Fabrication Considerations for Vanadium-Modified Cr-Mo Steel Heavy Wall Pressure Vessels

API TECHNICAL REPORT 934-B
FIRST EDITION, APRIL 2011

AMERICAN PETROLEUM INSTITUTE

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Downstream Segment

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Introduction

This document is intended as a best practice guideline to be used by fabricators, in conjunction with API 934-A, when constructing new heavy wall pressure vessels with vanadium-modified Cr-Mo steels intended for service in petroleum refining, petrochemical, or chemical facilities. These materials are primarily used in high temperature, high pressure services which contain hydrogen.

The document provides typical practices to be followed during fabrication based upon experience and the knowledge gained from actual problems that have occurred during the fabrication of vanadium-modified Cr-Mo steels.

Background

The use of chrome-molybdenum steel vessels in hydrogen service can be traced back to the mid 1920s in Germany where they were used for reactors in high pressure hydrogenation plants. These vessels were fabricated from 2.25 % to 3.8 % chrome-molybdenum alloys operating in the pressure range of 28 to 70 MPa (4000 to 10,000 psi). [1] These steels are now referred to as the "First Generation" technology and were in use until the mid 1960s. The steels have evolved with significant improvements in each generation that can be summarized as follows.

Second Generation (Mid 1960s to 1970s) The birth of modern hydroprocessing reactors manufactured from heavy wall 2$^{1}/_{4}$Cr-1Mo alloys with improved toughness (54 Joules at 10 ºC [40 ft-lbs at 50 ºF]), but with no particular temper embrittlement controls.

Third Generation (1970s to 1980s) Added J-factor limit of 180 to control temper embrittlement and developed improved toughness to 54 Joules at –18 ºC (40 ft-lbs at 0 ºF). Also, began step cooling tests with varying criteria, and precautions against weld overlay disbondment.

Fourth Generation (1980s to 1990s) Improved temper embrittlement control by lowering J-factor limit to 100 and achieving better results after step cooling. This generation also had toughness improvements to 54 Joules at –32 ºC (40 ft-lbs at –25 ºF)

Today "Fifth Generation" grades [2] of conventional 2¼Cr-1Mo steels have a 54-Joule (40 ft-lb) transition temperature typically lower than –40 ºC (–40 ºF), and even lower for conventional 3Cr-1Mo steels. Vanadium-modified Cr-Mo steels with 2$^{1}/_{4}$ % and 3 % Cr were introduced for service with higher strength levels and increased hydrogen attack resistance. These grades achieved a 54 Joule (40 ft-lb) transition temperature typically around –29 ºC (–20 ºF). The vanadium-modified steels also offered enhanced creep rupture properties, lower temper embrittlement susceptibility, and a much lower susceptibility to hydrogen disbonding of weld overlay compared with conventional Cr-Mo steels.

As of 2009, over four hundred vanadium-modified reactors have been fabricated around the world with many more under construction.

Fabrication Considerations for Vanadium-Modified Cr-Mo Steel Heavy Wall Pressure Vessels

1 Scope

This best practice report complements API 934-A and specifies additional fabrication considerations that should be observed when constructing a new heavy wall pressure vessel using vanadium-modified Cr-Mo materials intended for hydrogen service at elevated temperature and pressure. It applies to vessels that are designed, fabricated, certified and documented in accordance with ASME Code Section VIII, Division 2, including Paragraph 3.4 of the ASME Code, Supplemental Requirements for Cr-Mo Steels and ASME Code Case 2151, as applicable (or equivalent international codes).

Nominal material chemistries covered by this report are the vanadium-modified steels including 2$^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V, 3Cr-1Mo-$^{1}/_{4}$V-Ti-B, and 3Cr-1Mo-¼V-Cb-Ca steels. The interior surfaces of these vessels may have an austenitic stainless steel cladding or weld overlay to provide additional corrosion resistance.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Recommended Practice 582, *Welding Guidelines for the Chemical, Oil, and Gas Industries*

API Recommended Practice 934-A, *Materials and Fabrication Requirements for 2 $^{1}/_{4}$Cr-1Mo & 3Cr-1Mo Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service*

API Recommended Practice 941, *Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*

ASME *Boiler and Pressure Vessel Code* [1], *Section II, Materials, Part A, Ferrous Material Specifications*

ASME *Boiler and Pressure Vessel Code, Section II, Materials, Part C, Specifications for Welding Rods, Electrodes and Filler Metals*

ASME *Boiler and Pressure Vessel Code Section II, Materials, Part D, Properties*

ASME *Boiler and Pressure Vessel Code Section VIII, Div. 2 Rules for Construction of Pressure Vessels – Alternate Rules*

ASME SA 20, *Specification for General Requirements for Steel Plates for Pressure Vessels*

ASME SA 182, *Specification for Forged or Rolled Alloy Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service*

ASME SA 335, *Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

ASME SA 336, *Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts*

ASME SA 369, *Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High Temperature Service*

[1] ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.

ASME SA 387, *Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum*

ASME SA 435, *Specification for Straight-Beam Ultrasonic Examination of Steel Plates*

ASME SA 508, *Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels*

ASME SA 541, *Specification for Quenched and Tempered Carbon and Alloy Steel Forgings for Pressure Vessel Components*

ASME SA 542, *Specification for Pressure Vessel Plates, Alloy Steel, Quenched-and-Tempered, Chromium-Molybdenum, and Chromium-Molybdenum-Vanadium*

ASME SA 578, *Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications*

ASME SA 832, *Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum-Vanadium*

3 Definitions and Acronyms

3.1 Definitions

For the purpose of this report, the following definitions apply. Note that some of these definitions are also given in API 934-A and if there are any variations, the API 934-A definitions should be considered the industry standard. The definitions are repeated here for reader convenience.

3.1.1
advanced Cr-Mo steels
Family of alloys including both the vanadium-modified Cr-Mo steels and the enhanced Cr-Mo steels. The latter have their strength enhanced by special heat treatments.

3.1.2
ASME Code
ASME *Boiler and Pressure Vessel Code*, Section VIII, Division 2, including applicable addenda.

3.1.3
buyer
The firm or organization acting for and on behalf of the owner, who will issue the purchase order to design and fabricate the pressure vessels.

3.1.4
conventional Cr-Mo steels
Standard $2^1/_4$Cr-1Mo and standard 3Cr-1Mo steels, with no vanadium additions.

3.1.5
final PWHT
The last postweld heat treatment after fabrication of the vessel and prior to placing the vessel in service.

3.1.6
hot forming
Mechanical forming of vessel components above the final PWHT temperature (but typically >900 ºC [>1650 ºF] for these alloys).

3.1.7
Larson-Miller Parameter
Formula for evaluating heat treatments

$$LMP = T\,(20 + \log t)$$

where

T is temperature in degrees Kelvin (K);

t is time in hours (hr).

3.1.8
maximum PWHT
Specified heat treatment of test specimens used to simulate all fabrication heat treatments including austenitizing and tempering, all intermediate heat treatments above 482 °C (900 °F), the final PWHT, a PWHT cycle for possible shop repairs, and a minimum of one extra PWHT cycles for future use by the owner.

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller Parameter formula may be used; results to be agreed upon by purchaser and manufacturer.

3.1.9
minimum PWHT
Specified heat treatment of test specimens used to simulate the minimum heat treatment (austenitizing, tempering and one PWHT cycle, and ISR above 482 °C [900 °F]).

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller Parameter may be used; results to be agreed upon by purchaser and manufacturer.

3.1.10
owner
The firm or organization that will own and operate the pressure vessel.

3.1.11
seller
The successful bidder, the firm or organization receiving the purchase order to design and fabricate the pressure.

3.1.12
step cooling heat treatment
Specified heat treatment of test specimens used to simulate and accelerate embrittlement of test specimens for the purpose of evaluating the potential for temper embrittlement of alloy steels in high-temperature service.

3.1.13
sub-supplier
The firm or organization, acceptable to the buyer, which supplies materials and/or services to the seller in conjunction with design or fabrication of the pressure vessel.

3.1.14
vanadium-modified Cr-Mo steels
$2^1/_4$Cr-1Mo-$^1/_4$V, 3Cr-1Mo-$^1/_4$V-Ti-B, and 3Cr-1Mo-$^1/_4$V-Cb-Ca steels, with no vanadium additions.

3.2 Acronyms

For the purpose of this practice, the following acronyms apply:

CMTR certified material test report

DHT dehydrogenation heat treatment

FN	ferrite number
HAZ	heat-affected zone
HBW	Brinell hardness with tungsten carbide indenter
HV	Vickers hardness
ISR	intermediate stress relief
ITP	inspection and test plan
MDMT	minimum design metal temperature
MT	magnetic particle testing
NDE	nondestructive examination
PQR	procedure qualification record
PT	dye penetrant testing
PWHT	postweld heat treatment
RT	radiographic testing
UT	ultrasonic testing
WPS	welding procedure specification

4 Design and Fabrication

4.1 Background

Vanadium-modified 2^1/$_4$Cr-1Mo and 3Cr-1Mo alloys used for the fabrication of heavy wall pressure vessels offer definite advantages over conventional Cr-Mo alloys. The advantages include increased resistance to hydrogen attack, a lower susceptibility to hydrogen embrittlement, increased resistance to weld overlay disbonding, and higher strength providing thinner and lighter vessels. The vanadium-modified alloys are almost always supplied in the quenched and tempered condition. Typically when the thickness is above about 100 mm (4 in.), tempering temperature is below the final PWHT temperature. Both the conventional and vanadium-modified Cr-Mo steels are usually specified to be vacuum degassed with low tramp element levels.

The vanadium-modified alloys with improved properties have some less desirable fabrication considerations. The materials tend to exhibit characteristics such as higher hardenability which results in higher hardness in all areas around welds (weld, base metal, and heat affected zone), and the requirement for higher postweld heat treatment (PWHT) temperatures. The vanadium-modified alloys are also known for reduced notch toughness at lower temperatures in the as-welded condition, and thus require intermediate stress relieve (ISR) rather than dehydrogenation heat treatment (DHT) in restrained and highly stressed joints, such as nozzle-to-shell, nozzle-to-head welds and weld deposits for support rings and pads. Inadequate PWHT holding times can also leave welds with unacceptable low toughness areas.

Overall, vanadium-modified 2^1/$_4$Cr-1Mo and 3Cr-1Mo alloys offer considerable advantages over conventional Cr-Mo alloys provided they are constructed with extra care by a quality-focused and informed fabricator.

4.2 Identified Fabrication Problems

Vanadium-modified steels require additional considerations that need to be implemented during fabrication. The purpose of this document is to assist fabricators in successfully fabricating with vanadium-modified steels. This section lists some problems that have been encountered by different fabricators in the past during the course of fabricating with vanadium-modified steels and it is the intent of this document to inform the readers of these problems so that steps can be taken to ensure that they are not repeated.

4.2.1 Preheat and Interpass Temperature

It cannot be emphasized enough that correct preheat and interpass temperatures are extremely crucial when fabricating with vanadium-modified steels, even more so than for conventional Cr-Mo steels (although they are crucial for those alloys also). The preheat and subsequent interpass temperatures should be constantly monitored to ensure that the correct preheat is maintained. Too low a preheat or an interruption of preheat may cause cracking and this is a common cause of problems encountered during fabrication with vanadium-modified steels. A comprehensive fabrication plan should include preheat, the method of preheat application, and the method for monitoring preheat.

The maximum interpass temperature will vary based on the welding process and specific brand of filler metals. The limits range from as low as 230 ºC (445 ºF) to about 300 ºC (570 ºF) and in some cases on thinner plates, it results in the need to pause the welding. Also, on thinner plates, it can be important to measure the interpass temperature in the groove with digital thermometers rather than using tempil sticks on the surface. While large thickwall equipment like reactors usually have no problems with staying below the maximum interpass temperature, smaller, thinner components such as exchangers sometimes need a pause between passes to meet this requirement. See also 4.2.5.2.

4.2.2 Cutting

If flame or arc cutting is performed on vanadium-modified materials, the area to be cut should be properly preheated and the heat affected zones should be removed by grinding or machining. Experience indicates that about 3 mm (1/8 in.) of material should be removed for flame cutting and 1.5 mm (1/16 in.) for plasma cutting. Due to the extent of material removal, preparation by machining is recommended following all thermal cutting operations, with subsequent grinding. These steps should be followed by MT or PT.

4.2.3 Forming

The subject of forming has been a controversial issue with some fabricators. Apart from "hot" forming above the Ac_3 upper transformation temperature (above 900 ºC [1650 ºF]) which requires subsequent reheating and subsequent quenching and tempering, some fabricators take advantage of "cold" forming or forming below 480 ºC (900 ºF) to maximize the rolling effect of their rolls (this is also called warm forming). This is not to be confused with forming at ambient or near-ambient temperatures which can also be referred to as cold forming.

Cold forming or cold rolling vanadium-modified materials at ambient temperatures are not typically recommended, and a minimum through-thickness preheat temperature of 150 ºC (300 ºF) is typically used for all forming operations. This can be a challenge for some fabricators. However, if an adequate preheat is not used during cold forming or rolling, the fabricator runs the risk of cracking during the rolling operation and possibly the risk of catastrophic cracking through the entire plate width. 100 % MT inspection after forming should be specified when cold forming is carried out (and is required by API 934-A). Prior to cold forming, a forming procedure should be developed covering the plate edge preparation, preheating, forming steps and post heating.

4.2.4 DHT versus ISR

The question of DHT versus ISR comes up on every project. When fabricating with vanadium-modified steels, DHT should only be considered for non-restrained joints such as longitudinal and circumferential seams. In these cases DHT needs to be carried out at the appropriate temperature for the appropriate time. ISR is mandatory for restrained joints such as nozzle welds in shells or heads, internal beam support weld build ups and for other joints which are highly stressed during fabrication.

There have been multiple instances reported where a DHT was given in lieu of an ISR on restrained welds with the result of weld cracking. Some fabricators insist that DHT for welds in lieu of ISR is acceptable based upon their past experience. It should be remembered that driving out hydrogen from a weld is only half of the story. As-deposited Cr-Mo welds can have very low toughness, as indicated in Figure 1 and any flaw in the weld metal has the potential for generating cracks as the welded section cools to ambient conditions, or during subsequent handling at ambient temperature. The DHT specified in API 934-A for vanadium-modified steels is 350 ºC (660 ºF) for four hours minimum.

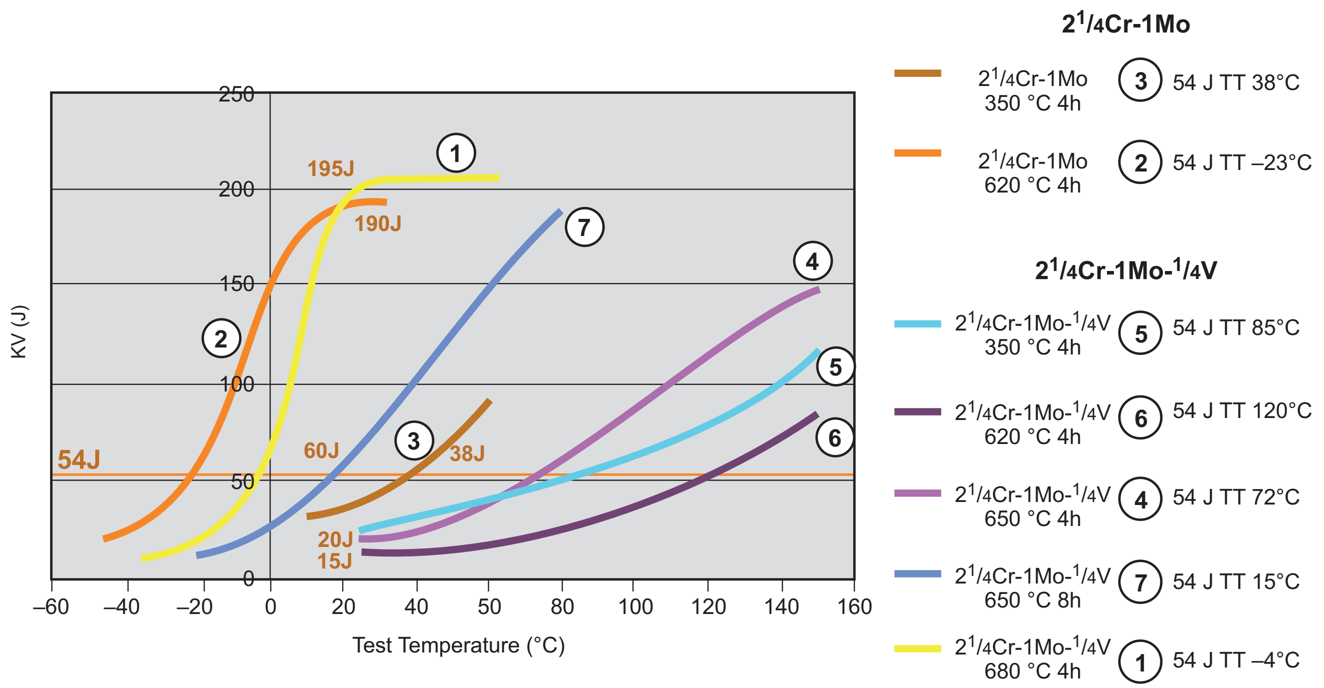


Figure 1—Charpy V-Notch Toughness of Conventional and Vanadium-modified 2 1/4Cr-1Mo Deposited Weld Metal after DHT and ISR Heat Treatment [13]

ISR should also be done at a minimum temperature of 650 ºC (1200 ºF) for four hours minimum or 680 ºC (1250 ºF) for two hours minimum as specified in API 934-A. The purposes of ISR are twofold; it reduces residual weld induced stresses, and improves the weld's toughness properties for handling prior to PWHT. Insufficient ISR hold time for vanadium-modified steels can result in insufficient residual weld stress reduction and low weld metal toughness which can manifest in subsequent cracking from stress raisers such as weld flaws.

It is important to maintain preheat temperature after welding up to the DHT or ISR operation. Some problems have been reported when the welded component has been permitted to cool below the preheat temperature following welding before being transported to the furnace to receive an ISR. Logistical problems can and sometimes do occur in getting a welded component into a furnace for ISR. For this reason, it is necessary to carefully plan not only all fabrication steps but also the necessary logistic steps to make sure that the component can be transported to the furnace and the furnace can be fired prior to the component cooling below the preheat temperature. Some fabricators perform a DHT after welding and before ISR to minimize the risk of problems during transporting to the furnace.

4.2.5 Examples of Past Problems

4.2.5.1 Reheat Cracking of SAW Welds

During the first half of 2008, multiple reactor fabricators experienced cracking in SAW welds made with filler metals from two different suppliers. Filler metals from a third supplier did not experience these issues. The cracking affected numerous welds on more than 30 reactors, causing many repairs, delays and cost overruns on the projects. [18] The cracking only occurred after a heat treatment cycle such as ISR or heating for rerolling, and was determined to be reheat cracking from various laboratory failure analyses.

All types of SAW welds were affected, including circumferential, longitudinal, head meridian and nozzle welds. The cracks were transverse to the welds in weld metal and were very small with heights and lengths of 2 mm through 10 mm. They were at scattered depths throughout the welds, and often occurred in clusters with a row of parallel cracks at the same depth.

The filler materials from the one supplier which did not experience this problem use a different manufacturing method (bonded flux) compared to those which experienced the cracking which were agglomerated fluxes. As a result, some of the steps used by bonded flux manufacturer to minimize the risk of reheat cracking (they have published tighter vanadium and oxygen ranges in the weld deposits which provide added resistance), could not be used by the agglomerated flux manufacturers. [19, 20, 21]

The root cause was eventually found to be a subtle change in one of the raw materials used for manufacturing the flux, which led to ppm levels of lead and bismuth in the deposited welds causing the cracking. For these contaminants, the researchers found that the acceptable levels were: [22]

$$K_{factor} = Pb + Bi + 0.03Sb < 1.5 \text{ ppm}$$

One screening test which showed whether a given wire/flux combination would be susceptible to reheat cracking due to any of the various contaminants or factors, was found to be Gleeble testing which is a high temperature tensile test with a specified strain rate. [21, 22]

The cracks required special ultrasonic test procedures to be detected, especially to ensure that the entire thickness was thoroughly inspected. These procedures have been added as an Addendum to API 934-A. [14] Many owners are now specifying Gleeble or similar testing, along with the special UT inspection, to minimize the risk of reheat cracking and to ensure detection of similar reheat cracking if this occurs again in the future. There are also joint industry participation (JIP) research projects in progress to refine the screening tests methods and research further metallurgical studies.

4.2.5.2 Wire/Flux Combination

There has been a reported case where a weld material manufacturer made slight changes to his flux composition without renaming the flux and without notifying the buyers who had previous qualifications made on the manufacturer’s old wire/flux combination. Serious weld cracking occurred due to this change in flux chemistry and caused significant delays in the project while the vessel fabricator and the steel manufacturer determined the cause of the problem.

This example illustrates that vanadium-modified steels are very sensitive to wire/flux combinations. Fabricators need to be vigilant and cognizant of any changes or improvements made by the wire/flux manufacturer and procedures need to be requalified when any changes are made to the wire/flux combination.

4.2.5.3 Exceeding Interpass Temperature Limits

Having too high of an interpass temperature has led to cases of low toughness on welding procedure qualification testing and on production test plates. This is especially a concern on thinner walls, which are typically used for heat exchangers. The maximum interpass temperature should meet the filler metal supplier’s recommended limit which varies by welding process as discussed in 4.2.1. Also, in some cases, it is important to measure the interpass temperature in the groove with digital thermometers rather than using tempil sticks on the surface. Pausing between passes was needed in some cases.

4.2.5.4 Cracking Due to Low Toughness After DHT

One case history of cracking during fabrication occurred when a catalyst dump nozzle cutout was machined through a beam seat weld buildup after it received a DHT. There were high localized weld stresses which were not relieved by the DHT. The as-deposited weld buildup had a very low toughness since it had not yet been postweld heat treated. The design of the reactor catalyst dump nozzle elevation was not optimum, as the nozzle cutout should not have penetrated the weld buildup (however, there are numerous designs where this cannot be avoided). Upon completion, the cutout became a significant stress raiser which resulted in a full circumferential crack in the beam seat weld buildup. To rectify the situation, the weld buildup had to be removed, rewelded and given an ISR.

4.2.5.5 Single-Wire SAW—Tempering and Grain Refinement

Poor weld toughness after PWHT was encountered by a fabricator using a single wire submerged arc welding (SAW) operation. The required weld metal impact toughness could not be achieved at one quarter of the weld thickness ($^1/_4T$) nor at 1.6 mm ($^1/_{16}$ in.) below the surface. Analysis by fractography indicated that regions of unrefined weld metal demonstrated poor toughness while refined regions demonstrated good toughness. The application of temper bead passes did not appear to be effective in improving surface toughness.

Deposited weld beads need to be relatively thin and flat to promote grain refinement during subsequent weld passes. The filler metal manufacturer's recommendation for maximum bead height should be followed and for SAW, the recommendations vary from 3 mm to 5 mm. With thicker beads, the amount of heat from subsequent passes appears to be insufficient to promote grain refinement, i.e. to re-crystallize previous passes, as the weld metal resists softening to produce the requisite tempering.

One suggestion, especially for less experienced fabricators, is that additional qualification impact tests be performed to verify that production welding will meet specification toughness requirements throughout the weld thickness. In addition to the specimens at $^1/_2$ thickness ($^1/_2T$), $^1/_4T$ and near surface specimens should be impact tested. When weld metal toughness problems occur, the solution may be to modify the welding parameters to achieve better grain refinement during the welding process.

The joint configuration can play a role in obtaining proper grain refinement. A narrow gap weld tends to give a uniform bead height and shape, and hence a uniform degree of grain refinement and tempering. For joints with a bevel angle, the placement of beads and the number of beads per layer can be critical.

4.3 Code References and Design Allowables

The need for higher design stress intensity values resulting in reduced wall thickness for reactors has been the driving force for the development of alternate vanadium-modified, enhanced strength materials. Table 1 indicates the relative tensile strengths and ASME VIII Division 2 design stress intensity values of the materials listed below along with other relevant data. The conventional and enhanced Cr-Mo alloys are included to facilitate comparison with the vanadium-modified Cr-Mo steels:

— conventional 2$^1/_4$Cr-1Mo alloy;

— enhanced 2$^1/_4$Cr-1Mo alloy (with strength enhanced through heat treatment);

— 2$^1/_4$Cr-1Mo-$^1/_4$V alloy;

— conventional 3Cr-1Mo alloy;

— 3Cr-1Mo-$^1/_4$V-Ti-B alloy;

— 3Cr-1Mo-$^1/_4$V-Cb-Ca alloy (Code Case 2151).

4.3.1 2$^1/_4$Cr-1Mo-$^1/_4$V Alloys

Due to the vanadium addition and the subsequent increase in tensile strength, 2$^1/_4$Cr-1Mo-$^1/_4$V achieves the highest permissible design stress values of all of the Cr-Mo materials discussed (12 % increase at 454 ºC [850 ºF] and 39 % increase at 482 ºC (900 ºF) over conventional 2¼Cr-1Mo material). Vanadium addition increases the tensile strength, creep rupture strength and the hydrogen attack resistance of these alloys. Depending on the design temperature, use of these allowables may require extra design analysis and weld procedure qualifications with stress rupture tests (on both conventional and vanadium-modified 2$^1/_4$Cr-1Mo alloys) per ASME Section VIII, Division 2, paragraphs 3.4.4.5 and 5.5 and Annex 3.F, and Code Case 2605.

Table 1—Typical Properties of Materials of Construction [2]

Alloy Types	Conventional 2¼Cr-1Mo	Enhanced 2¼Cr-1Mo	2¼Cr-1Mo-¼V	Conventional 3Cr-1Mo	3Cr-1Mo-¼V-Ti-B	3Cr-1Mo-¼V-Cb-Ca
ASME Spec or Code Case	SA-336-F22, Cl.3 (F) SA-387-Gr.22 Cl.2 (P)	SA-508-22, Cl.3 (F) SA-542-B Cl.4 (P) Formerly Code Case 1960	SA-336 Gr. F22V(F) SA-541 Gr. 22V(F) SA-542-D Cl.4a(P) SA 832 Gr. 22V(P) Formerly CC 2098	SA-336-F21, Cl.3 (F) SA-387-Gr.21 Cl.2 (P)	SA-336-F3V (F) SA-542-C Cl.4a (P) Formerly Code Case 1961	SA-336-F3VCb (F) SA-542-E Cl.4a (P) Code Case 2151
ASME Div.2 Max. Allowed Temperature	649 ºC (1200 ºF)	454 ºC (850 ºF)	482 ºC (900 ºF)	649 ºC (1200 ºF)	454 ºC (850 ºF)	454 ºC (850 ºF)
Room Temperature Tensile Strength	515 - 690 MPa (75 - 100 ksi)	585 - 760 MPa (85 - 110 ksi)	585 - 760 MPa (85 - 110 ksi)	518 - 690 MPa (75 - 100 ksi)	585 - 760 MPa (85 - 110 ksi)	585 - 760 MPa (85 - 110 ksi)
Room Temperature Yield Strength	310 MPa (45 ksi)	380 MPa (55 ksi)	415 MPa (60 ksi)	310 MPa (45 ksi)	415 MPa (60 ksi)	415 MPa (60 ksi)
Design Stress Intensity Value ASME Div.2 (Note 2)	151 MPa @ 454 ºC (21.9 ksi @ 850 ºF) 117 MPa @ 482 ºC (17.0 ksi @ 900 ºF)	151 MPa @ 454 ºC (21.9 ksi @ 850 ºF) N/A @ 482 ºC (N/A @ 900 ºF)	199 MPa @ 454 ºC (28.9 ksi @ 850 ºF) 164 MPa @ 482 ºC (23.8 ksi @ 900 ºF)	131 MPa @ 454 ºC (19.0 ksi @ 850 ºF) 90 MPa @ 482 ºC (13.1 @ 900 ºF)	178 MPa @ 454 ºC (25.8 ksi @ 850 ºF) 145 @ 482 ºC (21.0 @ 900 ºF)	164 MPa @ 454 ºC (23.8 ksi @ 850 ºF) N/A @ 482 ºC (N/A @ 900 ºF)
API 941 (Nelson Curve) Temperature Limit for >13.8 MPa Hydrogen Service	454 ºC (850 ºF)	454 ºC (850 ºF)	510 ºC (950 ºF)	510 ºC (950 ºF)	510 ºC (950 ºF)	510 ºC (950 ºF)

NOTE 1 (F) Forgings, (P) Plates

NOTE 2 Depending on the design temperature, use of these allowables may require extra design analysis and weld procedure qualifications with stress rupture tests per ASME Section VIII, Division 2, paragraphs 3.4.4.5 and 5.5 and Annex 3.F, and Code Case 2605.

4.3.2 3Cr-1Mo-$^{1}/_{4}$V Alloys

There are two 3Cr-1Mo-$^{1}/_{4}$V alloys similar in properties with minimum and maximum tensile strengths and minimum yield strengths of 585 MPa (85 ksi), 760 MPa (110 ksi), and 415 MPa (60 ksi), respectively. Both alloys are similar in composition with the exception being the 3Cr-1Mo-$^{1}/_{4}$V-Ti-B alloy, the former Code Case 1961, contains intentional additions of limited amounts of titanium and boron. The other alloy, 3Cr-1Mo-$^{1}/_{4}$V-Cb-Ca, Code Case 2151, contains limited amounts of columbium and calcium.

Both alloys utilize vanadium addition (nominal $^{1}/_{4}$ %) to enhance the materials' creep rupture strength and hydrogen attack resistance. Despite the vanadium addition; however, the maximum design temperature permitted by Section VIII, Division 2 of the ASME Code is 454 ºC (850 ºF) because experimental data suggests that these 3 % chrome alloys cannot meet the Section VIII, Division 2 creep rupture criteria at 482 ºC (900 ºF). The creep strength of these materials is lower than vanadium-modified $2^{1}/_{4}$Cr-1Mo. At 454 ºC (850 ºF), the vanadium-modified 3 Cr-1 Mo, alloys have approximately 9 % higher allowable stress intensity values than the conventional $2^{1}/_{4}$Cr-1Mo material.

The intentional addition of boron in the former Code Case 1961 material increases the hardenability of the material and assures uniform distribution of mechanical properties throughout the heavy cross sections. The addition of titanium helps to maximize the effect of boron. [4] The Code Case 2151 alloy utilizes columbium carbide, CbC, and minimizes reheat cracking by decreasing the intergranular microsegregation of sulfur. [5]

The Code Case 1961 alloy, now patented in the U.S., was developed in the early 1980s and was adopted as an ASME material in 1992. The first two commercial reactors were constructed for a client in Canada and went on stream in 1989. To date, some 50 commercial reactors have been built; however, none appear to be presently under construction. The 2151 material was accepted by ASME Code Case in April 1993 and to date five reactors have been built and none appear to be presently under construction. The same welding consumables are used for both types of materials and were developed by the same manufacturer.

4.4 Incorporation Into API 941

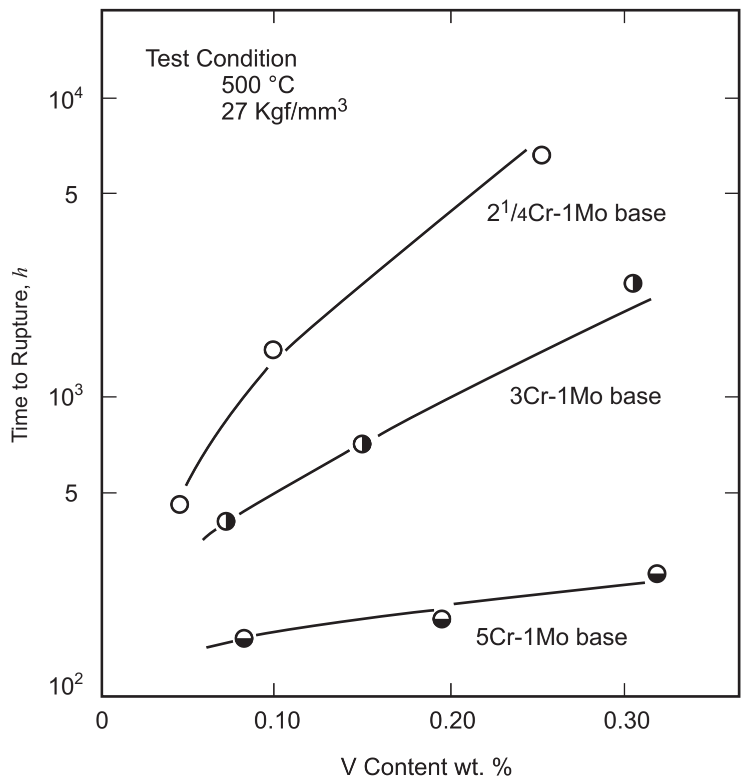
Hydroprocessor reactors generally operate in the temperature range of 400 ºC to 454 ºC (750 ºF to 850 ºF) with hydrogen partial pressures above 10 MPa (1450 psi), and API 941, *Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants* [6], is used to select materials with appropriate hydrogen attack resistance. Earlier versions of this recommended practice indicated that the materials of choice for the construction of these reactors, from hydrogen attack considerations, was $2^{1}/_{4}$Cr-1Mo steel or, in some cases, 3Cr-1Mo steel. As indicated earlier, $2^{1}/_{4}$Cr-1Mo alloy has been extensively used for the construction of hydroprocessing reactors up to the mid 2000s. The 3Cr-1Mo material has been used to a much lesser extent, when process conditions (i.e. the hydrogen partial pressure and temperature) resulted in a higher alloy steel being required.

In the late 1990s, the API 941 Committee placed $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V at the same level as the 3Cr-1Mo alloy on the API curves in terms of hydrogen attack resistance. This material has proven to have excellent resistance to hydrogen attack determined through extensive testing during the material's development phase. This resistance to hydrogen attack can be attributed to finely dispersed stable vanadium carbides which have a tendency to resist methane formation within the steel. Due to its excellent creep rupture properties and hydrogen attack resistance, this material is the only vanadium grade, low chrome material which is permitted to be used with design temperatures up to 482 ºC (900 ºF) with hydrogen partial pressures that are typical in hydroprocessing reactors.

API's recognition of the increased hydrogen attack resistance of $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V was a major turning point for industrial acceptance. Once the first reactor was built, others followed in quick succession. In 1996, the first $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V reactor was fabricated in Italy and shipped to India. Since that time and up to 2009, some 400 reactors have been fabricated using this material.

4.5 Additional Characteristics

Vanadium carbides in the newer vanadium steels result in improved high temperature strengths for these materials. Figure 2 indicates how vanadium addition enhances the creep rupture life of the 2$^1/_4$ % chrome steel to a greater degree than that for 3 % chrome and 5 % chrome steels. Additionally, the temper embrittlement susceptibility of vanadium-modified chrome moly steels is generally lower than that for the comparable conventional Cr-Mo steel. [7][8]



NOTE Test conditions 500 °C (932 °F), 27 kg/mm^2 (38,400 psi)

Figure 2—Vanadium Content versus Creep Rupture of Cr-1Mo-V Steels [9]

These new generation vanadium-modified 2$^1/_4$Cr-1Mo and 3Cr-1Mo steels exhibit superior resistance to disbonding than conventional Cr-Mo alloys. Extensive testing has shown, that under normal hydroprocessor operating conditions, disbonding is not expected to occur for the vanadium-modified alloys. [4][10][11] The lower susceptibility to disbonding has been attributed to the lower diffusivity of hydrogen in the vanadium steels caused by the hydrogen trapping effect of fine vanadium carbides.

The standard approach is to consider both plate and forgings for shell base metal up to about 250 mm (10 in.) wall thickness although historically forgings have been more economical in the thicker ranges. Many fabricators do not have the capabilities to form or roll plate greater than 152 mm (6 in.). If the raw material for forged rings and plate are sold on a near equal basis, then plate would be the more expensive option because of the additional cost to roll, reroll, weld, heat treat, and NDE the long seams.

4.6 Metallurgical Concerns During Fabrication

For successful fabrication using the vanadium-modified alloys, it is important to fully understand all the characteristics of the material including the ones that result in greater care being needed during fabrication.

4.6.1 Preheat and PWHT

The minimum preheat recommended by API 934-A [14] for the conventional Cr-Mo steels is 150 ºC (300 ºF) and a higher 177 ºC (350 ºF) for the vanadium-modified steels prior to and during all welding, rolling, thermal cutting and gouging operations. Preheat during welding is to be maintained until ISR or DHT is performed. Some fabricators use a higher preheat of 200 ºC (392 ºF) for the vanadium-modified materials.

As with preheat, the PWHT temperatures for vanadium-modified materials is slightly higher 705 ºC, ±14 ºC (1300 ºF ±25 ºF) than the PWHT temperature for conventional Cr-Mo steels 690 ºC, ±14 ºC (1275 ºF, ±25 ºF). The vanadium-modified weld metals have been formulated to meet the various required properties (strength, toughness, etc.) based on the thicker wall applications and hence are based on eight hours minimum PWHT. As a result, even the thinner components need to use PWHT times of eight hours minimum, even when this exceeds the required PWHT time based on thickness. This is addressed by API 934-A which requires eight hours minimum (some owners now require 10 hours minimum).

4.6.2 Hardness

The maximum hardness level usually specified for the base metal, weld metal and heat affected zones (HAZ) for the conventional Cr-Mo steels is 225 HBW and for the vanadium-modified steels is 235 HBW. This is required after minimum PWHT (one shop PWHT excluding future field PWHT cycles).

Figure 3 indicates the typical Vickers hardness (HV) values of conventional and vanadium-modified 2¼ Cr-1Mo alloys following DHT at 350 ºC (662 ºF) and ISR at 620 ºC (1150 ºF), 650 ºC (1200 ºF), and 680 ºC (1250 ºF) each for four hours and PWHT at 690 ºC (1275 ºF) and 705 ºC (1300 ºF) for eight hours. It can be seen that it is only after an eight hour PWHT did the typical hardness levels reduce to values less than or equal to the maximum permissible specified values of 225 HBW (236 HV) and 235 HB (247 HV), respectively, for the conventional and vanadium-modified Cr-Mo steels. (A longer PWHT hold time may be necessary to ensure that all hardness values meet the specification.)

4.6.3 Hydrogen and Residual Stress

The issue of DHT versus ISR can be a controversial one. For the submerged arc wire/flux combination used in the example outlined in Figure 4, the DHT reduces the hydrogen levels in the deposited weld metal to 0.02 ml/100 g of deposited weld metal and ISR reduced it to 0.008 ml/100 g. It can be argued that a DHT will suffice to remove hydrogen to safe levels to preclude hydrogen induced weld metal cracking upon cool down. An ISR not only provides greater weld metal hydrogen reduction, but it also helps to reduce localized weld induced stresses and improve pre-PWHT toughness as discussed in the next section.

4.6.4 Toughness

Hydrogen and residual stresses are only a part of the overall picture. Another important consideration is the toughness level of the deposited weld metal before and after DHT and ISR heat treatments. Excellent toughness is expected after PWHT with a minimum hold time of eight to ten hours, so this discussion is only applicable to the toughness at various stages during fabrication.

Different wire flux combinations provide different responses to heat treatments as indicated by the results from three wire manufacturers with their own specific wire flux combinations. Figure 1 shows the shift in transition curves following either a 4-hour DHT or a 4-hour ISR when performed at different temperatures on both conventional and vanadium-modified $2^1/4$Cr-1Mo deposited weld metal from the first of three wire manufacturers. It can be seen from these curves that a dehydrogenation heat treatment on the conventional Cr-Mo weld wire produces a notch toughness around 33 J (24.3 ft-lb) at 20 °C (68 °F).

Conversely, the notch toughness for the vanadium-modified wire after the same DHT is significantly (25 %) less, around 25 J (18.4 ft-lb), at 20 °C (68 °F). Figure 1 also shows that performing an ISR on the conventional Cr-Mo weld wire at 620 °C (1150 °F) for four hours will provide very good notch toughness results, yielding a 54 J (40.0 ft-lb)

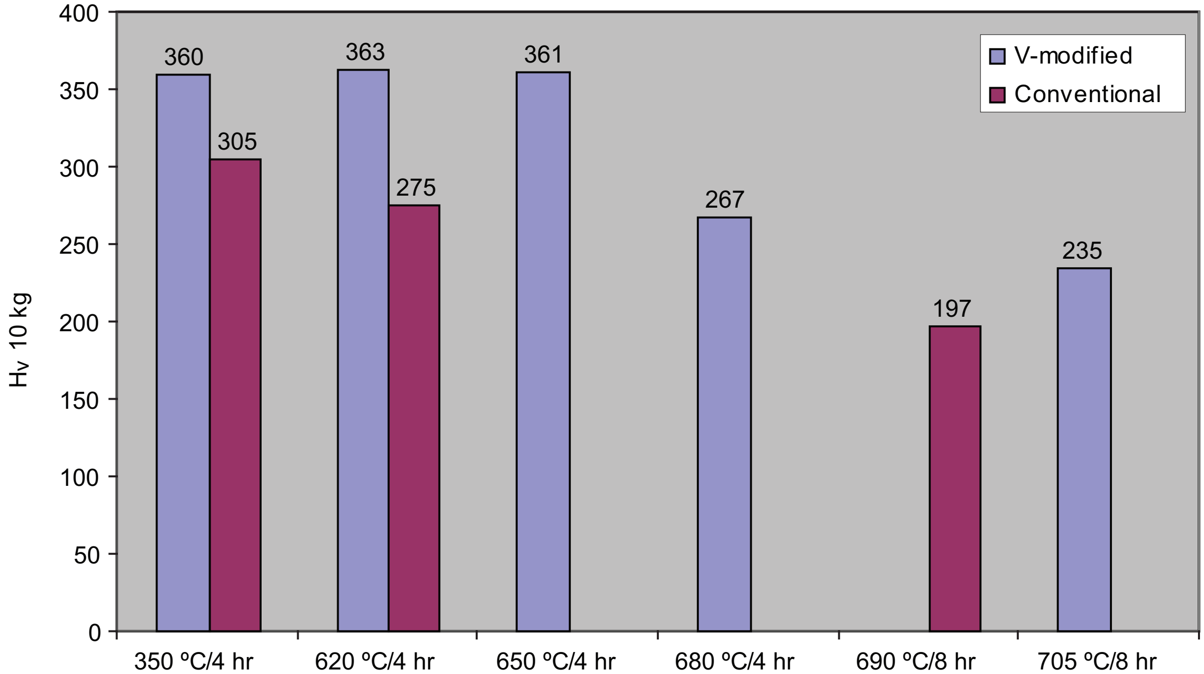


Figure 3—Typical Conventional and Vanadium-modified 2 1/4Cr-1Mo Weld Metal Hardness After Various Heat Treatments [13]

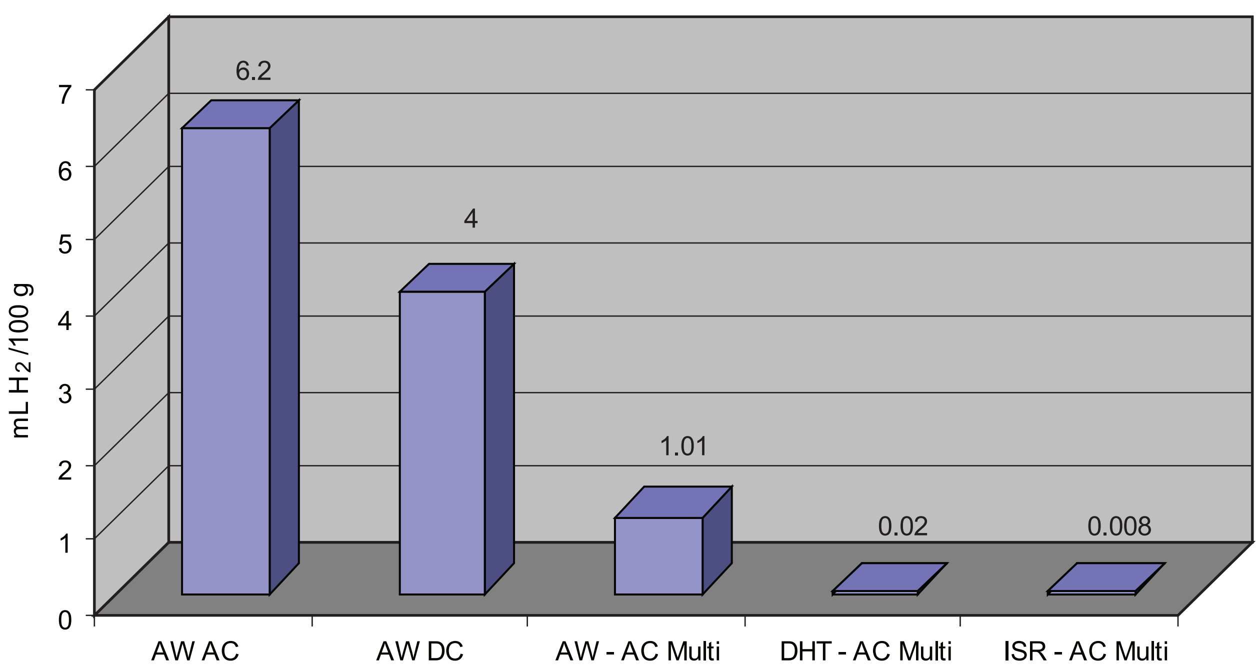


Figure 4—Diffusible Hydrogen Test Results for 2 1/4Cr-1Mo Weld Metal [13]

transition temperature of –23 °C (–9.4 °F). However, it is surprising to note that an ISR performed for four hours on the vanadium-modified alloy at the API 934-A recommended temperature of 650 °C (1200 °F), results in a 54 J (40.0 ft-lb) transition temperature of 72 °C (162 °F), and a notch toughness of 20 J (14.8 ft-lb) at 20 °C (68 °F). Thus, for this vanadium-modified wire, the data appears to indicate that performing a 4-hour ISR at 650 °C (1200 °F) will result in a slightly lower toughness in the weld than will a 4-hour DHT performed at 350 °C (660 °F). An ISR at 620 °C (1150 °F) for four hours was significantly lower toughness and hence is not recommended.

This data also surprised the vessel fabricator who, through performing testing subsequent to discovering cracking, determined that the as-welded toughness of the weld metal after DHT was around 8 J (6 ft-lb) and after an ISR at 650 °C (1200 °F) for 5 hours was 29 J (21.4 ft-lb) indicating a toughness improvement of the ISR treatment over the DHT treatment.

Increasing the holding time of the ISR at 650 °C (1200 °F) for 8 hours improves notch toughness of the deposited metal of this wire flux combination and produces a lower 54 J (40.0 ft-lb) transition temperature of 15 °C (59 °F).

Increasing the temperature of the ISR also improves the notch toughness even at reduced soak times. From Figure 1, it can be seen that following an ISR at 680 °C (1250 °F) for 4 hours for the vanadium-modified steel, the 54 J (40 ft-lb) transition temperature is –4 °C (25 °F).

For the second wire flux manufacturer, the story is a little different. Figure 5 indicates the charpy-V notch toughness of vanadium-modified weld deposits in the “as welded” condition and after ISR at 620 °C (1150 °F) and 660 °C (1220 °F) for 3 hours. Again, at ambient temperatures, the “as welded” material has quite low toughness. However, in this case the toughness response after an ISR for 3 hours at 620 °C (1150 °F) is markedly greater than indicated previously for the wire/flux combination from the first wire/flux manufacturer. Furthermore, following an ISR of 660 °C (1220 °F) for 3 hours, the toughness curve becomes near vertical indicating significantly greater toughness response after only 3 hours.

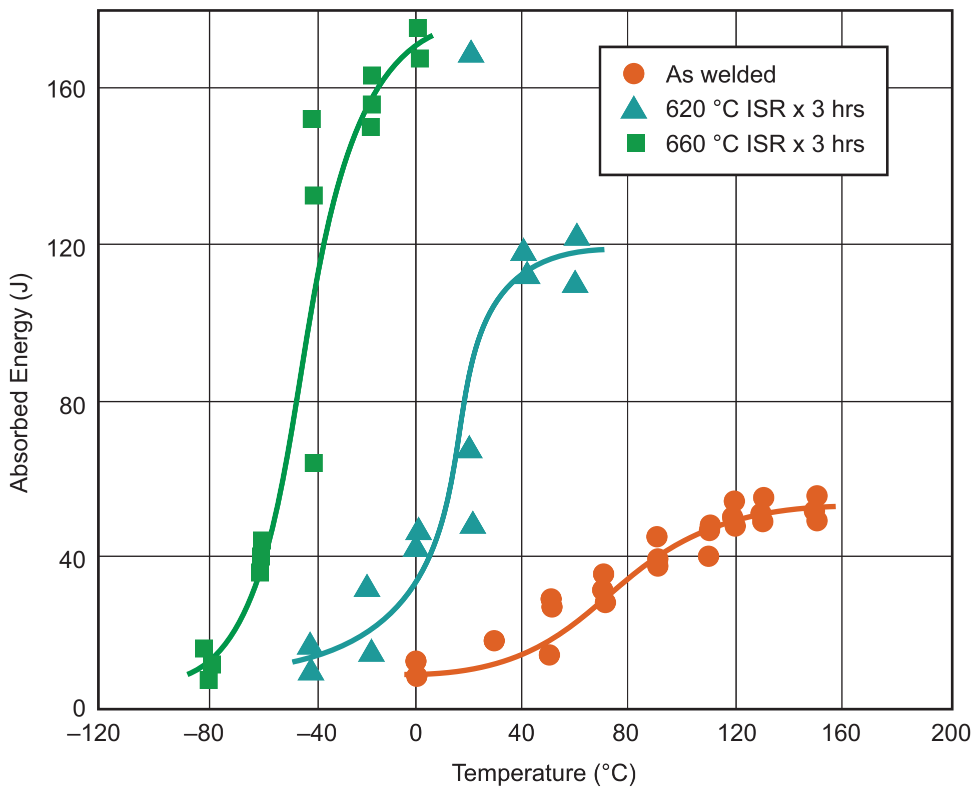
A third wire manufacturer’s ISR heat treatment results are provided in Table 2 [15]. As shown in the impact tests, performed at 0 °C (32 °F), the as-welded impact energy is again low and the response to heat treatment for this particular wire flux combination can be compared to the first manufacturer. The test results of these three manufacturers show that toughness response to heat treatment (ISR) can be significantly different for each different weld wire flux combination, but in each case the “as-welded” weld metals exhibit low toughness.

The recommendation for an ISR temperature for restrained joints is 650 °C (1200 °F) minimum with a holding time determined for the specific wire/flux combination utilized. It should provide not only a weld residual stress reduction but also improve the deposited weld metal toughness at ambient conditions. A minimum holding time of 4 hours at 650 °C (1200 °F) or 2 hours at 680 °C (1250 °F) is normally recommended.

4.6.4 Disbonding

Weld overlay disbonding is a phenomena, which has occurred in hydroprocessing reactors. It results in cracking along the weld overlay and the Cr-Mo base metal interface transition zone and has been observed in some instances to occur during reactor cool down on conventional Cr-Mo steels. The tendency for disbonding increases with increased hydrogen partial pressure and increased operating temperature, as well as faster cooling rates from the operating temperature during shutdown. Additionally, it has been found that welding parameters may also have an effect on the tendency for disbonding.

The cracking or disbonding phenomena has been studied in detail and reported in numerous papers. Findings indicate that the crack propagation occurs along the carbide precipitation zone and along the grain boundaries developing in the stainless steel overlay near the interface with the base metal. This crack propagation in the stainless steel overlay appears to be confined to a narrow region which is less than 80 % austenitic matrix and contains less than 15 % chromium. [15]



NOTE ISR at 620 °C (1150 °F) and 660 °C (1220 °F)

Figure 5—Charpy V-Notch Toughness of Vanadium-modified 2^1/4Cr-1Mo Deposited Weld Metal after ISR Using a Second Alternative Wire Flux Combination [16]

Table 2—Toughness Properties of Vanadium-modified Sub-Arc Weld Metal as Function of Heat Treatment Condition [17]

Heat Treat Condition	As Welded	ISR 650 °C/ 5 hr	ISR 670 °C/ 2 hr	ISR 670 °C/ 5 hr	ISR 690 °C/ 2 hr	ISR 690 °C/ 5 hr	PWHT 705 °C/ 10hr
Impact Tests (Joules at 0°C)	9, 7, 8	13, 6, 8	14, 9, 15	21, 23, 71	65, 80, 119	80, 147, 82	216, 205, 203

The modern vanadium-modified 2^1/4Cr-1Mo and 3Cr-1Mo alloys exhibit much less susceptibility to disbonding than the conventional Cr-Mo alloys. Extensive testing has shown, that under normal hydroprocessing operating conditions, disbonding is not expected to occur for the vanadium-modified alloys. [4][10] The lower susceptibility to disbonding has been attributed to the lower diffusivity of hydrogen in the vanadium steels caused by the hydrogen trapping effect of the vanadium carbides as well as improved welding processes. [2]

4.7 Best Practices for Fabricating V-Modified 2^1/4Cr-1Mo Vessels

4.7.1 Fabrication Sequence Planning

Before fabrication begins fabricator should be required to develop and submit a comprehensive fabrication plan which outlines all steps of fabrication. The purpose of this plan is to assist the fabricator in planning his work and developing an inspection and test plan (ITP). The basis for such a plan is included for reference in Annexes A, B, and C.

4.7.2 Two-Plate Shell Courses

In some cases, depending on the diameter of the reactor and actual plate length availability, it may be necessary to use two plates to form one shell course. In such cases, it is typically recommended that the plates be rolled separately to form two half shell courses, which then require two longitudinal welds to form the entire shell course. The difficulty of plate handling, furnace length limitations, and the rolling of relatively brittle welds all help to create a potential for weld cracking during the fabrication process if the plates are welded before rolling.

The initial fit up of the two flat plates is a relatively simple task which becomes substantially more difficult when the plates must be turned over for back welding. This turning operation not only requires that the preheat be removed for a significant time, but it also can place high stresses into a non-completed, and non-stress relieved weld that has low toughness. Following the completion of this weld, the plates will be given an ISR which will only partially restore ductility and toughness in the weld prior to rolling. Unless a fabricator has proven experience rolling welded plates of comparable materials and thicknesses, such operations are not recommended. If the fabricator does not have proven experience, it is preferred to have each longitudinal weld completed only after each individual plate has been rolled.

4.7.3 Preheat

Unless the fabricator has their own preheating method proven on similar shell course size and thickness, it is recommended that the application of preheat be not only provided by a local burner ring, but the entire ring be heated around the full circumference, or a significant portion of the circumference, of the shell course so that the entire shell course can expand rather than a small local area which can cause high local stresses to be generated. It is acknowledged that such circumferential heating may not be practical or possible in some cases, such as nozzle welds, so preheating over a significantly larger area around the nozzle may provide a more practical solution to reduce harmful local stresses. Another alternative would be to place burners inside the shell section to heat the upper two thirds of the shell section thus reducing the overall thermal stress effect resulting from concentrating the preheat burners around the nozzle weld. The recommended minimum preheat for vanadium-modified $2^1/_4$Cr-1Mo and 3Cr-1Mo alloys is 177 ºC (350 ºF), but 200 ºC (392 ºF) is often used. The recommended preheat in API 934-A for first layer of weld overlay is 94 ºC (200 ºF) minimum, with no preheating typically used for subsequent layers.

4.7.4 ISR/DHT

It is recommended that restrained joints such as nozzles be given an ISR which not only provides additional weld metal hydrogen removal but also provides additional weld metal stress relaxation. From Figure 1 it would appear that it would be prudent for the vessel fabricator to provide an ISR at higher temperatures, e.g. 680 ºC (1250 ºF) and/or longer times. It is to be noted however, that when multiple ISR cycles at 650 ºC (1200 ºF) or above are carried out on a component, consideration should be given to ensure that the total combined heat treatment cycle does not adversely affect material properties or cause unacceptable amounts of sigma phase formation in weld overlay. As a consequence, an ISR at 1200 ºF (650 ºC) held for at least four hours, is generally recommended. All ISRs should be included in the maximum heat treatment of test specimens.

The DHT or ISR should be applied before the base metal weld is permitted to cool below the minimum preheating temperature. DHT can be considered as an alternative to ISR only for non-restrained joints such as circumferential and longitudinal welds and only when demonstrated to the Buyer's satisfaction. Normally DHT is prescribed at a minimum metal temperature of 350 ºC (660 ºF) for 4 hours minimum.

Proposals to use DHT as an alternative to ISR for non-restrained joints should include sufficient information to support the plan, such as recent fabrication experience and experimental test data. The fabricator's request should include data on hydrogen controls for procurement and handling of welding consumables, hydrogen content of weld metals and HAZs after DHT, and nondestructive examination of weld joint. Some owners require the fabricator to do a high sensitivity ultrasonic examination of the weld joints after using a DHT. ISR is critical for all Category D (nozzle attachment) welds in vanadium-modified $2^1/_4$Cr-1Mo and 3Cr-1Mo steels.

4.7.5 PWHT

Postweld heat treatment on vanadium-modified materials is usually carried out at slightly higher temperatures than for conventional Cr-Mo materials to temper the weld metal and to relieve residual weld stresses. Postweld heat treatment at lower than the required temperature will usually not temper the welds sufficiently to produce less than maximum permissible hardness. On the other hand, postweld heat treatment at higher than recommended temperatures or for longer than the specified time will have the effect of lowering the base metal strength and may reduce the material and weld metal toughness. It is very important that in the fabrication process, PWHT be done at the correct PWHT temperature and for the correct holding time.

As discussed in 4.6.1, the vanadium-modified weld metals have been formulated to meet the various required properties (strength, toughness, etc.) based on the thicker wall applications and hence are based on eight hours minimum PWHT. As a result, even the thinner components need to use PWHT times of eight hours minimum, even when this exceeds the required PWHT time based on thickness.

4.7.6 Plate Versus Forging Construction

The 2006 market place for reactors was volatile because of the extremely high numbers of reactor orders. Some shops had major backlogs and were “no bidding” on various orders. There are a limited number of mills that make the forged rings and when they become backlogged, the price and delivery goes up. When this is the case, some reactors which previously would have used forged shell rings since forged rings would have been the economic choice, are more economical fabricated from rolled plates. In Europe, as in Japan, there are shops and mills that are geared towards offering heavier wall thickness for reactor shells manufactured from plates or a combination of plates and forgings.

The material specified for forgings of $2^1/_4$Cr-1 Mo-Vanadium-modified would be either SA-336 Gr. 22V or SA-541 Gr. F22V. The material specified in the same grade for plate would be SA-542 Type D, Cl.4a, or SA 832 Gr. 22V. When reviewing and comparing the material specs for SA-541 versus SA-542, they are identical in terms of chemistry and mechanical properties. In addition, the ASME Code allowable stresses are identical for the two product forms, therefore there would be no difference in wall thickness or weight. All of the longitudinal seams typically are specified to receive 100 % RT and UT, just like the circumferential seams, so there should not be a change in quality by going to either plate or forging. Hence, there are no technical distinctions between the two options, and the choice can be based on economics and delivery.

4.7.7 Welding Processes/Joint Configuration

The welded joint configuration should be developed by the fabricator to suit his specific welding equipment; however, narrow gap welding is the recommended configuration for through-thickness head and shell joints. Although there is no universal agreement on the definition of the term “narrow gap welding”, it is essentially self-explanatory. It involves a narrow weld bevel with almost parallel edges, and results in welds <25 mm (<1 in.) wide in 100 mm to 300 mm (4 in. to 12 in.) thicknesses using automated welding processes.

4.7.8 Welding Consumables

The weld wire manufacturer for vanadium-modified Cr-Mo steel whose data is shown in Figure 1, has studied and is currently studying the topic of the toughness of the weld metal after PWHT. Their present conclusion is that the actual chemical analyses used today, with the different weld wire/flux combinations of different weld wire manufacturers, appears to be the optimum one to fulfill the technical specifications, e.g. to guarantee high tensile strength, a 54 Joule (40 ft-lb) toughness at low test temperatures (–20 ºC [–29 ºF]) after minimum PWHT, good creep properties after maximum PWHT, low hydrogen levels in the as-welded deposited welds, and a high resistance to hydrogen attack.

5 Assessment of Fabricators

5.1 Current Worldwide Fabrication Capability

As of 2006, there were a limited number of fabricators with experience fabricating vanadium-modified Cr-Mo reactors. Some of these were in Japan, several in Italy, China, India, and Spain. There was at the time an extremely high demand for reactors, producing major backlogs in the experienced shops resulting in longer deliveries and higher costs for Buyers. Hence, there was a desire to “approve” vessel fabricators with experience on other materials for fabrication of Vanadium-modified reactors.

This should only be done with proper review that they have the equipment capabilities for the work, have researched the technical requirements and issues, and have the technical sophistication for this work. On equipment capabilities, one special review would be that the shop can handle the logistics of the preheating, DHT, ISR and PWHT requirements. An example of knowledge of technical requirements would be that the fabricator has confirmed that the materials suppliers (e.g. plates, nozzle forgings, flanges, weld metals) can meet the special chemistry limits including the J and X-factors, and the strict toughness requirements. Technical sophistication would be shown by the fabricator’s understanding of the minimum and maximum heat treatment definitions in API 934-A.

Examples of problems that have occurred with less experienced fabricators include:

a) changing the SAW flux without appropriate changes in the welding parameters or proper qualification of a new WPS/PQR, resulting in weld cracking;

b) incorrect PWHT temperatures;

c) letting the PWHT go for many extra hours, without realizing that could have detrimental affects;

d) insisting that DHT is acceptable “based on their past experience” on welds where an ISR is needed;

e) cooling to ambient temperatures before ISR because logistically it was difficult to move the vessel to the furnace and maintain the preheat temperature, and;

f) incorrect preheat and preheat maintenance.

5.2 Approving New Fabricators

5.2.1 General

Table 3 suggests a point system for evaluating potential new fabricators. It is designed to allow fabricators with some Cr-Mo fabrication experience, to fabricate “the next level” of alloy and/or thickness with the appropriate research and procedure development.

Notes on using “assessment” chart and point system are as follows.

1) Only one category of points is allowed from Sections V through IX (e.g. the fabricator should be rated based on their highest alloy, thickest past experience).

2) The items listed as “critical” are items that the fabricator “must have” to be considered for vanadium-modified reactor fabrication unless waived by the buyer.

3) Experience should be from same shop facility as proposed for new reactor for fabricators with multiple shop sites, unless otherwise approved by buyer.

4) For the specific reactor experience which is providing the fabricator rating from Sections V through IX, references should be supplied (either from the past reactor’s owner or buyer). The buyer for the new reactor should attempt to call these references to check on whether the past job had quality issues, major weld repairs, schedule problems, documentation lapses or any other similar negative reports. If there were significant

Table 3—Point System for Evaluating New Fabricators

	Fabricator Review Assessment Team	Points
I	Accreditation to ASME or other recognized fabrication Code	Critical
II	Quality Control Program:	
	- certification to recognized standard	Critical
	- in-house documented system which is verified to be in practice by shop visit	Critical
	- quality control personnel certified to recognized standard(s)	Critical
	- material—base material and weld metal—tracking control through fabrication steps (verified by shop visit)	Critical
	- attention to details such as preheat temperature measurement, welders having copies of WPS, weld materials in ovens when needed, stamping, cleanliness, etc to be verified by shop visit	Critical
III	Fabrication Equipment Capabilities (appropriate for reactor size)	
	- lifting/handling capacity	Critical
	- fabrication bay capacity	Critical
	- cutting equipment	Critical
	- forged ring or rolled plate size capabilities for handling	Critical
	- welding equipment for base metal welds	Critical
	- shell/head overlay welding equipment	Critical
	- nozzle overlay welding equipment (or subvendor plans/capabilities)	Critical
	- furnace size (or subvendor plans/capabilities)	Critical
	- radiography capabilities (or subvendor plans/capabilities)	Critical
	- other NDE capabilities (or subvendor plans/capabilities)	Critical
	- mechanical test capabilities (or subvendor plans/capabilities)	Critical
	- machining capabilities of gasket groove	Critical
IV	Fabrication Procedures (confirmed to be acceptable quality)	
	- Base Metal Weld WPSs/PQRs and Welding Maps for: (choose highest point level) Some grade of 1 % to 3 % Cr-Mo, Conventional 2$^{1}/_{4}$Cr-1Mo, or Vanadium-modified Cr-Mo	 Critical 2 5
	- Overlay WPSs/PQRs for: (choose highest point level) Conventional 2$^{1}/_{4}$Cr-1Mo, or Vanadium-modified Cr-Mo	 1 2
	- Overlay Disbondment Test Results for: (choose highest point level) Conventional 2$^{1}/_{4}$Cr-1Mo, or Vanadium-modified Cr-Mo	 4 6
	- NDE Procedures	Critical
	- PMI Procedure	Critical
	- Hardness Testing Procedure	Critical
	- Ferrite Testing Procedure	Critical
	- Heat Treatment Procedure including preheat, DHT, ISR, PWHT, and local PWHT.	Critical
	- Hydrotesting Procedure	Critical
	- Reactor or similar vessel fabrication sequence sketch (similar to Annex A)	1
	- Detailed Fabrication Plan including NDE (similar to Annex B)	3

Table 3—Point System for Evaluating New Fabricators (Continued)

Fabricator Review Assessment Team		Points
	- Flow Chart of Fabrication Schedule (similar to Annex C)	Critical
V	Experience with vanadium-modified reactor fabrication—shell thickness:	
	>150 mm (>6 in.)	35
	125 mm to 149 mm (5 in. to 6 in.)	30
	100 mm to 124 mm (4 in. to 5 in.)	25
	<100 mm (<4 in.)	20
VI	Experience with conventional $2^1/_4$Cr-1Mo reactor fabrication—shell thickness:	
	>200 mm (>8 in.)	15
	150 mm to 199 mm (6 in. to 8 in.)	10
	100 mm to 149 mm (4 in. to 6 in.)	8
	<100 mm (<4 in.)	5
VII	Experience with conventional $2^1/_4$Cr-1Mo fabrication for other vessels—shell thickness:	
	>200 mm (>8 in.)	10
	150 mm to 199 mm (6 in. to 8 in.)	8
	100 mm to 149 mm (4 in. to 6 in.)	6
	<100 mm (<4 in.)	4
VIII	Experience with $1^1/_4$Cr- $^1/_2$Mo reactor fabrication—shell thickness:	
	≥100 mm (>4 in.)	6
	50 mm to 99 mm (2 in. to 4 in.)	4
	<50 mm (<2 in.)	2
IX	Experience with $1^1/_4$Cr- $^1/_2$Mo fabrication for other vessels—shell thickness:	
	≥100 mm (>4 in.)	5
	50 mm to 99 mm (2 in. to 4 in.)	3
	<50 mm (<2 in.)	1

problems, this experience may be "deleted", or have reduced points at the buyers discretion. **If a favorable report is obtained, 5 points should be added.**

5) Fabrication Procedures (Section IV) can be from past jobs or can be developed by the fabricator for the potential new vanadium-modified reactor fabrication.

6) A shop visit by buyer is suggested under Section II in the table with various items to verify. During this visit, it is important to interview the welding engineer(s) to determine their experience and knowledge about vanadium-modified Cr-Mo steels.

7) Suggested required points for selecting fabricator for new vanadium-modified reactors based on shell thicknesses are:

>200 mm (>8 in.)	>50 points
150 mm to 200 mm (6 in. to 8 in.)	>40 points
12 mm to 150 mm (5 in. to 6 in.)	>30 points
100 mm to 125 mm (4 in. to 5 in.)	>25 points
<100 mm (<4 in.)	>20 points

5.2.2 Examples

EXAMPLE 1: A fabricator has successful experience with fabricating a 1$^1/_4$Cr-$^1/_2$Mo reactor, 75 mm (3 in.) thick. They obtain vanadium-modified 2$^1/_4$Cr-1Mo material and qualify WPSs/PQRs for base metal and overlay welding, and have disbondment tests done in accordance with API 934-A. From the past project, they have a fabrication sequence sketch and detailed fabrication plan, and meet all the "Criticals" in the assessment table. Their points are:

From Sections V through IX:	4 points
From Section IV:	17 points
High recommendation from reference:	5 points
Total	26 points

Suggested "acceptance" for vanadium-modified 2$^1/_4$Cr-1Mo fabrication: up to 125 mm (5 in.) thickness. Without the qualification work on the vanadium-modified materials, this fabricator would not have been approved for any vanadium-modified reactors.

EXAMPLE 2: A second fabricator has experience with 2$^1/_4$Cr-1Mo reactors up to 150 mm (6 in.) thick. From these past projects, they have 2$^1/_4$Cr-1Mo qualified WPSs/WQRs, disbondment tests, a fabrication sequence sketch and detailed fabrication plan, and they meet all the "criticals" in the assessment table. Their points are:

From Sections V through IX:	10 points
From Section IV:	11 points
High recommendation from reference:	5 points
Total	26 points

Suggested "acceptance" for vanadium-modified 2$^1/_4$Cr-1Mo fabrication: up to 125 mm (5 in.) thickness. This fabricator can increase to 150 mm thickness by doing qualification testing which meets API 934-A on vanadium-modified 2$^1/_4$Cr-1Mo.

EXAMPLE 3: A third fabricator has experience with vanadium-modified 2$^1/_4$Cr-1Mo reactors up to 90 mm (3.5 in) thick. From these past projects, they have vanadium-modified 2$^1/_4$Cr-1Mo qualified WPSs/WQRs, disbondment tests, a fabrication sequence sketch and detailed fabrication plan, and they meet all the "criticals" in the assessment table. Their points are:

From Sections V through IX:	20 points
From Section IV:	17 points
High recommendation from reference:	5 points
Total	42 points

Suggested "acceptance" for vanadium-modified 2$^1/_4$Cr-1Mo fabrication: up to 200 mm (6 in.) thickness.

Annex A
(informative)

SAMPLE Fabrication Plan

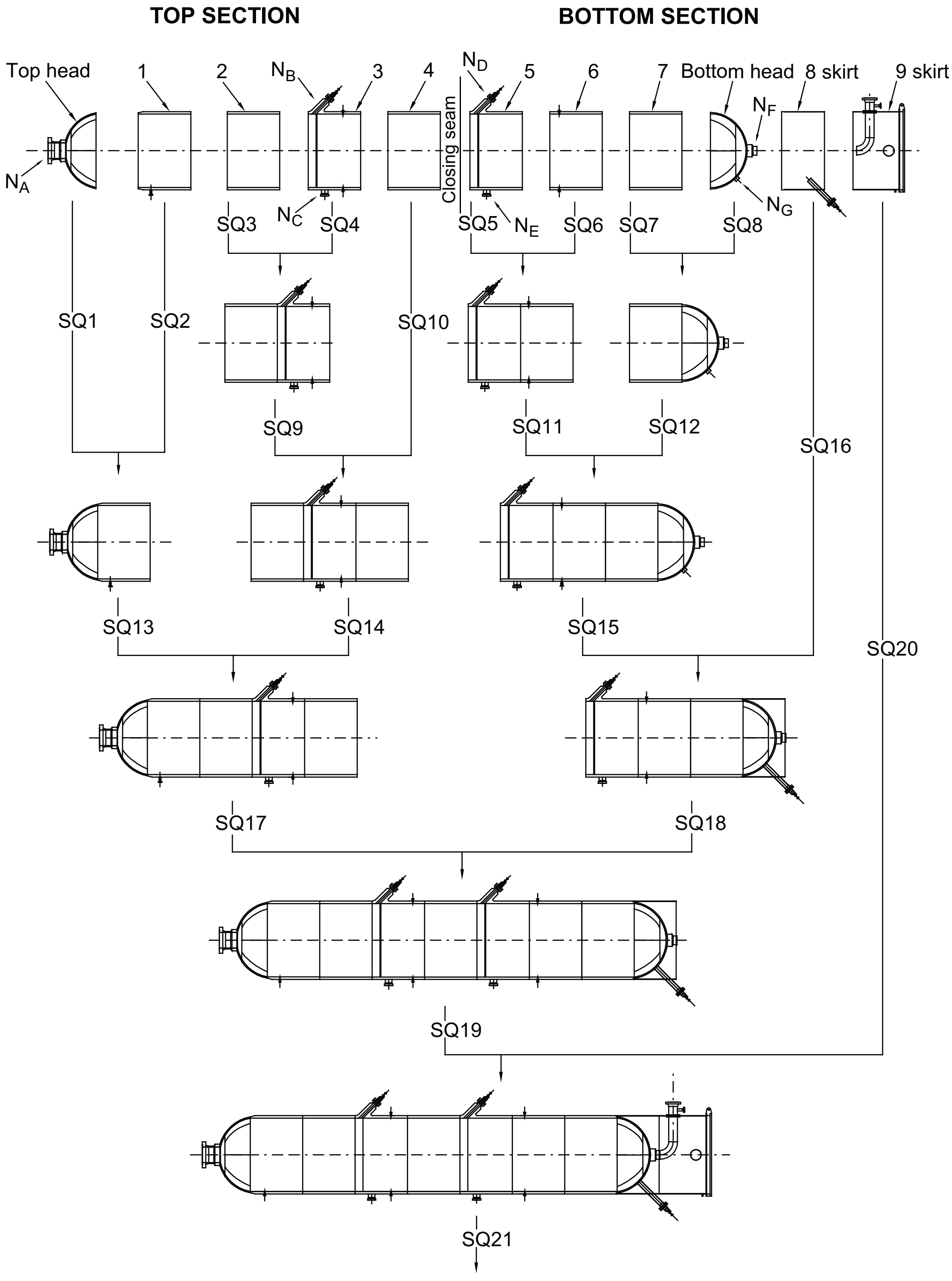


Figure A.1—Sample Fabrication Plan

Annex B
(informative)

Example of a Detailed Fabrication Plan

Table B.1—Example Construction Schedule

Sequence No.	Component	Construction Activities		
SQ1	Top Head	Preheat head segments 350 °F min Flame cut Bevel edges Dimension check MT edges Assembly Head Segments Dimension Check **Head Seams** Preheat 400 °F Minimum Weld Inside Back Gouging MT	**Head Seams** (Continued) Weld Outside DHT 570 °F / 4 hr Grind Flush Inside/Outside MT and UT Weld Machine Head/Shell Bevel PT or MT of Head from Inside Preheat 350 °F Weld Overlay (1 or 2 passes) PMI Examination and UT for Bonding MT of Nozzle Weld Preparation	Install temporary attachments on cladding Fit Up N2 Nozzle Dimensional Check Preheat 400 °F Minimum Weld Outside Back Gouging and MT Complete Weld from Inside Visual Testing ISR 1200 °F 1 hr/in. minimum 4 hr MT and UT and/or RT of N_A Nozzle Restore Cladding PT Cladding
SQ2	Can Section 1	Dimensional Check PT or MT Preheat to >220 °F Weld Overlay PMI Examination and UT for Bonding Preheat to 400 °F Remove Clad Burn Hole	Grinding Weld Preparation Inspection MT Testing BHN Weld Preparation Copper Sulfate Examination Install Temporary Attachments on Cladding Fit Up of Nozzle	Dimensional Inspection Preheat 400 °F Minimum Welding of Nozzle from Outside Back Gouging and MT Testing Welding Nozzle from Inside While hot move shell into ISR 1200 °F 1 hr/in. minimum 4 hr Complete Clad Restoring
SQ3	Can Section 2	Dimensional Check PT or MT	Preheat 350 °F Weld Overlay Strip	PMI Examination and UT for Bonding
SQ4	Can Section 3	Dimensional Check PT or MT Layout of Nozzles and Weld Build Up Area Preheat 350 °F Weld Overlay PMI Examination and UT for Bonding (Grid 100)	Repeat for all Nozzles: Fit Up of Nozzles Dimensional Inspection Preheat 400 °F Minimum Welding of Nozzle from Outside Back Gouging and MT Testing	Preheat for Weld Build Up 400 °F Weld Build Up of Complete Support Ring While hot move shell into ISR 1200 °F 1hr/in. minimum 4 hr Finishing Machining of Support Ring Preheat for Weld Overlay 400 °F

Table B.1—Example Construction Schedule (Continued)

Sequence No.	Component	Construction Activities		
		Preheat 400 ºF Minimum Machine Nozzle Holes Grinding Weld Preparation Inspection MT Testing BHN Weld Preparation Install Temporary Attachments on Cladding	Welding Nozzle from Inside While hot move shell into ISR 1200 ºF/2 hr Complete Clad Restoring UT and MT of Nozzles	Weld Overlay of Support Ring Grinding Topside of Support Ring
SQ5	Can Section 5	Dimensional Check PT or MT Layout of Nozzles and Weld Build Up Area Preheat 350 ºF Weld Overlay PMI Examination and UT for Bonding (Grid 100) Preheat 400 ºF Minimum Machine Nozzle Holes Grinding Weld Preparation Inspection MT Testing BHN Weld Preparation	Install Temporary Attachments on Cladding Repeat for all Nozzles: Fit Up of Nozzles Dimensional Inspection Preheat 400 ºF Minimum Welding of Nozzle from Outside Back Gouging and MT Testing Welding Nozzle from Inside While hot move shell into ISR 1200 ºF/2 hr Complete Clad Restoring UT and MT of Nozzles	Preheat for Weld Build Up 400 ºF Weld Build Up of Complete Support Ring While hot move shell into ISR 1200 ºF 1hr/in. minimum 4 hr Finishing Machining of Support Ring Preheat for Weld Overlay 400 ºF Weld Overlay of Support Ring Grinding Topside of Support Ring
SQ6	Can Section 6	Dimensional Check PT or MT	Layout Nozzles Preheat 350 ºF	Weld Overlay PMI Examination and UT for Bonding (Grid 100)
SQ7	Can Section 7	Dimensional Check PT or MT	Preheat 350 ºF Weld Overlay	PMI Examination and UT for Bonding (Grid 100)
SQ8	Bottom Head	Head Segments NDE Tested Assembly Head Segments Dimension Check Fix Head to Positioner **Head Seams** Preheat 400 ºF Minimum Weld Inside Back Gouging MT Dry Weld Outside DHT 570 ºF/4 hr Grind Flush Inside/Outside	Preheat 120 ºC to 150 ºC Weld Overlay PMI Examination and UT for Bonding (Grid 100) Machine Nozzle Holes MT of Nozzle Weld Preparation Install temporary attachments on cladding Fit Up 2 Nozzle Stubs Dimensional Check Preheat 400 ºF Minimum Weld Outside Heating up to 280 ºC Back Gouging and MT	Visual Testing While hot bring head into ISR 1200 ºF/2 hr MT and UT of 2 Nozzles Restore Cladding Fit Up Forged Ring Preheat 400 ºF Minimum Welding from Inside Back Gouging and MT Welding from Outside DHT 570 ºF/4 hr Flush Grinding of Weld MT and UT of Weld

Table B.1—Example Construction Schedule (Continued)

Sequence No.	Component	Construction Activities		
		MT and UT Weld	Complete Weld from Inside	Complete Clad Restoring
SQ9	Can Section 2 to 3	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside	Back Gouging MT Welding From Outside	DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside
SQ10	Can Section 4	Dimensional Check PT or MT	Preheat 350 ºF Weld Overlay	PMI Examination and UT for Bonding (Grid 100)
SQ11	Can Section 5 to 6	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside Back Gouging MT Welding From Outside DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside	Preheat 400 ºF Minimum Machine Nozzle Holes Grinding Weld Preparation Inspection MT Testing BHN Weld Preparation Copper Sulfate Examination Install Temporary Attachments on Cladding	Fit Up of Nozzles Dimensional Inspection Preheat 400 ºF Minimum Welding of Nozzle from Outside Back Gouging and MT Testing Welding Nozzle from Inside While hot move shell into ISR 1200 ºF/2 hr Complete Clad Restoring
SQ12	Can Section 7 to the Bottom Head	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside	Back Gouging MT Welding From Outside	DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside
SQ13	Can Section 1 to the Top Head	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside	Back Gouging MT Welding From Outside	DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside
SQ14	Can Sections 2, 3 to Section 4	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside	Back Gouging MT Welding From Outside	DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside
SQ15	Can Sections 5 and 6 to Section 7 and the Bottom Head	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside	Back Gouging MT Welding From Outside	DHT 570 ºF/4 hr Complete Clad Restoring MT and UT from Outside
SQ16	Skirt Section 8	Preheat of Plates 400 ºF Cutting of Shell Plates MT of Weld Preparation Preheat of 400 ºF Welding of Long Seam 8A	Welding of Long Seam 8B Spot MT Preheat 400 ºF Minimum Weld Butter Layer for Weld Preparation (CS11) MT on Completed Butter Layer	Back Gouging - MT Welding from Outside DHT 570 ºF/4 hr Flush Grinding of Weld MT and UT of Weld

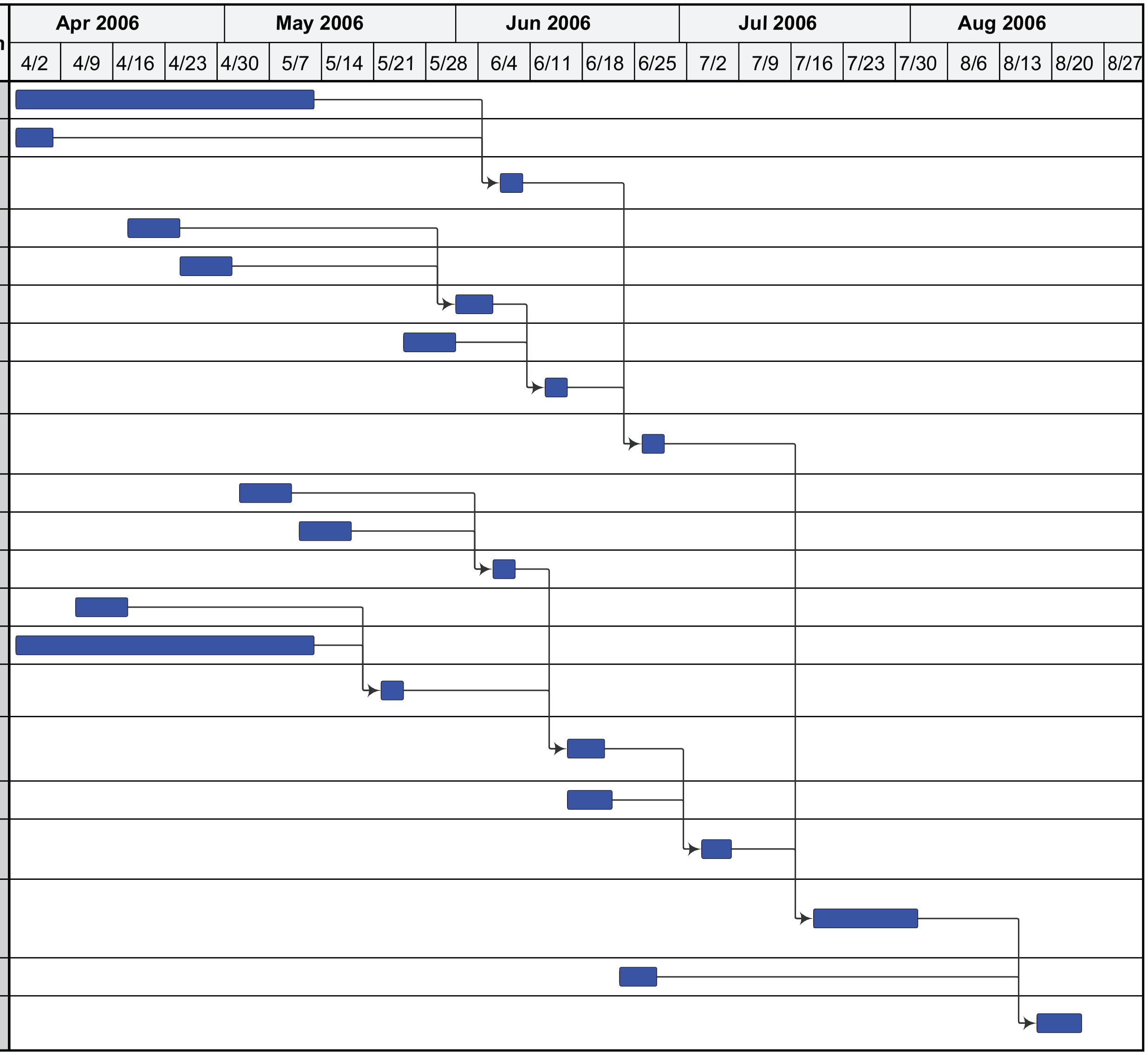
Table B.1—Example Construction Schedule (Continued)

Sequence No.	Component	Construction Activities		
		Rolling of Shell Course	Grinding of Weld Preparation	Complete Clad Restoring
SQ17	Can Sections 1 and Top Head to Can Sections 2, 3 and 4	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside Back Gouging	MT Welding From Outside DHT 570 ºF/4 hr	Complete Clad Restoring MT and UT from Outside TOFD Examination of Category A, B, and D Welds
SQ18	Can Sections 5, 6, 7 and Bottom Head to Skirt Section 8	Fit Up Circumference Seam Preheat to 400 ºF Welding of GTAW Root Layer	Dye Penetrant Testing of Root Layer Completion of Weld DHT 570 ºF/4 hr	Radiographic Testing of Weld MT from Outside
SQ19	Top and Bottom Sections (Closing Seam)	Fit Up Circumference Seam Preheat to 400 ºF Welding From Inside Back Gouging MT Welding From Outside DHT 570 ºF/4 hr	Complete Clad Restoring MT and UT from Outside TOFD Examination of Category A, B, and D Welds of Bottom Section and Closing Seam Assembly of Internals on Weld Overlay Assembly of Externals (Hold)	Transportation into Furnace PWHT 1300 ºF ±50 ºF/Holding Time 8 hr Transportation out of Furnace After PWHT 100 % Manual UT Testing of all Category A, B, and D Welds followed by 100 % MT
SQ20	Skirt Section 9	Cutting of Shell Plates VT of Weld Preparation	Rolling of Shell Course Welding of Long Seam	Spot MT Assembly and Welding of Base Ring Construction
SQ21	Vessel to Skirt Section 9	Fit Up Circumference Seam Dry Warming of Weld Area (80 ºC) Welding From Inside	Back Gouging - 100 % Dye Penetrant Testing Dry Warming of Weld Area (80 ºC) Welding From Outside	Spot MT of Weld Hydrostatic Testing

Annex C
(informative)

Sample Fabrication Schedule

No.	SQ	Description	Duration
1	1	Top Head	30d
2	2	Can #1	5d
3	13	Can 1 to Top Head	3d
4	3	Can #2	5d
5	4	Can #3	5d
6	9	Can 2 to 3	3d
7	10	Can #4	5d
8	14	Can 2, 3 to 4	3d
9	17	Can 1, Top Head to Can 2, 3, and 4	3d
10	5	Can #5	5d
11	6	Can #6	5d
12	11	Can 5 to 6	3d
13	7	Can #7	5d
14	8	Btm Head	30d
15	12	Can 7 to Btm Head	3d
16	15	Can 5, 6 to 7 and Btm Head	3d
17	16	Skirt Sect. 8	4d
18	18	Can 5, 6, 7 and Btm Head to Skirt 8	4d
19	19	Top and Bottom Sections (Closing Seam)	10d
20	20	Skirt Sect. 9	3d
21	21	Vessel to Skirt Sect. 9	4d



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