate for normal fabrication procedures of heavywall components. Table 10 shows how mechanical properties vary with time at temperature. A minimum of 2-3h at temperature in the range 750-760°C (1382-1418 °F) is required, or longer for thicker sections. This temperature-time aspect is recognized by EN 1599 which specifies a PWHT requirement of 750-770°C for 2-3h for welding consumables. However, it is important to limit PWHT temperature to avoid the risks of austenite reformation and the transformation to fresh untempered martensite, particularly in weld metal with elevated nickel. (16,18, 35, 36)

Caution must also be observed when conducting PWHT on thin sections (< 10mm; 0.375 in.). Data suggests that 15 to 30 minutes at 760C (1400F) is adequate for satisfactory tempering of thin section weldments. In the absence of specific empirical data, sections over 10mm (0.375 in.) should receive two hours of PWHT, minimum, to achieve proper tempering.

Table 10. Mechanical properties resulting from different times for E9015-B9 PWHT @ 760°C (1400°F) (23)

Time, Min.	UTS, ksi	Yield 0.2%	Elong, %	CVN ft-bs@68°F
As –Welded [46 R_c]	210 [119 @ 1022°F]	-	-	3
45	120.3	101.8	17	13
120 [240-260 HV_{10}]	104.7	83.5	23	53

The effect of extended time and PWHT on toughness and hardness are further presented in Figures 12 and 13. It has been suggested that 760°C (~1400 °F) is the optimum PWHT temperature, pending heating equipment capability and nickel content of the welding filler metals. And, even though codes permit less time, PWHT should be conducted for a minimum of two (2) hours at temperature, even for weld metal testing, to provide sufficient tempering.

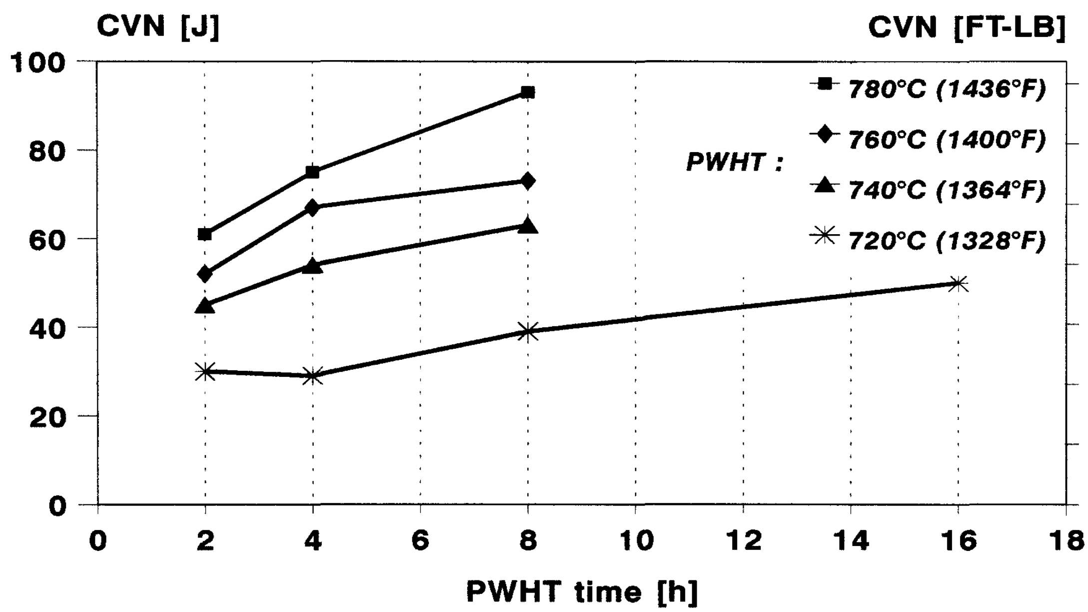

Figure 12. Influence of PWHT Time and Temperature on Toughness (2,10)

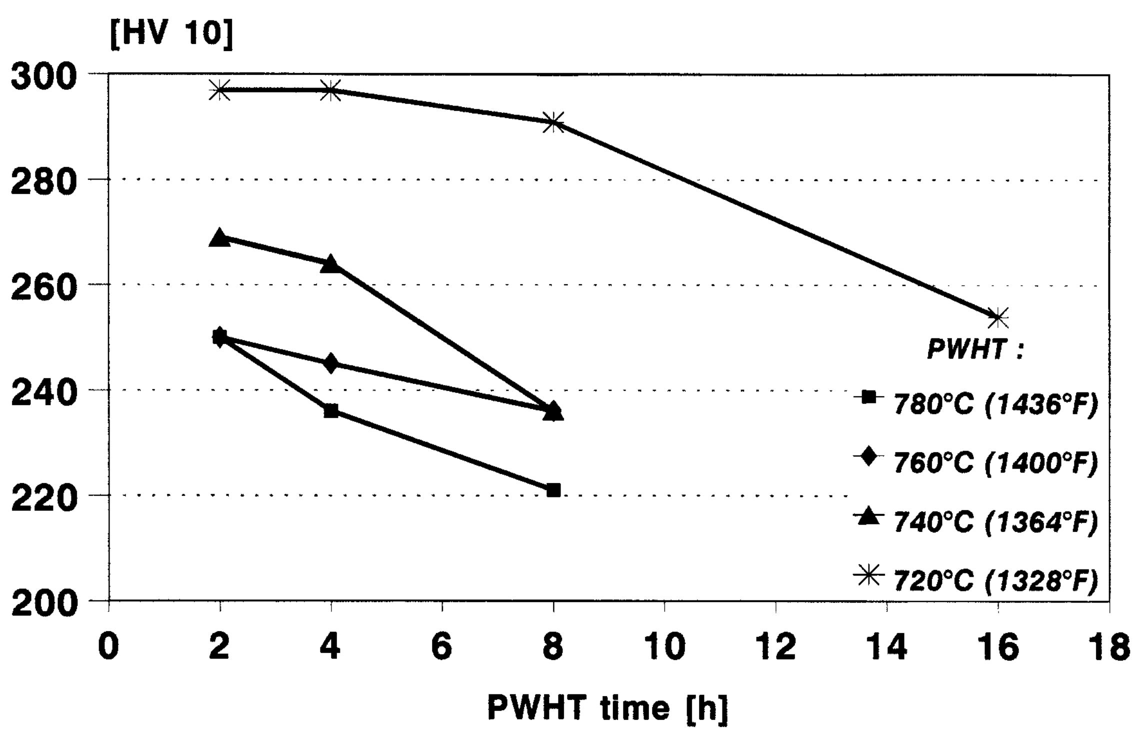

Figure 13. Influence of PWHT Time and Temperature on Hardness.(2,10)

Questions arise over performing PWHT above 1400^0F on ASME B31.1 work because of the 704^0C (1300^0F) to 760^0C (1400^0F) range specified in Table 132. Interpretation 24-5 offered the following: (24)

Interpretation:	24-5
Subject:	B31.1 Table 132, Postweld Heat Treatment
Date Issued:	October 27, 1993
File:	B31-93-015
Question:	Is it permissible to postweld heat treat SA-182 F91 materials at 1400^0F-1450^0F instead of 1300^0F-1400^0F as specified for P-No. 5 in Table 132?
Reply:	Yes, provided the lower critical temperature of the SA-182 F91 material is not exceeded. See Para. 132.2(A).

Figure 14 presents typical preheat, welding/interpass and PWHT schedules for P91 to P91. This figure **illustrates cooling the weldments to room temperature prior to post weld heat treat to permit complete transformation to a martensitic structure**. On large vessels and heavy-wall piping, **this is not always practical**. **Successful practice** over two decades has shown that satisfactory results can be obtained by **allowing the completed weld to cool to the preheat temperature and holding this temperature continuously up to initiation of the post weld heat treat**. Success is dependent on close attention to maximum interpass temperatures and time at temperature during the final post weld heat treat. As mentioned earlier, further investigation is needed to clarify this difference in methodology. Conversely, it was absolutely necessary to cool to room temperature prior to post weld heat treatment where X20 materials were involved. Thus, this flexibility offered by P91 materials is much more attractive to fabricators and installers. (9,18,19,20,35,36)

Also of critical importance on heavy sections, may be implementation of a post weld bake when using flux-type processes. This bake should be at least at the preheat temperature if the fabrication schedule requires the weldment to cool to room temperature in process or prior to application of post weld heat treatment. Post bake times and temperatures vary from 4 hours at 260^0C (500^0F) to only 15 minutes at 316^0C (600^0F). Success with this much variation is due to the advances made in consumable formulation and implementation of proper preheat, welding, welding consumable storage and handling practices.

Methods available for preheat, post baking and post weld heat treatment vary in ease of use, complexity and effectiveness. Approaches include furnace, flame, electrical resistance heating and electrical induction heating. Each approach exhibits specific implementation and technical characteristics. These are further discussed in Pratical Considerations, Para. 7.1.

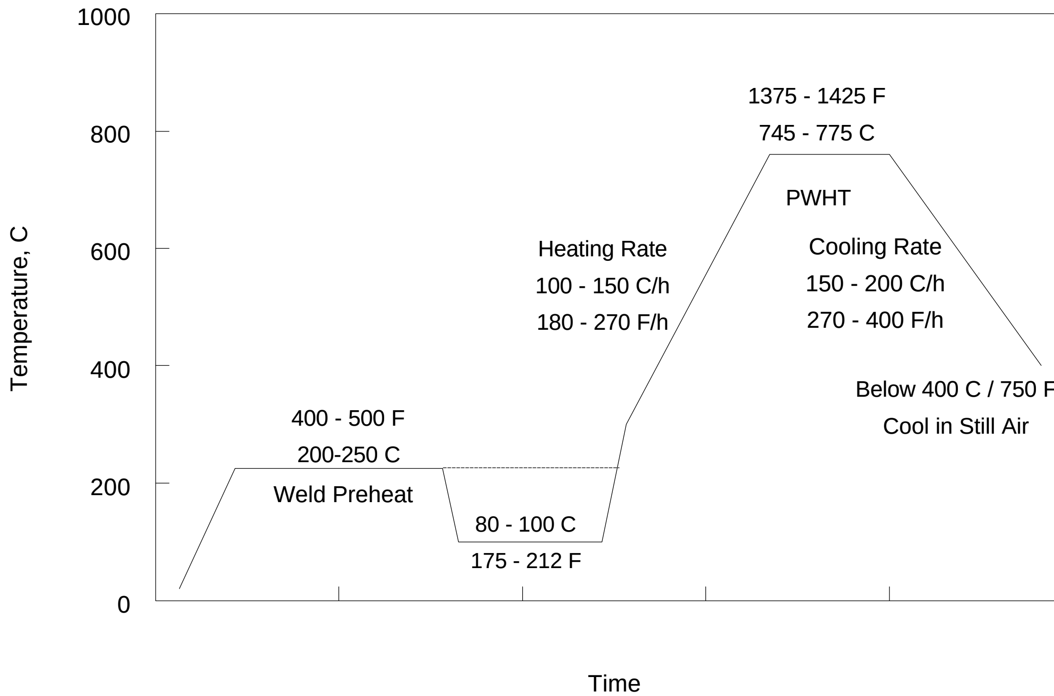

Figure 14. Typical thermal cycles observed during welding and PWHT. (9,25)

4.3.3 Welding Process Effects

Mechanical property results vary with welding process. This is especially true for processes that rely on fluxes and slag systems for alloying and/or shielding gases for protection of the molten weld pool. Primary factors that can affect weld metal properties include: heat input versus amount of weld metal deposited, grain size produced versus bead shape, and influences from wetting agents, crack inhibitors, deoxidizers and slag formers as they affect gas levels, microalloying and introduction of tramp or residual elements for the SMAW, FCAW and SAW processes.

Reductions in mechanical properties, primarily toughness, as a function of welding process are summarized in Table 11.

Table 11. Toughness Properties as a Function of Welding Process (17)

(GTAW = 100% of achievable properties)

Welding Process	Typical Toughness Reduction	Wetting Agents, Crack Inhibitors, Deoxidizers or Slag Formers
GTAW	None	Si, Mn, Ti
SAW	25-50%	SiO_2, MnO_3, etc.
SMAW	40-50%	$CaCO_2$, etc.
FCAW	50-70%	Varies

During original development of the Grade 91 SMAW consumable and in later manufacture, it was found that even though a lot of electrodes had proper chemistry, tramp elements and coating variables could actually result in an electrode that exhibited nil ductility. Thus, mechanical testing, including tensile and impact tests, is recommended on a lot to lot, per size per diameter basis, to ensure that the proper material has been produced and supplied.

4.3.4 Bead Shape and Position Effect

Bead shape and welding position have a significant effect on toughness. Most test data is reported in the flat welding position (1G). Bead shape plays an important role as shown in Figure 15. Thin, wide beads that permit some degree of tempering from the heat of welding induce grain refinement on previously deposited metal. Thicker bead cross-sections minimize grain refinement. Loss of toughness is normally observed in the vertical (3G) and overhead (4G) positions with SMAW– mostly due to the bead shape in the weldment. Even with an elevated weld metal nickel content (0.76 wt.%) to enhance toughness, the effect of position and corresponding bead shape and inability to provide tempering or induce grain refinement is evident and is as shown in Figures 15 and 16. However, some new FCAW wires have shown improvent in toughness in out-of-position welding. Increased interbead tempering is believed to be the cause. (19)

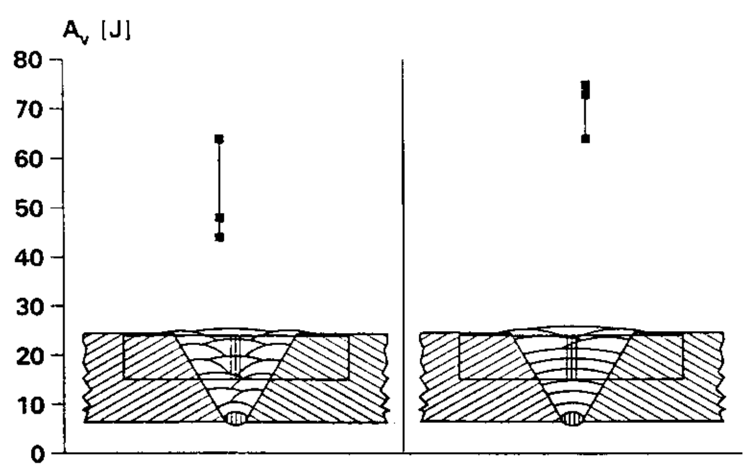

Figure 15. Influence of Bead Shape on Weld Metal Toughness for Typical FCAW and SAW Applications. (2,19,23)

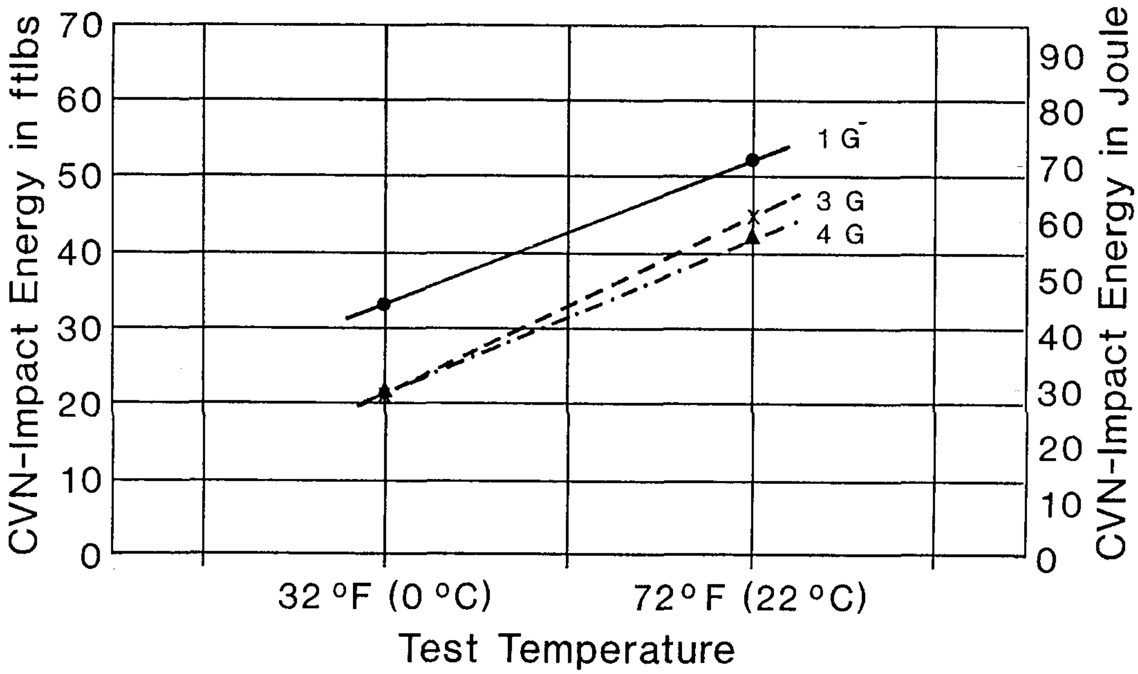

Figure 16. Effect of Welding Position on Toughness for SMAW. (2)

4.3.5 Toughness Testing Temperature

It must also be noted that the test temperature used when conducting toughness tests can have a dramatic effect on the results. (3,21) Experimental work has shown that the transition temperature for this alloy hovers around room temperature. Up to a 30 to 50 percent increase in toughness can be observed when tests are performed at 22-23^{0}C (72-75^{0}F) as opposed to 20^{0}C (68^{0}F)! (3,4,30)

5.0 DISSIMILAR WELDING

Dissimilar welds involving P91, P11 and P22 and austentic stainless steels are performed on a routine basis. Welds between the low alloy ferritic steels utilize either P91 or materials matching the lower alloy type base metals. In such weldments, carbon diffusion occurs during the tempering heat treatment due to the difference in chromium content of the materials. Carbon will migrate from the lower chromium material to the higher chromium one. For example: When P22 (E901X-B3/ER90S-B3/EB3) filler metal is used, the decarburized zone will be in the P22 weld metal next to the P91 with the carburized zone located in the P91 HAZ. If P91 weld metal is used, the carbon depleted zone will be located in the coarse grained P22 HAZ and the carburized zone in the P91 weld metal. The extent of the decarburized zone depend on the tempering temperature and time at temperature. The only way to avoid this condition is to use a nickel-base welding consumable. (9)

Decarburization in these dissimilar weldments typically only affect room temperature toughness properties. Creep rupture properties are usually not affected. (9)

Transitions or dissimilar welds between P91 and austenitic stainless steels normally uses nickel-base weld material. The weld metal can be applied to or involves buttering a P91 "pup" piece that can be heat treated and then field installed. In this manner, one weld can be made and PWHT as a P91 to nickel base while the other a nickel base to stainless steel. (9)

EPRI/RRAC work (39) showed that estimated life was improved considerably for DMW's where P91 was buttered with E9018-B3, the butter subjected to a PWHT 760^{0}C (1400^{0}F), then the final weld completed to the P22 followed by PWHT at 677^{0}C (1250^{0}F) to 704^{0}C (1300^{0}F). This technique produced results that were approximately two times greater than a DMW that is completed without the buttering step. The improvement was believed to be due to improvement of the HAZ from the butter PWHT and has a projected service life of approximately 350,000 hours. Further, conducting PWHT at 732^{0}C (1350^{0}F) versus 677^{0}C (1250^{0}F) on E9018-B3 for DMW's resulted in substantially better projected service life. This work showed that use of E9018-B3 weld metal for P91 to P22 DMW's is both prudent and sufficiently adequate.

Additional tests were conducted using nickel-base filler metal (ENiCrFe-3) in both a buttered/non-buttered sequence with similar results for a buttered-multiple PWHT approach. Due to recent service failures (40) identified with using ENiCrMo-3 for selected P91 DMW's, it is recommended that ENiCrFe-2 or –3 filler metals be used until further work is completed. Table 12 illustrates projected results from the recent EPRI/RRAC work on DMW's. (39)

Table 12. Estimated Remaining Life at 566^{0}C (1050^{0}F) based on experimental results and extrapolation of Isostress Curves. (39)

Estimated Life @ 566^{0}C (1050^{0}F) and 52.8 MPa (7.8 ksi)	Weldment PWHT 677^{0}C (1250^{0}F)	Weldment PWHT 732^{0}C (1350^{0}F)
E9018-B3	53,158	347,809
E9018-B3 w/butter PWHT @ 760^{0}C (1400^{0}F)	551,445	642,573
ENiCrFe-3	177,017	122,484
ENiCrFe-3 w/butter PWHT @ 760^{0}C (1400^{0}F)	362,446	293,892

1. Stress rupture test coupons were centered on P91-side of weld joint and includes base, HAZ, butter (if present) and weld metal. No P22 base metal was included in the test specimens.
2. Cross-weld stress rupture tests were performed for ENiCrFe-3 weldments resulting in specimen failures within the P22 HAZ.

Extreme care and planning must be observed concerning post weld heat treatment of dissimilar weldments involving P91. "Pup" pieces or multiple buttering/PWHT operations may be required when joining P91 to P11 or low carbon steels because tempering temperatures necessary for P91 may exceed lower transformation temperatures for some of the lower strength alloys. In these cases, P91 is oftentimes buttered with P22 or -B3 (or lower) type weld metal, PWHT at P91 temperatures, then the field weld is made with the lower strength alloy, followed by a subsequent PWHT a temperatures appropriate to the lower alloy.

Typical dissimilar weld (DMW) combinations and corresponding approaches are presented in Table 13. Weld filler metal selection possiblities for DMW's are shown in Table 14. Guideline PWHT temperatures are included in Table 15. In most cases, use of the lower strength weld metal is recommended. The temperatures shown, particularly where B9 weld metal is involved, are selected to provide proper tempering of the weld metal. These temperatures may not necessarily coincide with traditional code values and may require specific knowledge of the transformation temperatures or special properties of the materials involved and additional welding procedure qualifications. For example, ENiCrMo-3 ("625") should NOT be used because it will embrittle at the PWHT temperatures required for Grade 91.

Table 13. Dissimilar Weld Combinations and Approach (9, 22)

Combination	Approach
P91 to P22	B3 & PWHT @ 1350^{0}F
P91 to P11	Butter P91 w/B2 & PWHT @ 1350^{0}F; Then, join w/B2 & PWHT @ 1100^{0}F
P91 to SS	Butter P91 w/Ni & PWHT @ 1400^{0}F; Then join to SS w/Ni

Table 14. Dissimilar Welding Filler Metal Selection (9, 22,26,27)

P(T)	**11**	**22**	**23**	**91**	**911**	**92**	**SS**
11	B2	B2	B2	B2	B2	B2	309
22	B2	B3	B3,G	B3	B3,G	B3,G	309,Ni
23	B2	B3,G	W, B3,G,Ni	G,Ni	W,G	B, W,G, B9	G,Ni,SS
91	B2	B3	G, Ni	B9	W,B9,G	W,G, B9	Ni
911	B2	B3,G	W,G	W,B9,G	W,G	B, W, G, B9	Ni
92	B2	B3,G	B, W,G,B9	B, W,B9, G	B, W,G,B9	B,W,G	Ni
SS	309	309,Ni	G,Ni,SS	Ni	Ni	Ni	SS,Ni

G = Nonstandard composition
B2 = 1-1/4 Cr ½Mo
B3 = 2-1/4Cr 1 Mo
B9 = 9 Cr 1 Mo V
W = Tungsten Modified
B = Boron Modified, etc.
Ni = Nickel Base (ENiCrFe-2 or –3)
SS = Stainless, 308H, 309H, 316H, 347H, 16-8-2

Butter or buffer layers may be required.

NOTE: ENiCrMo-3 (“625”) should NOT be used because it will embrittle at the PWHT temperatures required for Grade 91.

Table 14 selections are options based on current technology or practice. Other filler metals may be necessary depending upon service conditions, buttering and overall PWHT requirements.

Table 15. Recommended PWHT Temperatures (^{0}F) for Dissimilar Welds (9,22,26,27)

P(T)	**11**	**22**	**23**	**91**	**911**	**92**	**SS**
11	1350 ± 25	1350 ± 25	Butter 11 1350 ± 25	Butter 91 1375 ± 25; 1275 ± 25	Butter 911 1375 ± 25; 1275 ± 25	Butter 92 1375 ± 25; 1275 ± 25	Butter 11 (opt) 1275 ± 25
22	1350 ± 25	1350 ± 25	Butter 22 1350 ± 25	1375 ± 25	1375 ± 25	1375 ± 25	Butter (opt) 1350 ± 25
23	Butter 11 1350 ± 25	Butter 22 1350 ± 25	None	Butter 91 1375 ± 25	Butter 911 1375 ± 25	Butter 92 1375 ± 25	None
91	Butter 91 1375 ± 25; 1275 ± 25	1375 ± 25	Butter 91 1375 ± 25	1400 ± 25	1375 ± 25	1375 ± 25	Butter 91 1375 ± 25
911	Butter 911 1375 ± 25; 1275 ± 25	1375 ± 25	Butter 911 1375 ± 25	1375 ± 25	1375 ± 25	1375 ± 25	Butter 911 1375 ± 25
92	Butter 92 1375 ± 25; 1275 ± 25	1375 + 25	Butter 92 1375 ± 25	1375 ± 25	1375 ± 25	1375 ± 25	Butter 92 1375 ± 25
SS	Butter 11 (opt) 1275 ± 25	Butter (opt) 1350 ± 25	None	Butter 91 1375 ± 25	Butter 911 1375 ± 25	Butter 92 1375 ± 25	None

Notes:

1. The recommendations in the above table were developed from References 9,22,26 & 27.
2. The objective in dissimilar welding is to maintain properties while addressing differences in the respective base metals, HAZ's and PWHT temperatures. See Table 14 for weld metals.
3. Buttering and multi-step PWHT is used where PWHT required for one base metal, HAZ or weld metal is excessive for one or more of the others.
4. Where "Butter" is shown, "Butter" the indicated base metal, perform PWHT of the butter at the temperature listed, then join the other material to the butter and perform PWHT of the completed weldment at the second temperature.
5. T23 has shown tendancies toward reheat cracking from PWHT. This alloy was originally designed to be used without PWHT. Thus, buttering may be required.
6. T24 typically does not require PWHT. Thus, buttering may be required.
7. Caution must be observed when selecting PWHT temperatures that will not encroach on the A_{C1} of the lowere temperature material.
8. Where B9 weld metal is used for buttering or joining, 1400 ± 25F is the recommended heat treatment temperature.

6.0 WELDING PROCESSES

Welding of P91 can be accomplished with FCAW, GMAW, GTAW, SAW and SMAW processes. Welding filler metals have been formulated to complement the base metal but do require multiple refining operations to achieve the low levels of residual elements, especially phosphorus. A major effort was initiated on a worldwide basis to formulate weld metals that would exhibit friendly weldability while maintaining the required mechanical properties. Combustion Engineering formulated and tested nearly 200 different SMAW compositions in the original test program – only two or three of the compositions exhibited both satisfactory mechanical properties and welder appeal. (17)

Welding process selection is normally a funciton of thickness, diameter, position and quantity. Table 16 illustrates typical production rates as a function of welding process. Clearly, the SAW process offers significant potential where it can be used.

Table 16. Typical Manhours for Pipe to Pipe Welds as a Function of Welding Process (37.5 degree V-groove, Schedule 40). (17,28-30))

Welding Process	Manhours per Pipe Size, Diameter			
	3-inch	6-inch	12-inch	24-inch
GTAW	0.7	1.9	6.4	27.5
SMAW	0.5	1.0	2.8	12.1
FCAW	0.2	0.3	0.8	3.5
SAW	N/A	0.1	0.3	1.4

NOTE: Manhours based on average operating factors and deposition rates. Fit-up and groove preparation not included. Estimates based on using single process from root to cap.

6.1 Gas Metal Arc Welding (GMAW)

The situation with GMAW, particularly with active gas mixtures, is more complex because of the variable recovery of key elements such as Mn, Si, and Nb/Cb. Modifications to the compositions of solid or metal cored wires are similar to those applied to covered electrodes and these are beneficial for microstructural control even though toughness may far exceed many specification requirements.

It must be strongly noted that qualification and use of solid wire GMAW should be approached with much caution! The "-B9" composition is lean on deoxidizers, which are important to proper operation and results with GMAW. Because of this, wetting action is reduced and the preponderance for lack of fusion type defects and oxide inclusion content affect the ability to perform successful welding. A few fabricators have qualified GMAW, but few have implemented it into production because of it's operator specific characteristics and inability to perform in a reproduceable manner.

6.2 Gas Tungsten Arc Welding (GTAW)

Weld metal deposited with GTAW typically exhibits far greater toughness than weld metal deposited by processes using flux and slag systems. (e.g. FCAW, SMAW or SAW). This variation is explained by a significant difference in weld metal oxygen content and the increase in the populations of non-metallic inclusions. GTAW weld metal made with solid wires typically contains less than 100ppm oxygen compared with 400 - 800ppm for the fluxed processes. Although much slower than other processes, the GTAW process still provides weld deposits with the highest integrity. (19)

It is recommended that rod diameter be restricted to 3.2mm (1/8-inch) maximum for manual GTAW. Insufficient heat is available to implement interbead tempering with the puddle size associated with the larger diameter rods. (19)

6.3 Flux Cored Arc Welding (FCAW)

The operability of the GMAW process using a fabricated wire (FCAW) is strongly influenced by the type of the shielding gas. In general, a suitably high content of CO_2 in the gas is beneficial. However, higher CO_2 levels will normally increase the weld metal oxygen level which has been shown to be detrimental to impact toughness, as illustrated by Figure 11, except for *Supercore F91* that has been formulated to operate with either Ar-CO_2 (80-20 or 75-25) or 100% CO_2 shielding. Results with 100% CO_2 have actually shown somewhat better toughness in certain situations. This is believed to be due to the higher penetration and thus greater interbead tempering action of previously deposited weld beads. (9)

Flux cored wire, 1.2mm (~0.045-in.) diameter, is capable of a deposition rate which is competitive or exceeds all other arc welding processes except SAW (2). This advantage is particularly notable for in-position welding. Compared with solid wire gas metal arc welding (GMAW), a faster burn-off rate for tubular FCAW is also promoted by higher current density at the wire tip and I^2R resistance heating of the wire extension from the contact tip. Moreover, the flux cored wire process, which can utilize spray transfer, produces reliable fusion and penetration in all welding positions. The duty cycle possible with the FCAW process is also higher than for the GTAW and SMAW processes, which further improves potential productivity when compared to these processes. The better duty cycle can be attributed to two main factors: the continuous nature of the process and the all-position capability of the process without the need for a change in welding parameters. For some applications, especially numerous short welds, the duty cycle of the FCAW process may also compete with SAW if the set-up times and positioning of the joints into the flat position contribute a significant proportion of the time. The ability of FCAW to weld thick section joints relatively quickly in all positions may allow the FCAW process to compete with SAW in these situations.

The FCAW process is expected primarily to replace the SMAW process. The GTAW process will still be required for pipe roots and other small diameter or thin wall pipe, and the SAW process will be preferred for very thick section welds that can be rotated or manipulated into the flat position.

The FCAW process is mainly used in the hand held semi-automatic mode, which provides optimum adaptability and ease of use for both shop and site welding. For joints which lend themselves to mechanization, the productivity of the FCAW process may be further improved by the use of suitable automated equipment, Figure 17.

Figure 17. Use of *Supercore F91* FCAW in machine orbital (double-up) mode for utility P91 piping. (Photo courtesy of Florida Power & Light & J.A.Jones/Lockwood-Greene)

6.4 Shielded Metal Arc Welding (SMAW)

Application of the SMAW process is well understood. In most cases, acceptable mechanical properties are easily achieveable, provided that the electrode formulation is consistant with the "-B9" composition (Ni + Mn $\leq$ 1.5) and sufficient welder skill is available.

Greater success has been observed with the "-15" type electrode coatings than other varieties. Primary factors influencing this success are enhanced compositional control of tramp elements and better control of bead shape plus interbead tempering during welding as compared to the iron power type formulations. For example, when using iron powder additions, deliterious tramp elements or elevated phosphorous can "come along with the ride".

6.5 Submerged Arc Welding (SAW)

Submerged arc welding of P91 materials is readily accomplished by the use of automatic, machine or semi-automatic processes using both constant current or constant voltage power sources. When using a semi-automatic apparatus either for semi-automatic use or for an adaptive machine type use, a big disadvantage is the stiffness of the B9 welding material when feeding through the sharper turn of the standard semi-automatic heads. Two possible solutions to this problem are available, either a reduction in the size of the wire or a double annealing manufacturing process of the wire, which is available in some consumables. When using the standard machine type head this stiffness translates into a greater need to adjust the straightening rollers of the SAW apparatus to correct for the helix or cast of the wire. This also affects contact tube/tip life. (30)

Parameters will usually yield heat inputs below approximately 55 J/in. It is imperative that interbead tempering be accomplished (see Bead Shape) while welding. Also, it should be noted that when using fused as opposed to agglomerated fluxes, the fused flux will operate at approximately two volts less – this is to ensure that the molten puddle and flux remain fluid long enough for gases to escape. (25)

7.0 PRACTICAL CONSIDERATIONS

Other than the heat control measures, submerged arc welding of P91 material can be considered reasonably similar to the welding of carbon steel materials. There is an inherent sluggishness of the weld puddle, typical of higher alloy weld materials. This sluggishness translates into increased difficulty in narrow (or semi-narrow) groove applications and can lead to lack of side wall fusion or slag entrapment problems. The travel speed of the first bead in pipe welding may have to be slow enough to allow a larger puddle to assist in the side wall fusion which requires an increased heat input. Once the bevel design is wide enough to allow multiple beads per layer, the welder or welding operator must be careful in the placement of the subsequent beads in order to avoid slag entrapment should there be any slag remaining along the side of the previous bead. A good rule of thumb is to place the wire and therefore the arc immediately over the top of the edge of the previous bead so as to concentrate the heat of the arc at the crevice point of the bead. Crossover/stepover points, as well, must be approached with greater care than carbon steels. (30)

Welding parameters typical of carbon steels must be reduced, to maintain desirable weld bead characteristics. Due to the alloy content, Grade 91 (B9) fillers are more sensitive to changes in volts, amps, electrical stickout and travel speed.

> **Due to the high chromium level, these materials air harden and exhibit very little ductility in the as welded condition, therefore the application of elevated preheat, interpass temperature controls and post weld heat treatment are absolutely necessary with grade P91 weldments, regardless of diameter or thickness.** See 4.3.2. (17)

7.1 Preheat, Postbake & PWHT Methods & Approaches

A variety of methods are used to monitor or perform preheat, interpass, postbake, and PWHT operations. **Proper application of heating operations is critical to the success of Grade 91 welding.** Application and rigorous control of preheat, interpass and post weld heat treatment operations are required to ensure that desired toughness and creep-resistance are obtained. Control of preheat and interpass and even postbaking operations are necessary to avoid hydrogen retention/cracking problems in this extremely hardenable alloy family. Flame, furnace heating, electrical resistance and electrical induction heating are those methods typically used. Temperature monitoring and control of thermal gradients is extremely important. Where doubt with the process or method used exist, mock-ups should be utilized to verify the operation.

Caution: Extreme care must be used where welding procedure qualifications are conducted. In many cases, the test coupon preheat, PWHT and monitoring may be

conducted under ideal conditions such as in a laboratory oven. Shop and field operations do not typically enjoy this level of control. Thus, to rely soley on the fact that a welding procedure has been "qualified", may in no way guarantee or represent that actual operations will be conducted in a similar manner.

Flame

The use of oxy-fuel torches is not generally recommended except for thin sections or under very controlled conditions. Where used, care must be taken to obtain uniform temperature gradients and not result in hot or cold spots. Many fabrication shops have successfully used torch heating to establish preheat. This is far more difficult to control in a field or site situation.

Furnace

Large gas-fired furnaces are often used in fabrication shops for post weld heat treatment operations. Provided that hot/cold spots are known and monitored, successful operations can be conducted.

Electrical Resistance

Localized preheating and PWHT is often conducted with electrical resistance equipment. The equipment includes a power source that provides power to resistence wires typically woven into ceramic pads. Heating pads are normally arranged in zones about the weldment and energy is supplied/controlled via an electronic controller. This method is used widely in field operations. Many fabrication shops also use this method for preheating and/or PWHT of weldments in complex multi-weld spool assemblies. Heater pad(s), zone control and insulation placement are critical. Care must be taken to insure that an adequate heated band is achieved and is consistent with the required temperatures. Chiminey and position effects must be considered and if unknown, mock-ups should be used to establish heated band, soak times and actual thermal gradients.

Electrical Induction

Although not new, use of electrical induction for preheat and postweld heat treatment is gaining favor because equipment and implementation have become smaller, more portable and more user friendly. Induction heating involves the application of alternating (AC) current to coils (usually liquid cooled) wrapped around the work piece. A magnetic field is produced around the conductor or coil(s). The magnetic field penetrates the part around which the conductor wrapped. Since an alternating current is used, the magnetic field alternates in phase with the current, sweeping through the workpiece, collapsing, then building up in the opposite direction. A current is induced in the part because a current is produced whenever there is relative motion between a mangetic field and a conductor. Resistance to this induced current plus hysteresis loss heats the part. Current work suggests that properly applied induction heating may result in reduced thermal gradients within a weldment and a more uniform heated band. Induction techniques have demonstrated the ability to achieve preheat and upramp temperatures much faster than other conventional heating means.

Temperature Monitoring & Thermal Gradients

A variety of devices are available for measuring and monitoring temperature. For preheat and welding operations, instantaneous devices such as temperature indicating crayons, contact pyrometers or direct reading thermocouples with analog or digital readout are satisfactory. All devices should be calibrated or have some means of verifying their ability to measure the desired temperature range. It is never acceptable to make or take readings that would result in contamination of the weld groove. Because of their ability to provide continuous monitoring, thermocouples using chart recorders or data acquisition systems are preferable over instantaneous measuring devices for both preheat and PWHT operations.

For PWHT operations, the importance of thermocouple placement, number of thermocouples, and redundancy cannot be over emphasized. This is especially true where complex shapes, dissimilar thicknesses, chimney/position effects, hot/cold spots in ovens and potential thru-wall thermal gradients are encountered. Single point monitoring is typically unacceptable. Where access to the ID is possible, monitoring for unacceptable thermal gradients should be accomplished.

It is well known that thermal gradients will exist on weldments when applying preheat and postweld heat treatment. **As diameter and thickness increase, so will the thermal gradient. For example; it is not unusual to observe 50 to 100 F (10 to 38 C) gradients from OD to ID in large bore weldments (2-inch wall x 20-inch OD)!** When monitoring temperature from the outside of a pipe weldment, such gradients may be acceptable for some alloys, but not for Grade 91. (41)

7.2 Preheat

The literature suggests that 200^0C (~400^0 F) is adequate for preheating P91 weldments. Fabricators typically aim for 200^0C to 250^0C (~400^0F to 500^0F), but will go as low as 121^0C (~250^0 F) for root and hot pass layers, thin walled components or where GTAW is utilized. Preheat temperature should be considered an interpass minimum, since cooling to room temperature before the completion of the weld, without proper precautions, is not advisable when using flux bearing processes. (9)

7.3 Interpass Maximum

A typical interpass maximum is 300^0C (~600^0F), slightly less is acceptable but no more than 370^0C (700^0F). The interpass maximum helps to prevent the possibility of hot cracking due to the silicon and niobium content of the weld metal. Also, allowing the weldment to cool to below the martensitic start temperature (M_s; typically less than 200^0C/400^0F, and in some cases ~100^0C (~200^0F)) allows at least a portion of the martensitic microstructure to be tempered by subsequent beads. (9,20)

7.4 Post Weld “Bake-Out”

A post weld “bake-out” may be of critical importance, especially for heavy sections or where flux-type processes are used. This involves maintaining the preheat/interpass window for an extended period of time subsequent to interruption or completion of the weld in order to facilitate hydrogen diffusion from the weldment. Of the many variables involved when attempting to establish the length of time necessary, are the thickness of the material , length of time the weldment has been exposed to the heat regime and the extent of "low hydrogen" practices. If the fabrication schedule requires the weldment to cool to room temperature prior to PWHT, a 4 hour bake-out at the preheating temperature is a good starting point. Shorter times at higher temperatures are also common; e.g. 15 minutes at 316^0C (600^0F). **Where proper consumables and storage/handling are implemented, bake-outs can be minimized or even eliminated.** (9,30)

7.5 Interruption of the Heat Cycle

Interruption of the heat cycle should be avoided if at all possible, but due to production schedules, this is not always the case. If it becomes necessary, great care should be exercised. The **mass of the weldment should also be considered**. Increases in pipe wall thickness translates into increases in both the restraint on the weld and the cooling rate from welding temperatures. Therefore, the weld area is subjected to high residual stresses at a time when it may have minimum section thickness (or strength) and be less ductile. As the percentage a weld is completed increases, the more the strength and rigidity of the joint resemble the completed weld. Given this**, any interruption of the welding should be avoided** until a specified minimum amount of the joint has been deposited. Grade 91 weldments should be completed without interruption, but if interruption is unavoidable, at least 1/4 of the wall thickness should be deposited and preheat must be maintained until the groove is completed or a post bake implemented.

7.6 Miscellaneous Precautions

To minimize crater cracking or undesirable grain boundary phenomena, low residual element content (X factor < 15) weld filler metal, strict adherence to the preheat and interpass temperature requirements, plus use of covered electrodes and fluxes meeting "H4" and/or H5 criteria are advisable. In all cases, **low hydrogen controls must be implemented and maintained** during fabrication operations. Such controls are even more important for procurement, use and storage of welding consumables. Manufacturers recommendations for storage and reconditioning must be observed. If electrodes or submerged arc welding flux absorbs moisture, they should be discarded. Most covered electrodes are available with H4 formulations. SAW fluxes should also be of the low hydrogen variety and meet at least an H5 designation. Figure 18 illustrates exposure criteria for a selected FCAW wire. Note that this FCAW product meets H4 criteria.

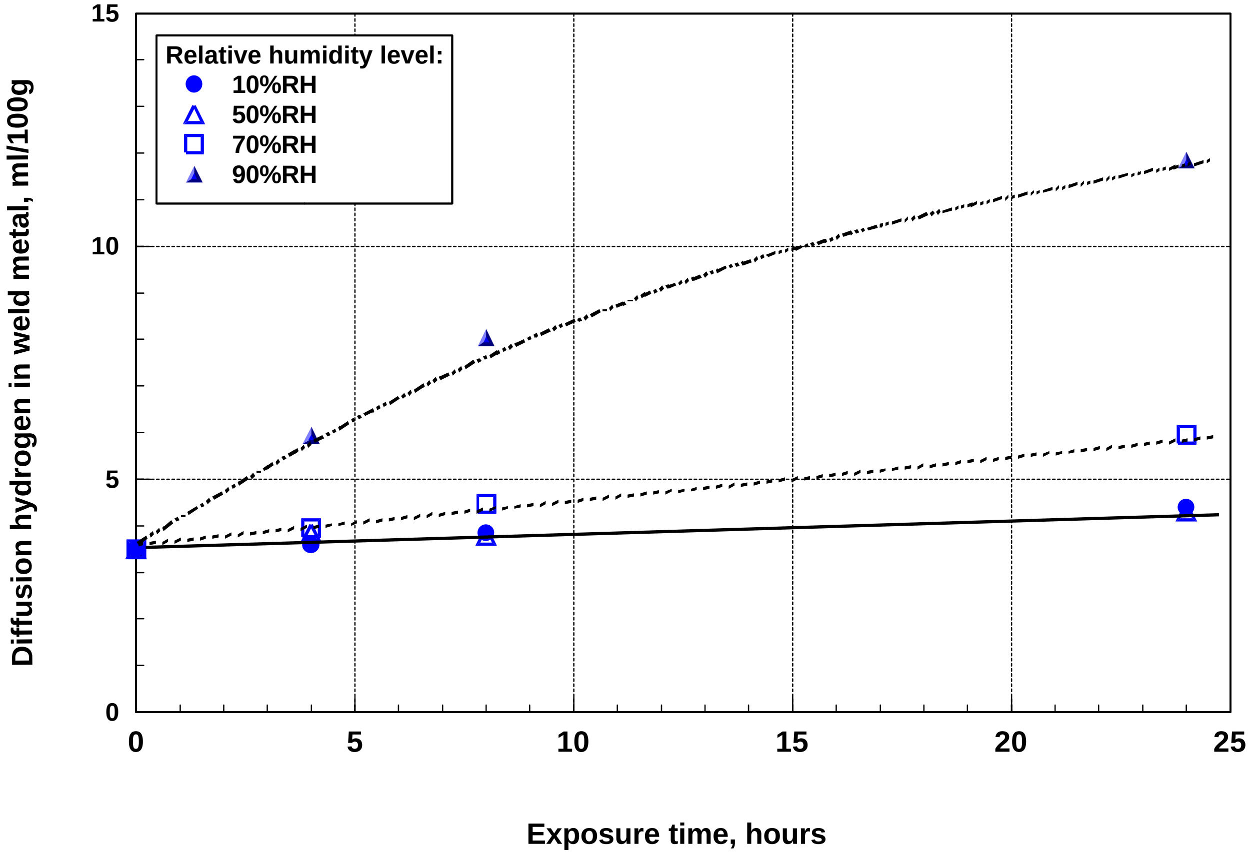

Figure 18. Effect of exposure time/condition on weld metal hydrogen content for *Supercore F91* P91-type FCAW wire. (23)

Traditional code required NDE (UT and/or RT) may not identify crater, hot or cold cracking in P91 weldments. Repetitive patterns of seemingly nonrelevant indications should be evaluated with more sensitive NDE techniques.

Root passes in piping, tubing or other components **require purging with 100 % welding grade argon or 100% N_2** until at least the root and hot pass have been deposited. Both gases provide adequate shielding. Purge dams and fixturing should be able to accommodate temperatures up to 300^{o}C (~< 600 ^{o}F) to ensure equipment operability and maintenance of a proper purge, given the elevated preheats.

Heat inputs are typically maintained on the lower end of the process's usable range with bead shape being of primary importance. Successful manual procedures rarely exceed 25 to 30 KJ/in (~ 10 to 12 KJ/cm), FCAW and SAW may approach 55 KJ/in.

Extreme care must be observed during fabrication (lifting, handling, fixturing, etc.) to avoid applying unnecessary bending stresses or loading to weldments that have not seen PWHT!

7.7 Hardness Control

Certain system applications have maximum hardness limitations. This is particularly true in systems where hydrogen sulfide is present. Maximum values of 235 BHN are not uncommon. The Grade 91 welding alloys, after typical 2-hour post weld heat treatment, may exceed such values. 210 to 240 BHN are common for SMAW, while 230 to 270 are seen for GTAW, SAW and FCAW. However, by selective application of elevated PWHT time and temperature (Figure 13), control of bead shape during welding (Figure 15) to enhance interbead tempering or softening and specifying weld metal composition limitations (Figure 10, Table 8) that enable use of elevated PWHT temperatures, lower hardness can be achieved in the weld deposit.

8.0 WELD METAL AVAILABILITY and PROCUREMENT

8.1 Availability

It was not until 1996 that a recognized national code included specifications for the Modified 9Cr-1Mo welding alloys. Subsequent to these specifications, users referred generically to the material as “505 Modified” or “P/T91”with respect to the standard 9Cr-1Mo composition which was classified as “505” material. In fact, the “505” requirements were included in the stainless steel specifications – a situation that is being remedied upon future specification revisions.

The American Welding Society amended specifications A5.5 (low alloy steel coated electrodes) and A5.28 (low alloy steel solid wires for gas shielded welding) to accommodate this alloy and assigned the “-B9” designation to certain 90-series filler metals. Specification A5.23-97 (low alloy steel wire and flux for SAW) has been revised and includes data for the “EB9” composition. Table 3 provides summary data on the base metal and various weld filler compositions.

Flux core or metal core fabricated wire products do not currently have an AWS classification and must be ordered to a “G” classification under A5.29 or A5.28, respectively, or by trade name and a specified chemistry and mechanical property criteria.

8.2 Procurement

All material should be procured to a recognized specification. Where commercial or technical criteria prevent direct reference to an existing specification, the nearest specification should be used and augmented, as necessary, to provide accurate communication between the user and supplier.

Recognized domestic weld filler metal specifications for P91 welding consumables are provided in Table 17. Note that specific classifications are not provided for P91 FCAW weld metal and that such material would have to be procured under a “G” classification; i.e. the properties and composition are agreed upon between the user and manufacturer. This situation is due to the fact that FCAW wires have not been commercially available until recently.

In the case of –B9 consumables, the user needs to know what they are depositing. A typical test certificate or certificate of conformance may accompany the product, but it would not necessarily represent testing done on the exact lot delivered. The certificate would only indicate that the product supplied meets the requirements for classification such as E9015-B9 in accordance with AWS A5.5. Whether the actual product delivered was actually tested or not remains uncertain. Whether the product will deposit a weld metal that exhibits toughness at room temperature or will not be adversely affected by PWHT is unknown. Therefore, what was required for the application may or may not be what is delivered!

For weld metal, AWS A5.01 “Filler Metal Procurement Guidelines” provides an excellent means for organizing the procurement of both standard and special welding consumables. For example, crater cracking and other undesirable grain boundary phenomena can be minimized by specifying weld metal with low residual element content (X Factor < 15) while nil ductility concerns for SMAW can be addressed by specifying toughness testing on a per lot per size basis.

By using the AWS A5.01 standard, the purchaser can specify a lot class, C1. Then, the purchaser can further specify schedule K testing and even with the use of an actual specified WPS. This higher level of testing ensures that there will be little room for statistical uncertainty in the weld deposit and it will be a certifiable result rather than a prediction based on another lot of material.

The standard also provides detailed definitions and criteria for items including dry batch, dry blend, wet mix, heat, heat number, controlled chemical compositions and lot classification for covered electrodes, bare wires, cored electrodes, and fluxes in addition to specifying the level of testing schedules shown here.

Further, ordering covered electrodes (SMAW)to "H4", FCAW and SAW (flux) to “H5” moisture criteria also reduces the potential for hydrogen or moisture related phenomena. Consumables must be stored and handled to avoid moisture pick-up. This typically requires using holding ovens for storing open containers of SMAW electrodes and SAW fluxes. Where controls are difficult to implement, such as in field operations, consumable packaging should be selected to minimize waste or storage issues; e.g. size SMAW or FCAW packaging for the amount that can be used in one-half shift, etc.

While obtaining material with “G” classifications makes some users apprehensive concerning what they are actually receiving, A5.01 provides a means with which to specify exactly what is required. Assuming that the supplier complies with the specified requirements, one actually has more assurance of receiving the proper material than if they just order a commodity product manufactured in accordance with a standard AWS classification and hope that it will meet their requirements!

Since A5.01 is a recognized ANSI/AWS standard and an ASME adopted standard as SFA 5.01, it also provides an excellent means for communicating with filler metal producers worldwide. By using and including the information outlined in the suggested procurement detail form(s), translation of important details becomes easily referencable to the base specification. Therefore, both parties have a basis for understanding and translating what product and requirements are specifically required.

It should be pointed out that even though the methodology of A5.01 is implemented, confusion may still exist because of non-domestic nomenclature or test standards referenced on test certificates. Table 18 illustrates a comparison between domestic and European test certificate approvals and what they actually include or represent.

Table 19 provides procurement information in the format recommended in A5.01. (31)

Table 17. P91 Weld Metal Specifications (Domestic) (22)

Process	AWS Specification	Classification (s)
SMAW	A5.5-96	E9015-B9,E9016-B9,E9018-B9,E90XX-G*
SAW	A5.23-97	EB9,EG*
GTAW/GMAW	A5.28-96	ER90S-B9, ER90S-G*, E90C-G*
FCAW	A5.28-96	E90C-G*
FCAW	A5.29-XX (Draft)	E101T1-B9 (pending)
All	None	"505 Modified" –G*

*The "-G" classification is utilized to procure P91 material to an internal corporate specification or to obtain material that is similar to an AWS classification but has one or more elements outside the listed AWS composition range. For example, there is no current specification for P91 FCAW wire. Therefore, the material must be ordered as "505 Modified", to a corporate specification or manufacturers brand.

Table 18. Comparison of Test Certificates (32,37))

Certificate Comparison	
USA	European [EN 10205]
Certificate of Conformance (C of C) [no testing required]	"2.1" [no testing required]
Typical [once per year or per the manufacturers program]	"2.2" [statistical annual average or per the manufacturers program]
Certified Material Test Report (CMTR) [based on ACTUAL testing]	"3.1b" [based on ACTUAL tests]

Table 19. Example AWS A5.01 Procurement Specification Guideline Outline. (31)

Guideline Procurement Specification (Ref. AWS A5.01-93)				
I. General				
[Suggested Procurement Detail Form	[Table A2]	[Table A1]	[Table A4]	[Table A3]
A. Quantity	100 lbs.	1,089 lbs.	1,100 lbs.	660 lbs.
B. AWS Specification	A5.28	A5.5	A5.23	A5.29
C. AWS Classification	ER90S-B9	E9015-B9	EB9	"E101T1-B9" (-G) {pending}
D. Supplemental Designators	N/A	H4	N/A	H4
E. Diameter	3/32" (2.4mm)	3/32" (2.5mm)	3/32" (2.4mm)	0.045" (1.2mm)
F. Length	39" (1000mm)	14" (350mm)	N/A	N/A
G. Unit Package Type and Weight				
1. Carton		33 lbs.(15 kg)		
2. Can				
3. Other	11 lbs. (5kg)		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. Impring / Marking	Heat No. & Classification	Lot No. & Classification	Label w/Heat No. & Classification	Label w/Lot No. & Classification
B. Stamping or Tagging	Stamp	Stamp	Label	Label
C. Report Tensile/Yield Strength	Yes	Yes	N/A	Yes
D. PWHT: 760^{0}C , 2 hrs. min.	Yes	Yes	N/A	Yes
E. Report Toughness @ Temp.	N/A	Yes @ 72^{0}F	N/A	Yes @ 72^{0}F
F. X-Factor (Bruscato Number)	< 15	< 15	< 15	< 25
G. CMTR or "3.1B" Required	Yes	Yes	Yes	Yes

Notes:

a. H4, Optional Diffusible Hydrogen Designator, indicates that the diffusible hydrogen in the deposited weld metal did not exceed 4.0 mL/100g when tested in accordance with AWS A4.3 and A5.5 specifications.

b. Where [-G] designation is used in the classification, chemical composition of the electrode shall be as agreed to by purchaser and supplier. In this example, it is as follows: **(Some Users Request: Meets the mechanical requirements of E9015-B9 instead of "-G")**

C	0.07-0.13%	Cr	8.00-9.50%	Ti	<0.004%	Cu	<0.20%
Mn	1.25% max.	Ni	1.00% max.	As	<80ppm	N_2	0.03-0.07%
Si	0.20-0.50%	Mo	0.80-1.10%	Sb	<30ppm	Other	<0.50% Total
S	<0.010%	Nb	0.02-0.10%	Sn	<30ppm		
P	<0.010%	V	0.15-0.25%	Al	< 0.04%	**Mn + Ni = 1.5% max.**	

8.3 CODE APPROVALS

8.3.1 American Welding Society

The EPRI work has attracted the attention of the AWS Filler Metal Committee. Given the availability of commercial products, consideration has been given to incorporate specifications for the respective filler metals in A5.5 (low alloy SMAW), A5.23 (low alloy SAW wires &– metal core) and, A5.28 (low alloy solid and metal core) to include "-B9" classifications. EPRI, Metrode, work of others and demand for FCAW has attracted the attention of the AWS Filler Metal Committee. Efforts are being accelerated to incorporate criteria for a "-B9" classification into A5.29 (low alloy flux core). A revision that incorporates FCAW criteria has passed in committee and is expected to be issued late 2001 or early 2002.

8.3.2 ASME (32)

Although approval and incorporation into ASME Section II, Part C, Welding Rods, Electrodes, and Filler Metals, typically lag AWS approvals, once included, they typically mirror the AWS filler metal requirements. This is the case for the Grade 91 Consumables.

It should be noted that it is not unusual for Code Cases to be issued to cover new base materials (ASME Section II, Parts A and B) far ahead of weld filler metal development or code acceptance. The Grade 91 materials offer a primary example.

8.3.3 ISO

A new ISO standard, No. 14344, is in the approval process. This international standard incorporates A5.01 nearly in its intirety as the means for communicating procurement information on a global basis.

9.0 CONCLUSIONS

Thousands of tons of P91 materials are in use worldwide. The two major reasons cited by domestic fabricators and end users for not using the P91 Modified material are being addressed or will be in the future. These reasons include:

- All welds require post weld heat treat, regardless of thickness or diameter
- Installation and heat treatment of dissimilar weldments (e.g., P22 to P(T)91) can be complex in either shop or field applications.

However, this situation is changing at a rapid rate in the USA. Designs for retrofits and new installations, particularly cogeneration units, are using P(T)91 as the material of choice. Key to successful fabrication of this material are the following criteria:

- ***P(T)91 should not be treated as just another CrMo steel***. The alloy requires considerable care during joining to assure acceptable long term properties.

- **PWHT is one of the single most important factors in producing satisfactoryweldmentsinP(T)91 materials. The PWHT methodology and implementation must be verified to ensure that the weldments are ACTUALLY receiving PWHT at the proper temperature. Additional thermocouples or qualification testing are encouraged.**

PWHT

- PWHT should be conducted for a minimum of two (2) hours at temperature on heavywall weldments, even for weld metal testing, to provide sufficient tempering. This is consistent with current manufacturing practice by major fabricators (domestic and European) of utilizing a minimum of 2 hours at temperature, regardless of thickness.
- PWHT on thin sections (< 10mm, 0.375 in.) can be satisfactory in as little as 15 to 30 minutes at 760C (1400F), provided the actual sequence is verified.
- P91 weld metal that is properly PWHT will normally exhibit a hardness range of 220 to 280 BHN, depending on welding process. When hardnesses below 220 or above 280 BHN are observed, further evaluation is warranted.
- Post bakes at temperature from preheat to 600F (300C) are needed prior to cooling when the weldment will cool to room temperature prior to PWHT. PWHT temperature should range from 745 to 760 ^{0}C (1375 to 1400^{0}F), with 760 ^{0}C (1400^{0}F) perhaps being optimum.
- In many cases, the test coupon preheat, PWHT and monitoring may be conducted under ideal conditions such as in a laboratory oven. Shop and field operations do not typically enjoy this level of control. Thus, to rely soley on the fact that a welding procedure has been "qualified", may in no way guarantee or represent that actual operations will be conducted in a similar manner.
- For PWHT operations, the importance of thermocouple placement, number of thermocouples, and redundancy cannot be over emphasized. This is especially true where complex shapes, dissimilar thicknesses, chimney/position effects, hot/cold spots in ovens and potential thru-wall thermal gradients are encountered. Single point monitoring is typically unacceptable. Where access to the ID is possible, monitoring for unacceptable thermal gradients should be accomplished.
- It is well known that thermal gradients will exist on weldments when applying preheat and postweld heat treatment. As diameter and thickness increase, so will the thermal gradient. When monitoring temperature from the outside of a pipe weldment, such gradients may be acceptable for some alloys, but not for Grade 91.

Dissimilar Welding

- Improvement of the HAZ from butter PWHT's has the ability to offer a projected service life of approximately 350,000 hours.
- Conducting PWHT at 732^{0}C (1350^{0}F) versus 677^{0}C (1250^{0}F) on E9018-B3 for DMW's resulted in substantially better projected service life.
- EPRI work has shown that use of E9018-B3 weld metal for P91 to P22 DMW's is both prudent and sufficiently adequate.

- Estimated life was improved considerably for DMW's where P91 was buttered with E9018-B3, the butter subjected to a PWHT 760^{0}C (1400^{0}F), then the final weld completed to the P22 followed by PWHT at 677^{0}C (1250^{0}F) to 704^{0}C (1300^{0}F).
- In most cases, use of the lower strength weld metal is recommended. PWHT temperatures, particularly where B9 weld metal is involved, are selected to provide proper tempering of the weld metal. These temperatures may not necessarily coincide with traditional code values and may require specific knowledge of the transformation temperatures or special properties of the materials involved and additional welding procedure qualifications. For example, ENiCrMo-3 ("625") should NOT be used because it will embrittle at the PWHT temperatures required for Grade 91

<u>Filler Metal Procurement</u>

- Use of A/SFA 5.01 provides an excellent means for specifying the technical requirements needed for proper procurement of consumables for P(T) 91 weldments.
- Crater cracking and other undesirable grain boundary phenomena can be minimized by ordering weld metal with low residual element content (X Factor < 15; using a –15 or –16 coating), observing a Mn/S ratio greater than 50, plus strict adherence to preheat and interpass temperature controls. Ordering covered electrodes to "H4" or SAW fluxes to H5 moisture criteria is also recommended to reduce the potential for hydrogen or moisture related phenomena.
- Ordering covered electrodes (SMAW)to "H4", FCAW and SAW (flux) to "H5" moisture criteria also reduces the potential for hydrogen or moisture related phenomena. Consumables must be stored and handled to avoid moisture pick-up. This typically requires using holding ovens for storing open containers of SMAW electrodes and SAW fluxes. Where controls are difficult to implement, such as in field operations, consumable packaging should be selected to minimize waste or storage issues; e.g. size SMAW or FCAW packaging for the amount that can be used in one-half shift, etc.
- SMAW and FCAW electrodes should undergo actual chemical and mechanical testing on a per lot per size basis to verify properties. A satisfactory chemical analysis does not guarantee acceptable mechanical properties, especially toughness.
- Testing and reporting actual chemical analysis for GTAW and SAW bare wires is normally satisfactory.
- P91 weld filler metals should be procured with a maximum Ni + Mn of 1.5 to insure that PWHT can be conducted without fear of exceeding the lower critical transformation temperature of the weld metal. Thus, the actual level of Ni and Mn must be known.
- All welding consumables should be ordered with CMTR's or EN10204 3.1B's on a per size per lot basis to ensure that the actual composition and/or

mechanical properties are known to avoid compromising the integrity of weldments by subsequent heat treatment operations.

Mechanical Properties

- Although not required in the traditional piping codes, having some level of toughness is important for start-up/down and hydro testing. Current procurement specifications of some fabricators and OEM's require at least 17 to 20 ft-lbs. at room temperature.
- The transition temperature of Grade 91 weld metal is near room temperature. Toughness results improve when tests are conducted at 22-23C (72-74F) versus 20C (68F).
- Lower hardness can be achieved in the weld deposit by selective application of elevated PWHT time and temperature, control of bead shape during welding to enhance interbead tempering or softening and specifying weld metal composition limitations that enable use of elevated PWHT temperatures.

Fabrication Requirements

- Where thermal straitening or other bending operations are implemented, caution must be observed to not encroach on the lower critial (AC1) temperature of the materal. If this is exceeded, the component must again be normalized and tempered. Some authorities make these additional heat treatments mandatory for P(T)91.
- All processes are available plus an FCAW wire with satisfactory and reproduceable mechanical properties, including operation with both $ArCO_2$ (80-20, 75-25) mixtures or 100% CO_2 shielding gas.
- Inert gas purging is mandatory. Either argon or nitrogen may be used successfully.
- Interruption of preheat should be avoided during welding. If required, a post bake operation is adviseable.

Further investigation should include gathering additional service experience and creep data plus information and study related to dissimilar weldment design, implementation and performance.

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11.0 ACKNOWLEDGEMENTS

This paper would not have been possible without the technical assistance provided Kent Coleman and David W. Gandy at EPRI's Repair and Replacement Application Center in Charlotte, NC. Additional technical input and experimental results were also provided by: Mr. Roger A. Swain of Euroweld, Ltd.; Dr. Siegfreid Dittrich (retired, Thyssen Schweiâtechnik GMBH), Germany; Ian Barnes of I.A. Barnes Co., United Kingdom; Dr. C. Farrar, Dr. Z. Zhang, Graham Holloway and Adam Marshall of Metrode, Ltd., United Kingdom; Hermann Zentner, Consultant for Bavaria Schweiâtechnik, Germany; James W. Hales, Specialty Welding & Machining, Inc.; J. Franklin Turner, Electrode Engineering, Inc.; J.R. Scott, B.F. Shaw Co.; J. D. Duncan, H. Mantle and W. Spear, Bechtel Corporation; H. Clark and C. Patrick, Fluor-Daniel; and Randy Davis, Consultant.