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RECOMMENDED PRACTICES FOR LOCAL HEATING OF WELDS IN PRESSURE VESSELS

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FOREWORD

The framework for this document is based upon the American Welding Society document AWS D10.10/D10.10M: 1999, *Recommended Practices for Local Heating of Welds in Piping and Tubing*. During the process of revising this AWS document, it was recognized that it might be appropriate to prepare a separate document pertaining to recommended practices for local heating of welds in pressure vessels. At the same time, a request was received to prepare a guideline regarding postweld heat treatment (PWHT) of repairs for heavy-wall hydro-processing reactors. This request was made by a joint industry project on aging hydro-processing reactors. Additionally, an ASME Boiler & Pressure Vessel Code Ad Hoc Task Group on Local PWHT, operating under the Section VIII Subgroup Fabrication and Inspection, was developing requirements for local PWHT. The confluence of these three activities was responsible for the development of this document.

The document was essentially last updated in May 1997. The requirements (paragraphs UW-40 and AF-410, see Appendices A and B) for local PWHT in Section VIII of the ASME Boiler and Pressure Vessel Code were significantly revised in July 1998. This document does not reflect any of these revisions.

The changes to ASME Section VIII pertaining to local PWHT are summarized below:

1) The term soak band had been added, defined and its width revised.

2) The use of non-uniform width or temperature 360-degree band PWHT for attachments has been added.

3) The use of local circular spot PWHT for attachments on spherical shells/heads has been added.

4) The use of other local spot PWHT based upon sufficiently similar, documented experience evaluations has been allowed.

These issues are discussed in this document, although not in terms of the July 1998 revision to ASME Section VIII. In addition, detailed guidelines for items 3 and 4 above (item 4 in particular) are not available at the present time. A joint industry project sponsored by the Pressure Vessel Research Council has recently been initiated to support these code changes and to establish a complete standard for local PWHT. Based upon these considerations, The Pressure Vessel Research Council concluded that there was benefit in publishing this document in its present (May 1997) form.

The reader is directed to AWS D10.10/D10.10M: 1999, *Recommended Practices for Local Heating of Welds in Piping and Tubing* for the most current comprehensive treatment of many of the issues pertaining to local heating of welds. Sections in this AWS document are cited to specifically direct the reader to additional information and recommendations. In addition, "Recommended Practices for Local 360-Degree Band Postweld Heat Treatment," *Welding in the World,* pp 40–49, Vol. 43, No. 1, 1999 provides a recent treatment of local PWHT issues.

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The authors acknowledge the contribution of the AWS Subcommittee D10P, Subcommittee on Local Heat Treating of Pipework. The efforts of the Subcommittee members and reviewers outside of the subcommittee who provided important input during the current process of revising AWS D10.10/D10.10M: 1999 are greatly appreciated. Likewise, the members of the ASME Boiler and Pressure Vessel Code Ad Hoc Task Group on Local PWHT under Section VIII Subgroup Fabrication and Inspection made an important contribution to this document. Helpful comments were also provided by various members of the Pressure Vessel Research Council. In addition, the access to documents being reviewed by the ASME Board of Pressure Technology Codes and Standards Task Group Post Weld Heat Treatment was very useful. The efforts of various former Cooperheat staff members in providing information and support during the preparation of this document are also acknowledged, particularly, for the contributions of by Neil Williamson, Dennis Thompson, Bob Nugent and Mike Sciascia.

CONTENTS

Recommended Practices for Local Heating of Welds in Pressure Vessels

Joseph W. McEnerney* and Pingsha Dong**

1. Scope

This document considers the various issues associated with local heating of welds in pressure vessels. It specifically addresses application of controlled heat to the weld metal, heat affected zone (HAZ) and a limited volume of base metal adjacent to the weld, as opposed to heating the complete weldment in a furnace or oven. Although aimed at local heating, various issues common to both local and furnace heating are also discussed. In some cases, the need to locally heat may be best accomplished by heating larger sections, multiple overlapping sections, or the entire pressure vessel. Such heating is also discussed within the context of the need for local heating.

In the manufacture, field fabrication and/or repair of weldments, it may be necessary to heat parts before welding (bake-out or preheating) between passes (interpass heating), or after welding (postheating or postweld heat treatment [PWHT]). This document addresses all four of these purposes for heating, with the main emphasis on PWHT.

Although heating of pressure vessels is frequently performed in a furnace, weldment size, convenience, or use of a process such as preheat/interpass heating may preclude the use of a furnace. In such cases, the weld and adjacent material may be locally heated by one of the methods discussed in these recommended practices. Local heating is also very common during field fabrication and/or repair of components. The method used will often be determined by the availability of equipment, the accessibility of the area to be heated, constraints imposed by adjacent materials or components, and the type of heating operation to be performed.

2. Referenced Codes, Standards & Practices

Except for postheating, specific hold temperature and time requirements are not discussed in this document. However, extensive reference to general local heating requirements found in common pressure vessel codes, standards and practices is made to aid the user of this document. These referenced codes, standards and practices include:

Pressure Vessel Fabrication Codes:

ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 & 2, Rules for Construction of Pressure Vessels, 1995 Edition, with Addenda through 1996.

ASME Boiler and Pressure Vessel Code, Section III, Division 1—Subsection NB, Class 1 Components, Rules for Construction of Nuclear Power Plant Components, 1995 Edition, with Addenda through 1996. (Note that although direct reference is made to Subsection NB and its related paragraphs, Subsections NC & ND for Class 2 & 3 components have essentially the same requirements.)

British Standard Specification for Unfired fusion welded pressure vessels (BS 5500), 1997 Edition.

Australian Standard Unfired Pressure Vessels Code (AS 1210), 1989 Edition.

Repair Codes:

NBIC National Board Inspection Code (ANSI/NB-23), 1995 Edition, with Addenda through 1996.

API Pressure Vessel Inspection Code [Maintenance, Inspection, Rating, Repair, and Alter-

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ation] (ANSI/API 510), March 1992 Edition, with Supplements through #2, January 1995.

Recommended Practices Regarding Service Environment:

Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments (NACE RP0472-96), 1995.

Guidelines for Detection, Repair, and Mitigation of Cracking of Existing Petroleum Refinery Pressure Vessels in Wet H_2S Environments (NACE RP0296-96), 1996.

Avoiding Environmental Cracking in Amine Units (ANSI/API 945), 1990.

Materials and Fabrication Practices for New Pressure Vessels Used in Wet H_2S Refinery Service (NACE 8X194), 1994.

3. Purposes for Local Heating

A brief discussion of the purposes for bake-out, preheat/interpass heating, postheating, and PWHT is provided in this section.

3.1 Bake-Out

Although a standard term for this process is not recognized by AWS, such heating is performed to remove hydrogen from material prior to manufacture, fabrication or repair activity. One common source of hydrogen is the service environment, such as found in wet H_2S service. Therefore, this heating is frequently applied to service exposed material prior to repair activity. The purpose of removing the hydrogen is to prevent weld metal and/or HAZ cracking. Since the objective is to facilitate diffusion to free surfaces, time-temperature parameters are selected such that sufficient hydrogen mobility is provided to accomplish the desired degree of removal during the allotted hold time.

Considerations in selecting parameters include: initial hydrogen content, desired final hydrogen content (based upon knowledge of the critical level for the material), hydrogen diffusion coefficient as a function of temperature for the material, diffusion path or distance to free surface (typically one-half of the material thickness), and the model used to describe the diffusion process. A detailed methodology for selecting hydrogen removal parameters is available [1]. In most cases, a quantitative approach (i.e., one accounting for all of the above considerations) to the selection of parameters is not applied. Instead, experience-based parameters are used. As expected, fabrication codes contain no guidance with regard to bake-out parameters. However, API 945 (para. 4.5.3) and NACE RP0296 (para. 5.3) do provide recommendations as shown in Table 1. When specifying experience-based parameters, it is recommended that time be specified as a function of thickness to account for the variable diffusion path, with a minimum time requirement. For example, 500 to 600°F (260 to 316°C) for 2 hours per inch (25.4 mm) of thickness, with 2 hours minimum, is reported [2] to be a reasonable approach for carbon and low alloy steels.

Table 1—Comparison of Recommended Hydrogen Bake-Out Practices

Repair Code or Practice	*Temperature °F (°C)*	*Time (hours)*
NACE RP0296	Above 400 (204)	up to 4
API 945	450–600 (230–315)	2 to 4

3.2 Preheating and Interpass Heating

These processes generally have the same purposes and are aimed at achieving the minimum preheat and interpass temperatures. The former is applicable to the base metal immediately prior to the start of welding and the latter to the weld area (weld metal, HAZ and adjacent base metal) prior to start of each pass in a multipass weld.

One principal reason for preheating and interpass heating is to prevent hydrogen cracking in the weld metal and/or HAZ. This objective is accomplished by the interaction of several effects including:

1) driving off moisture prior to the start of welding;
2) reducing the cooling rate; and
3) increasing the rate of hydrogen diffusion.

A reduced cooling rate provides greater time for redistribution of solidification stresses, promotes the formation of more ductile microstructural constituents which are less cracking sensitive, and provides more time for hydrogen diffusion.

A second principal reason for preheating or interpass heating is to reduce the cooling rate in materials which form hard or brittle microstructural constituents when cooled too rapidly from welding temperatures.

The previously referenced fabrication and repair codes provide guidance or requirements regarding specific temperatures. The temperature requirements are typically based upon the material type and thickness. These fabrication codes may also utilize preheat and interpass temperature requirements to provide exemptions from PWHT.

More restrictive preheating and interpass requirements should be imposed for repairs involving highly restrained weldments and for specialized welding such as controlled deposition, as described in section 14. In addition, for materials with higher hardenability and for welding processes or consumables with increased hydrogen potential, maintenance of preheating/interpass heating may be required until the application of postheating or PWHT.

For reasons explained above, most welding procedures specify a minimum preheat temperature that must be maintained whenever welding takes place. Many welding procedures also specify maximum interpass temperatures which should not be exceeded prior to depositing the next pass in the same area. The latter may be specified to protect the health and the effectiveness of the welder. Interpass temperature may also be limited for metallurgical reasons such as maintaining the notch toughness of ferritic steels and the corrosion resistance of austenitic stainless steels and some non-ferrous alloys.

3.3 Postheating

By definition, this process encompasses all heating performed after the completion of welding, including PWHT. However, it is generally recognized that postheating is performed at a lower temperature, generally 300–600°F (149–316°C) versus 1,000–1,400°F (538–760°C), and with a different primary objective than PWHT.

The primary objective for postheating is the removal of hydrogen and the prevention of hydrogen induced cracking. The latter is also known as underbead or delayed cracking since it occurs most frequently in the HAZ and at times up to 48 hours after the weldment has been cooled to ambient temperature. This is of special concern when joining high strength and alloyed steels (other than austenitic stainless steels), when the hydrogen potential of the welding consumables, such as moisture, wire drawing compounds, oil, and grease, is not adequately controlled, or when the preheat/interpass heating is inadequate. As such, much of the bake-out discussion in section 3.1 is also applicable to this section. Depending upon the actual temperatures used, some degree of tempering may also occur. Also, the higher the martensite forming temperature in the HAZ and weld metal, the greater the self-tempering on cooling.

If postheating is deemed necessary due to concerns regarding hydrogen cracking, then the minimum preheat/interpass temperature should be maintained until the application of such postheating.

Frequently, postheating is applied in situations where some delay is expected between the completion of welding and the application of PWHT. In those cases where it is not practical or cost effective to maintain the preheat/interpass temperature until PWHT, postheating may be used. Another example is the use of postheating with controlled deposition welding as described below.

Fabrication codes generally do not specify requirements for postheating. However, ASME Section VIII, Divisions 1 & 2, ASME Section III, API 510 and NBIC (Part RD-1000) do provide specific postheating requirements after use of temper bead or controlled deposition welding as an alternative to PWHT. These requirements are shown in Table 2. It is again recommended to specify time as a function of thickness to account for the variable diffusion path, with a minimum time requirement. For example, 500 to 600°F (260 to 316°C) for 2 hours per inch (25.4 mm) of thickness, with 2 hours minimum, appears to be a reasonable approach for carbon and low alloy steels.

Table 2—Comparison of Recommended Postheating Practices

Repair Code or Practice	*Temperature °F (°C)*	*Time (hours)*
ASME Section VIII, Divisions 1 & 2	400–500 (204–260)	minimum 4
ASME Section III, Subsection NB	450–550 (232–288)	minimum 2
API 510	450–550 (232–288)	minimum 2
NBIC	500–550 (260–288)	minimum 2

3.4 Postweld Heat Treatment (PWHT)

As discussed in the previous section, PWHT is performed after welding, generally at a higher temperature and with different objectives than postheating. As with postheating, PWHT may need to be applied without allowing temperature to drop below the minimum for preheat/interpass.

Local PWHT of carbon and low alloy steels is typically performed below the lower critical transformation temperature and is therefore referred to as subcritical. The lower and upper critical transformation temperatures indicate where the crystal structure of steel begins and finally completes a change from body centered cubic to face centered cubic (upon heating, the reverse upon cooling).

There are several reasons why local supercritical PWHT (above the upper critical transformation temperature) such as annealing or normalizing is not desirable. First and foremost, the temperature gradients inherent to local PWHT would produce subcritical, intercritical and supercritical temperature regions. Depending upon the prior heat treatment of the material, this could result in a detrimental effect on properties (tensile and yield strength and impact toughness) and/or local inhomogeneity. Additionally, reduced material strength at supercritical temperatures creates a greater likelihood for distortion.

For reasons relating to carbide precipitation and the need for rapid cooling, localized solution annealing of austenitic alloys such as 300 series stainless steels is also generally not desirable. The discussion of PWHT below and in other parts of this document refer to subcritical PWHT, unless otherwise noted.

PWHT can have both beneficial and detrimental effects. Two primary benefits of PWHT are recognized. Consequential benefits such as improved ductility, toughness and corrosion resistance result from the primary benefits. The two primary benefits are tempering and relaxation of residual stresses. At the higher temperatures associated with PWHT, high hydrogen mobility generally enables adequate hydrogen removal during the customary hold periods. Therefore, hydrogen removal generally occurs as an unplanned benefit. It is important that PWHT conditions be determined based upon the desired objectives. With regard to local PWHT, this is especially true for stress relaxation, as will be discussed in later sections. When tempering has the objective to achieve specific hardness requirements, it is important to recognize that fabrication code minimum temperatures may not be adequate. This is also discussed in later sections.

Excessive or inappropriate PWHT temperature and long holding times can adversely affect properties. These adverse effects can include reduced tensile strength, reduced creep strength, and increased fracture transition temperature. The influence of PWHT on properties primarily depends upon the composition of the weld metal and base metal and prior thermal and mechanical processing of the base metal. Stout [3] and a recent state of the art review [4] provide good summaries of the effect of PWHT on properties.

The fabrication codes cited in section 2 provide detailed requirements regarding local PWHT. Requirements to apply PWHT are generally triggered by material type and thickness. The need for PWHT based upon service environment is not treated by the fabrication codes cited in section 2. Instead, recommended practices regarding service environment, such as those cited in section 2, provide guidance and will be discussed in a later section. Additional discussion regarding key PWHT parameters is provided in subsequent sections. Several comprehensive reviews regarding PWHT of welded structures are available [3,5,6]. In addition, The Japan Welding Engineering Society has published a document which specifically addresses local PWHT considerations related to pressure vessels [7].

Recent assessments of issues related to ASME Code and Japan High Pressure Institute Standard (HPIS) PWHT practices are available [8,9]. Some of the issues currently being considered include:

1) thickness at which PWHT is required;
2) adequacy of hold temperatures and variation between codes;
3) appropriateness of longer times at lower temperatures; and
4) non-circumferential local heating.

For PWHT to be successful, it must be based upon engineering assessment and optimization of parameters to meet the desired objectives. For example, as discussed previously, PWHT may degrade notch toughness for certain materials. Consideration of issues such as those stated above must be included in the assessment/optimization. As a result, engineering judgment, in addition to stated code requirements, is often necessary.

4. Special Terminology for Local Circumferential Heating

Due to the lack of standard terminology, the following terms are described and used: soak band, heated band, and gradient control band. Although aimed primarily at PWHT, these terms may also be applied to the other purposes for heating. Figure 1 provides a schematic diagram which uses these terms to describe local heating.

4.1 Soak Band (SB)

The volume of metal which must be heated to the minimum but not exceed the maximum required temperature. As a minimum, it should consist of the weld, HAZ, and a portion of the base metal adjacent to the weld being heated.

4.2 Heated Band (HB)

The surface area over which the heat source is applied to achieve the required temperature in the soak band and limit induced stresses in the vicinity of the weldment. It should consist of the soak band plus any adjacent base metal necessary to control the temperatures within the soak band and limit induced stress.

4.3 Gradient Control Band (GCB)

The surface area over which insulation and/or heat source(s) are placed. It should encompass the soak band, heated band, and sufficient adjacent base metal such that excessive axial temperature gradients can be avoided.

4.4 Control Zone

A control zone consists of a grouping of one or more heat sources which are controlled (turned on or off) based upon input from a single temperature measuring device (typically a thermocouple). One or more zones may be present in the circumferential and/or axial directions.

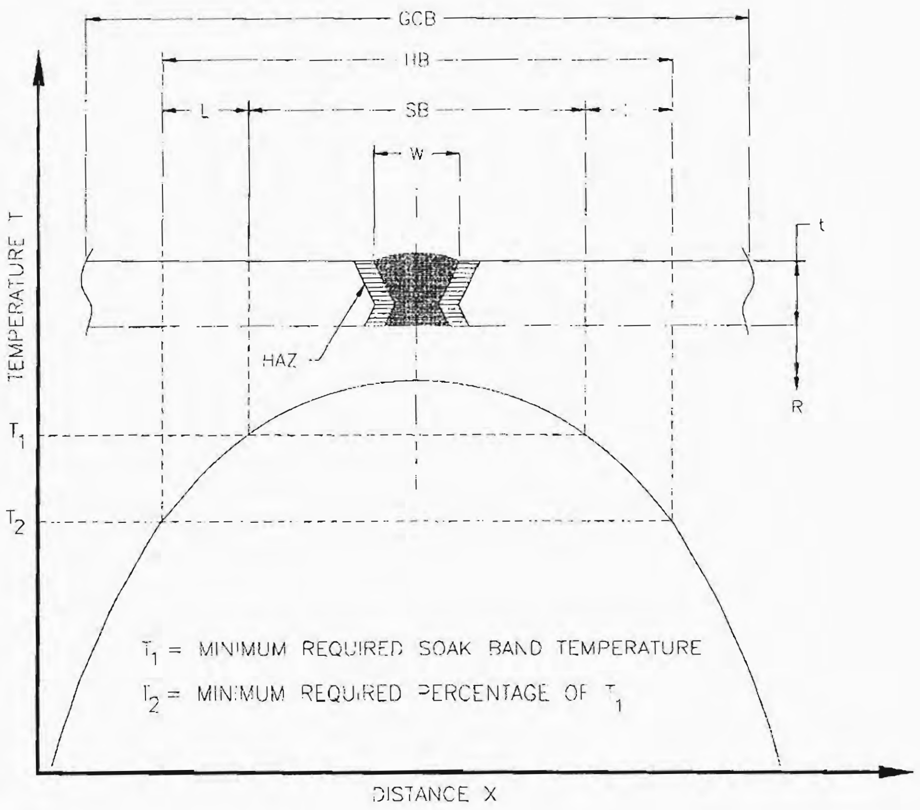
5. Local Circumferential Heating

[Refer to Section 6 and Annexes A and B of AWS D10.10/D10.10M: 1999 for additional information and recommendations.]

The cited fabrication codes are based upon the use of circumferential bands for local heating. The temperature around the circumference of these bands is generally uniform, especially for PWHT. However, practices are discussed in section 5.7.2.1 which address non-uniform temperature circumferential heating. If local hot spots are created, these areas may become permanently distorted, contain high levels of induced residual stress, or have their properties altered.

Some of the cited fabrication codes provide specific guidance only with regard to the degree of temperature uniformity during heating and cooling. For example, ASME Section III limits temperature variation during heating and cooling to not more than 250°F (138.9°C) within any 15 ft (4.6 m) interval of weld length. ASME Section VIII limits temperature variation during heating to not more than 250°F (138.9°C) within any 15 ft (4.6 m) interval of length and to 150°F (83.3°C) between the highest and lower temperatures during the hold period, unless further restricted by the allowed soak band temperature range. The limit of 250°F (138.9°C) within any 15 ft (4.6 m) interval of weld length generally acts as a circumferential temperature gradient due to the fact that it is most often applied to heating of circumferential butt welds. Generally, the required uniformity during the hold period amounts to staying within the bounds of the maximum and minimum temperature requirements specified by the codes.

The cited fabrication codes typically specify only soak band width for preheat/interpass heating. For PWHT, the cited fabrication codes may specify soak band width, heated band width and/or axial temperature gradients. However, non-specific terms such as



Nomenclature:
W = Widest width of weld.
HAZ = Heat affected zone.
SB, SB_n = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t or t_n on each side of the weld).
L = Minimum distance over which the temperature may drop to a percentage of that at the edge of the soak band.
HB = Heated band (width of heat source).
GCB = Gradient control band (minimum width of insulation and/or gradient heat source).
t, t_n = Nominal thickness of shell, head, or nozzle neck.
R, R_n = Inside radius of shell, head or nozzle neck.

Fig. 1—Schematic diagram for description of local heating.

"so that the temperature gradient is not harmful" may be used. Since local heating of pressure vessels is typically from one side, radial (through-thickness) temperature gradients must be considered, but are not addressed by the cited fabrication codes. The cited codes do not address any of these issues with respect to bake-out or postheating.

The following sections provide detailed considerations regarding the soak band, heated band, gradient control band, axial temperature gradients, proximity of pipe-to-nozzle welds to shell, intersection of heated regions with nozzles/attachments, and practices for common welds. **Since requirements may differ between different codes and specifications, the applicable version of these documents should govern for each specific application.**

5.1 Soak Band

The soak band is sized to insure that the required volume of metal achieves the temperature needed to produce the desired effect. Tables 3 and 4 compare the preheat/interpass heating and PWHT soak bands used for the cited fabrication codes. The requirement for preheat/interpass heating an area 3 inches (75 mm) in all directions from the point of welding appears to work well and is also used by piping and structural welding codes.

Table 3—Comparison of Preheat/Interpass Heating Soak Band Sizes

Fabrication Code	*Soak Band Size*
ASME Section VIII, Divisions 1 & 2	all areas within 3 in (75 mm) of the point where a weld is to be started
ASME Section III, Subsection NB	none specified
BS 5500	none specified
AS 1210	all areas within 75 mm (3 in) of the point where a weld is to be started

Note the desirability of the ASME Section III PWHT sizing approach which prevents the soak band from becoming unnecessarily large as thickness increases. In addition, the ASME Section III PWHT sizing approach is more desirable than either BS 5500 or AS 1210, in that it establishes a specific

Table 4—Comparison of PWHT Soak Band Sizes

Fabrication Code	*Soak Band Size*
ASME Section VIII, Division 1	Shell Section Welds: 2 times the shell thickness on each side of the greatest width of the weld Nozzles or Other Welded Attachments: 6 times the plate thickness on either side of the nozzle or attachment weld Pipe or Tubing Welds: 3 times the greatest width of the weld on each side of the weld centerline
ASME Section VIII, Division 2	Shell Section Welds: 2 times the shell thickness on each side of the greatest width of the weld Nozzles and External Welded Attachments: 6 times the plate thickness on either side of the nozzle or attachment weld Pipe, Tubing or Nozzle Neck Welds: 6 times the pipe, tubing or nozzle neck thickness on either side of the weld
ASME Section III, Subsection NB	Thickness of the weld or 2 inches, whichever is less, on either side of the weld face at its greatest width
BS 5500	Weld and heat affected zone
AS 1210	Weld metal and heat affected zone

size and assures attainment of the minimum temperature in the adjacent base metal to relax residual stresses present there.

The cited fabrication codes do not provide guidance regarding sizing of the soak band for bake-out or postheating. The soak band for bake-out should be larger than that for either preheat/interpass heating or PWHT. This is to insure that hydrogen does not diffuse back into the weld area during welding. A reasonable approach would be to heat an area at least 6 in (152.4 mm) or 3t (where t = wall thickness), whichever is greater, in all directions from the weld. The sizing used for PWHT appears adequate for postheating.

5.2 Heated Band

The size of the heated band is important with regard to two considerations. Because of the inherent radial temperature gradient, the band must be large enough to insure that the minimum required temperature extends through the thickness in the soak band. In addition, local heating of a cylindrical segment can generate high thermal stresses in both hoop and axial directions if severe axial and through-thickness temperature gradients are present. The resulting bending moments and compression during local PWHT can cause global buckling distortions. High Local-PWHT induced residual stresses can occur. The maximum thermal stresses and induced residual stresses are strongly affected by the width of the heated band, axial temperature distribution, and through-thickness temperature gradients [43, 44].

ASME Sections III and VIII do not provide specific guidance regarding the size of the PWHT heated band. BS 5500 and AS 1210 provide a minimum recommended PWHT heated band width of $5\sqrt{Rt}$ centered on the weld for circumferential welds and $2.5\sqrt{Rt}$ on either side of welds which connect nozzles or attachments to the shell, where "R" is the internal radius and "t" is the shell thickness. None of the codes provide guidance with regard to the heated band size for bake-out, preheat/interpass heating, or postheating.

5.2.1 Through-Thickness Temperature Gradient: From heat conduction theory, a linear through thickness temperature distribution can always be achieved if the heating rate on the outer surface can be maintained in such way that a quasi-steady state heat conduction process is followed during heating. As far as thermal stresses are concerned, a linear through-thickness temperature distribution should not generate any significant thermal stresses within the weld region in a large diameter vessel, regardless of the actual temperature differential between outer and inner surfaces. However, other considerations such as those for metallurgical reasons require through-thickness temperature gradients to be as small as possible. In this case, it should be noted that in addition to the requirements of heating to be quasi-static, the inner surface convection conditions dictate the actual inner surface temperature. However, in local heating of pipes or small diameter vessels, through-thickness linear gradients can generate thermal stresses due to additional restraints in both axial and hoop directions. For specific applications, finite element analysis may be performed in a straight-forward manner to determine the required width of heated band for achieving desirable temperature gradients under given convection conditions [e.g., 43–44]. While a systematic development of such guidelines is currently underway within the Pressure Vessel Research Council (PVRC) [45], current Codes and Practices as well as data from the open literature are summarized below.

Shifrin reported [10] on experimental work performed on pipe from which it was concluded that through-thickness temperature gradients are proportional to the width of the heated band on the surface regardless of the thickness, diameter, or energy source. He further concluded that if the heated band size is at least 5t on the outside surface, the temperature on the outside surface at an axial distance of "t" from the centerline of the weld will be approximately the same as that on the inner surface at the root of the weld. Concerns have been expressed [11] that the 5t width is not sufficient, especially as the internal radius increases with no internal insulation.

Work has been reported [12] on the effect of the heated band size on the PWHT soak band temperature achieved at the inner surface (6 o'clock position) for 6.625 in. (168 mm), 12 in. (305 mm), and 18 in. (457 mm) diameter pipes. It was suggested that a ratio be used to establish a relationship between the heat flow from the heat source and heat losses due to conduction through the wall and radiation from the inner surface. Equation (1) describes this ratio.

$$H_i = A_e/(2A_{cs} + A_i) \tag{1}$$

where: A_e = area of heat source on the outside surface
A_{cs} = cross sectional area of pipe wall
A_i = inside surface area of soak band (assumed 4t wide, centered on weld)

The results of the work demonstrated that for one zone control, with a control temperature of 1,150°F (621°C) at the 12 o'clock position, on an 18-inch (0.46 m) diameter, 1-inch (25 mm) wall thickness pipe, a temperature difference of 120°F (67°C) could occur between the outside top (12 o'clock position, centered on the weld) and inside bottom (6 o'clock position, 2t from the centerline of the weld). It was concluded that by sizing the heated band such that the ratio was at least 5, a temperature difference between the top outside and bottom inside of less than 50°F (28°C) would occur, thereby assuring achievement of the minimum temperature, 1,100°F (593°C) throughout the thickness. It was further demonstrated that the use of insulation on the inner surface reduced the temperature difference to 24°F (13°C). It should be noted the use of a ratio equal to 5 is specific to one zone control. As multiple control zones are used, with the ability to vary the set point temperature, different ratios would be appropriate. Therefore, the specific ratio of 5 is not directly applicable to pressure vessels, where internal insulation and multiple control zones are generally used. In any event, the important aspect of the work is that it highlights the need to size the heated band for through-thickness temperature gradient considerations based upon all of the factors which contribute to heat loss.

5.2.2 Induced Stresses and Distortion: During local PWHT, the interactions between thermal stresses induced during PWHT and as-welded residual stresses are very complex. Analyzing such detailed interactions had not been possible only until recently [43–44, 46–47]. These recent efforts showed that as far as weld residual stresses are concerned, three dominant mechanisms are present during local PWHT: (1) compression during heating; (2) creep relaxation during holding (soaking); (3) global stress recovery on cooling. The final weld residual stress state is mostly determined by the interactions of these three mechanisms under given local PWHT conditions. Early efforts to address the stresses resulting from local PWHT were first reported by Rose and Burdekin [13,14]. One of the bases of this work was to establish parameters which produced approximately the same degree of stress relaxation in the vicinity of the weld as achieved in a furnace. As an approximation, the hot yield strength of the material at PWHT temperature was used as the target level of stress relaxation. As a result of this work, a heated band size of $5\sqrt{Rt}$ centered on the weld was proposed. In addition, the axial temperature gradient was limited by the temperature at the edge of the heated band being no less than 1/2 the peak soak band temperature. Many international pressure vessel and piping codes have adopted this approach, including BS 5500 and AS 1210, as previously discussed.

Concern has been expressed that a heated band size of $5\sqrt{Rt}$, as required by BS 5500 and AS 1210, may be overly conservative. For example, a supplement or attachment to a German standard [15] explains the basis for changing the heated band sizing requirement from $5\sqrt{Rt}$ to $4\sqrt{Rt}$. In summary, this German standard references work suggesting that a heated band size of $2.83\sqrt{Rt}$ is adequate. As a result, a multiplier of 5 produces a safety factor of 1.77, while a multiplier of 4 has a safety factor of 1.42. The safety factor associated with the multiplier of 4 was believed to be adequate. A simplified model [16] to estimate the effect of heated band size on induced stress appears to agree with the German standard, in that a total heated band size as small as $4\sqrt{Rt}$ may provide adequate control of stresses.

5.2.3 Recommended Approach for Sizing the Heated Band: When attempting to size the heated band, the user must of course insure that its width is adequate to achieve the minimum temperatures required in the soak band. Further consideration must then be made with regard to the effect of stresses induced by the local heating. Such consideration should include assessment of distortion and residual stresses. In cases where residual stress is a concern, such as environments in which stress corrosion cracking is operative, larger heated band sizes may be considered necessary. Further discussion of this issue is provided in section 12, which addresses service environment.

For PWHT heated bands, a minimum size of the soak band width plus $2\sqrt{Rt}$ on either side of the soak band is recommended. Table 5 provides a comparison of this minimum recommended size with the BS 5500 and AS 1210 requirements for various vessel dimensions, assuming an ASME Section VIII soak band requirement of 2t beyond the each edge of the weld, and a temperature of 1,200°F (649°C) at the edge of the soak band. The ability to accommodate greater residual stress and/or distortion may enable the use of smaller heated bands and greater axial temperature gradients. Specific residual stress limits based upon failure mechanisms such as stress corrosion cracking may result in the need for larger heated bands and lower axial temperature gradients.

Selection of the heated band size for bake-out, preheat/interpass heating, and postheating would, as previously discussed, is dependent upon the insulation being used. If insulation is present on the surface opposite that for heating, it may be appropriate to use 3t or 3 in (76.2 mm), whichever is greater, on either side of the soak band. If insulation is not

Table 5—Comparison of Minimum Recommended Heated Band Size and Maximum Thermal Gradient with BS 5500 and AS 1210

Vessel Dimensions		*Section VIII*	*Minimum Recommended*			*BS 5500 and AS 1210*		
Shell Thickness t, (in)	*Inside Radius R, (ft)*	*SB (note 1) 5t (in)*	*HB (note 2) 2L + SB, (in)*	*GCB (note 3) (in)*	*Max TG (note 4) (F/ft)*	*HB 5 × Sqrt(Rt) (in)*	*GCB 10 × Sqrt(Rt) (in)*	*Max Tg (note 5) (F/ft)*
0.5	2.0	2.5	16.4	30.2	1039	17.3	34.6	831
1.0	2.0	5.0	24.6	44.2	735	24.5	49.0	588
2.0	2.0	10.0	37.7	65.4	520	34.6	69.3	416
3.0	2.0	15.0	48.9	82.9	424	42.4	84.9	339
4.0	2.0	20.0	59.2	98.4	367	49.0	98.0	294
0.5	4.0	2.5	22.1	41.7	735	24.5	49.0	588
1.0	4.0	5.0	32.7	60.4	520	34.6	69.3	416
2.0	4.0	10.0	49.2	88.4	367	49.0	98.0	294
3.0	4.0	15.0	63.0	111.0	300	60.0	120.0	240
4.0	4.0	20.0	75.4	130.9	260	69.3	138.6	208
1.0	6.0	5.0	38.9	72.9	424	42.4	84.9	339
2.0	6.0	10.0	58.0	106.0	300	60.0	120.0	240
3.0	6.0	15.0	73.8	132.6	245	73.5	147.0	196
4.0	6.0	20.0	87.9	155.8	212	84.9	169.7	170
5.0	6.0	25.0	100.9	176.8	190	94.9	189.7	152
1.0	8.0	5.0	44.2	83.4	367	49.0	98.0	294
2.0	8.0	10.0	65.4	120.9	260	69.3	138.6	208
3.0	8.0	15.0	82.9	150.8	212	84.9	169.7	170
4.0	8.0	20.0	98.4	176.8	184	98.0	196.0	147
5.0	8.0	25.0	112.6	200.3	164	109.5	219.1	131
2.0	10.0	10.0	72.0	133.9	232	77.5	154.9	186
3.0	10.0	15.0	90.9	166.8	190	94.9	189.7	152
4.0	10.0	20.0	107.6	195.3	164	109.5	219.1	131
5.0	10.0	25.0	123.0	221.0	147	122.5	244.9	118
6.0	10.0	30.0	137.3	244.7	134	134.2	268.3	107
2.0	12.0	10.0	77.9	145.8	212	84.9	169.7	170
3.0	12.0	15.0	98.1	181.3	173	103.9	207.8	139
4.0	12.0	20.0	116.0	212.0	150	120.0	240.0	120
5.0	12.0	25.0	132.3	239.7	134	134.2	268.3	107
6.0	12.0	30.0	147.6	265.2	122	147.0	293.9	98
3.0	14.0	15.0	104.8	194.6	160	112.2	224.5	128
4.0	14.0	20.0	123.7	227.4	139	129.6	259.2	111
5.0	14.0	25.0	140.9	256.9	124	144.9	289.8	99
6.0	14.0	30.0	157.0	284.0	113	158.7	317.5	91
7.0	14.0	35.0	172.2	309.3	105	171.5	342.9	84
4.0	16.0	20.0	130.9	241.7	130	138.6	277.1	104
5.0	16.0	25.0	148.9	272.9	116	154.9	309.8	93
6.0	16.0	30.0	165.8	301.5	106	169.7	339.4	85
7.0	16.0	35.0	181.6	328.3	98	183.3	366.6	79
8.0	16.0	40.0	196.8	353.5	92	196.0	391.9	73

Notes:

1. The ASME Section VIII soak band (SB) is 2× shell thickness (t) on either side of the weld, with the weld assumed to be 1t wide.
2. The heated band (HB) is based upon L = Sqrt(Rt) on either side of the soak band (SB).
3. The gradient control band (GCB) is based upon 4 × Sqrt(Rt) on either side of the soak band (SB).
4. The maximum thermal gradient (TG) is based upon a temperature drop of ½ of the peak temperature (1,200F) over the distance L from the edge of the SB.
5. The maximum thermal gradient (TG) is based upon a temperature drop of ½ of the peak temperature (1,200F) to the edge of the heated band.

Peak temperature (F) = 1200

present on the opposite surface from heating, it may be appropriate to use $2\sqrt{Rt}$ on either side of the soak band.

5.3 Gradient Control Band

As the name implies, this band is used to control the axial temperature gradient. The gradient control band generally serves two functions. It minimizes heat losses in the heated band and helps to control the axial temperature gradient. The characteristics of the insulation (both thickness and thermal properties) directly affect the power requirements of the heat source. A detailed discussion of insulation characteristics is provided in section 8. The size of the insulated area directly affects the axial temperature gradient. ASME Section III and VIII do not provide any guidance with regard to the size. BS 5500 and AS 1210 recommend a $10\sqrt{Rt}$ PWHT gradient control band centered on the weld. PWHT gradient control band sizes between two and three times that of the heated band are frequently recommended.

Based upon the previously recommended minimum heated band of $2\sqrt{Rt}$ on either side of the soak band, a minimum gradient control band of $2\sqrt{Rt}$ on either side of the heated band is recommended for

PWHT. This results in a total recommended gradient control band width of $8\sqrt{Rt}$ plus the width of the soak band. With the lower temperatures associated with bake-out, preheat/interpass heating, and postheating, the size of the gradient control band is not critical. In fact, for preheat/interpass heating using electric resistance heaters, insulation is frequently limited to covering just the heaters. A distance of 3t or 3 in (76.2 mm), whichever is greater, on either side of the heated band appears to be an appropriate size for the gradient control band for bake-out, preheat/interpass, and postheating.

It is also important to note that if vessel wall thickness changes, or attachments are present within the gradient control band, the use of supplemental heat source(s) may be required. Several examples of situations requiring supplemental heat sources are in section 17, which provides detailed descriptions of case histories.

5.4 Axial Temperature Gradient

The axial temperature distribution plays an important role in limiting the previously discussed thermal stresses during PWHT. The axial temperature gradient is not generally specified for bake-out, preheat/interpass heating, or postheating because of the lower temperatures associated with these processes.

Table 6 provides a comparison of the requirements for controlling axial temperature gradients during PWHT in the cited fabrication codes. Note that ASME Sections III and VIII do not define harmful gradient. BS 5500 and AS 1210 provide specific requirements to limit the gradient to the edge of the heated band, i.e. a temperature drop of not greater than one-half the peak temperature over the soak band distance $2.5\sqrt{Rt}$. It should be noted that a different minimum temperature results depending on the temperature scale being used. Using the Fahrenheit scale and an assumed soak band temperature of 1,100°F (593°C), the minimum temperature allowed at the edge of the heated band would be 550°F (288°C). Using the Celsius scale and an assumed soak band temperature of 593°C (1,100°F), the minimum temperature allowed at the edge of the heated band would be 297°C (567°F). Based upon the magnitude of the difference, this is not expected to be significant.

Both BS 5500 and AS 1210 recommend that insulation placed a minimum distance of $2.5\sqrt{Rt}$ beyond the edge of the heated band, as previously discussed in the section 5.3 above, to insure the achievement of acceptable gradients.

The Japan Welding Engineering Society [7] presents an approach for the determination of an acceptable axial temperature gradient based upon limiting stress so as not to exceed the creep strength of the material at the stress relaxation temperature. This approach requires creep curves at various PWHT temperatures for each material.

Table 6—Comparison of PWHT Gradient Control Requirements

Fabrication Code	*Gradient Control Requirement*
ASME Section VIII, Divisions 1 & 2	The portion of the vessel outside of the circumferential band shall be protected so that the temperature gradient is not harmful.
ASME Section III, Subsection NB	The temperature of the component or item from the edge of the controlled band outward shall be gradually diminished so as to avoid harmful thermal gradients.
BS 5500	The temperature at the edge of the heated band is not less than half the peak temperature. In addition, the adjacent portion of the vessel outside the heated zone shall be thermally insulated such that the temperature gradient is not harmful.
AS 1210	The longitudinal temperature gradient shall be such that the temperature of the cylinder at a distance on each side of the weld not less than $2.5\sqrt{Rt}$ shall not be less than half the heat-treatment temperature.

As discussed above, justification for changes to the heated band size in a German standard [15] and unpublished work [16] regarding a simplified model to estimate the effect of heated band size on induced stress suggest that limiting the temperature drop to one half of the peak soak band temperature to the edge of a heated band as small as $4\sqrt{Rt}$ may provide adequate control of stresses.

The Dutch pressure vessel code [17] limits the temperature drop at two locations: one-half the distance to the edge and at the edge of the heated band. The minimum temperature required at one-half the distance to the edge is 80%, while that at the edge is 50%. Such a requirement provides greater assurance of a uniform axial temperature gradient.

It is recommended that as a minimum, the axial temperature gradient during PWHT be controlled such that the temperature at a distance of $2\sqrt{Rt}$ from the edge of the soak band be no less than one half the temperature at the edge of the soak band during heating, hold and cooling. A comparison of this recommended maximum temperature gradient and that used for BS 5500 and AS 1210 is shown in Table 5. Where concerns exist regarding distortion or the presence of residual stress, a larger distance can be specified and/or multiple locations used to specify the axial temperature gradient.

Based upon the lower temperatures normally associated with bake-out, preheat/interpass heating, and postheating, control of the axial thermal gradient is not required. If temperatures above 800°F (427°C) are to be used, then the axial temperature gradient recommended for PWHT should be used.

5.5. Proximity of Pipe-to-Nozzle Welds to Shell or Head

Local circumferential PWHT of pipe-to-nozzle welds may result in heating the nozzle and/or surrounding shell or head section to temperatures such that concerns arise with regard to distortion and induced stresses. This is generally not a concern at the lower temperatures normally associated with bake-out, preheat/interpass heating, and postheating.

ASME Sections III and VIII and BS 5500 do not address considerations regarding the proximity of pipe-to-nozzle or flange-to-nozzle welds to the shell or head during local heating. AS 1210 provides detailed requirements regarding this issue during PWHT. The following briefly summarizes the additional heating requirements of AS 1210 beyond those associated with the pipe-to-nozzle weld. Requirements for additional heating in AS 1210 are based upon the distance N_L, as defined in Figure 2. When the distance N_L is less than $5\sqrt{R_n t_n}$, requirements are imposed to heat sections of the shell. When $5\sqrt{R_n t_n} > N_L \geq 2.5\sqrt{R_n t_n}$, the nozzle-to-shell junction must be heated and the temperature gradient controlled such that the temperature of the shell at a distance of $2.5\sqrt{Rt}$ from the nozzle-to-shell junction not be less than one-half the temperature at the junction. When $N_L < 2.5\sqrt{R_n t_n}$, a full circumferential band on the shell must be heated as required when applying PWHT to a weld connecting a nozzle or attachment to the shell. This would consist of a full circumferential soak band on the shell (the entire nozzle would be included in this soak band), heated band extending $2.5\sqrt{Rt}$ on either side of the shell-to-nozzle attachment weld, and the temperature at edge of the heated band not less than one-half the soak band temperature at the shell to nozzle junction.

An evaluation to determine the feasibility of local stress relieving of a circumferential pipe-to-nozzle field weld positioned close to the shell of a large pressure vessel has been reported [18]. Due to cost restrictions, a relationship was assumed between the weld to shell distance and the weld to nozzle taper distance. The assumption was that the weld to shell distance was 6-inches (152.4 mm) greater than the weld to nozzle taper distance. In addition, the evaluation was performed using a heating and cooling rate of 100°F/hr (55°C/hr). The governing maximum allowable stress was based upon 90% of yield strength. It was concluded that the minimum feasible distance from the field weld to the shell was 18.4 times the pipe wall thickness plus 6-inches (152.4 mm). It was noted that this minimum feasible distance was applicable only to the configuration which was evaluated, with the maximum stresses occurring at the root of the nozzle taper.

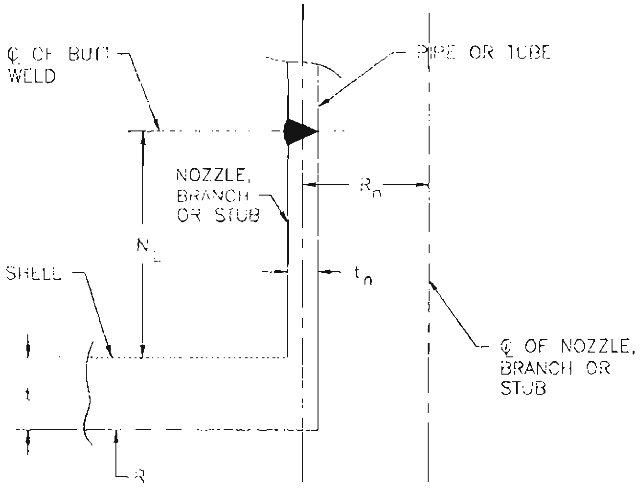


Fig. 2—Schematic diagram used by AS 1210 to specify requirements relating to the proximity of pipe-to-nozzle welds to the shell.

The following rationale has been applied with regard to establishing a general recommendation. It is recognized that the approach in AS 1210 does not take into account specific features of the nozzle, such as the weld to nozzle taper region which was shown to exhibit the highest stress in the above reported evaluation. Therefore, it was felt that an adaptation of the AS 1210 approach which required heating of the entire nozzle at a distance N_L greater than $2.5\sqrt{Rt}$ might help address this deficiency. In addition, it was desired to provide a more simplified criteria.

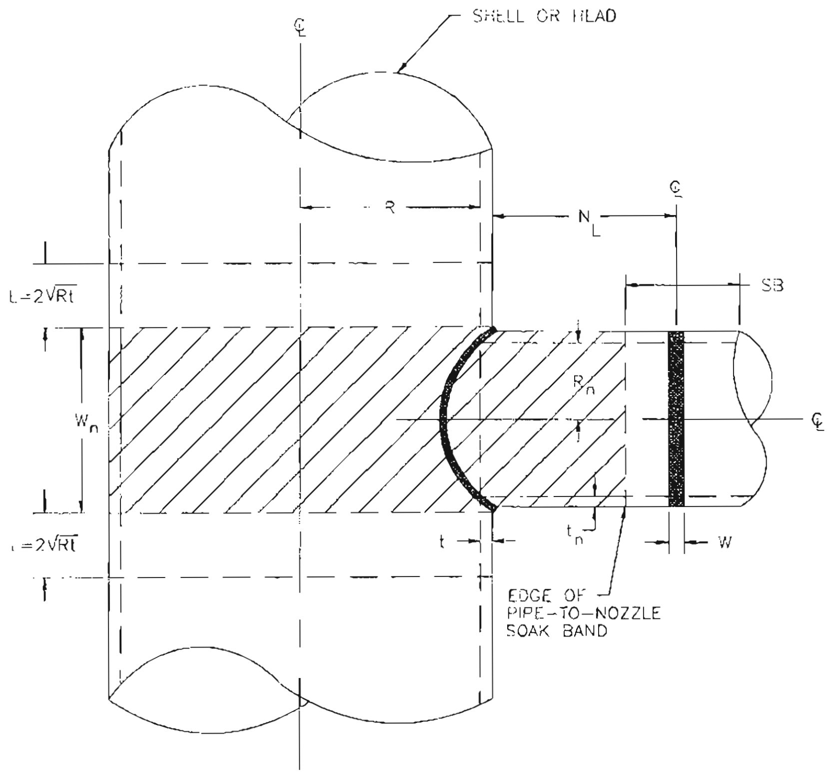
As a result, the following minimum requirements, as shown in Figure 3, are recommended. Note that these requirements are in addition to those required for PWHT of the pipe-to-nozzle weld itself. If the distance N_L, shown in Figure 3, is less than $4\sqrt{R_n t_n}$, a full circumferential band around the shell or head, and including that part of the nozzle outside of the pipe-to-nozzle weld soak band, should be heated to at least 70% of the temperature at the edge of the soak band for the pipe-to-nozzle weld. In addition, the axial temperature gradient shall be controlled beyond the edge of the area on the shell or head being heated to 70% of the temperature at the edge of the pipe-to-nozzle weld soak band. The temperature at a distance of $2\sqrt{Rt}$ from the area being heated to 70% shall be at least one-half of the temperature at the edge of the soak band for the pipe-to nozzle weld.

It is also recognized that based upon experience or analysis, shorter distances of N_L may be acceptable before requiring heating of the nozzle and shell.

5.6 Intersection With Nozzles and Attachments

Nozzles, branch connections or other attachments which do not require PWHT may intersect either the soak band, heated band, or gradient control band. As a result, there may be concerns with regard to distortion and/or induced residual stress in the nozzles, branch connections or attachments. This is generally not a concern at the lower temperatures normally associated with bake-out, preheat/interpass heating, and postheating.

In order to avoid distortion and/or induced residual stresses during PWHT, a good practice is to minimize the temperature gradient across these



Note: The recommended practice shown in Figure 5 can be used for the pipe-to-nozzle weld.

Nomenclature:

W = Widest width of the pipe-to-nozzle weld.

W_n = Widest width of the nozzle attachment weld.

Shaded area = A circumferential band W_n wide on the shell or head and the region on the nozzle outside of the pipe-to-nozzle soak band heated to at least 70% of the temperature at the edge of the pipe-to-nozzle soak band.

SB = Soak band for pipe-to-nozzle weld (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t_n on each side of the weld).

N_L = Distance from centerline of pipe-to-nozzle weld to shell or head.

L = Minimum distance over which the temperature may drop to one half of that at the edge of the pipe-to-nozzle soak band.

t, t_n = Nominal thickness of shell, head, or nozzle neck.

R, R_n = Inside radius of shell, head or nozzle neck.

Fig. 3—Additional heating required for pipe-to-nozzle welds closer than $N_L = 4\sqrt{R_n t_n}$ to the shell or head.

components. This may require the application of a supplementary heat source(s) to the nozzle, branch connection or attachment.

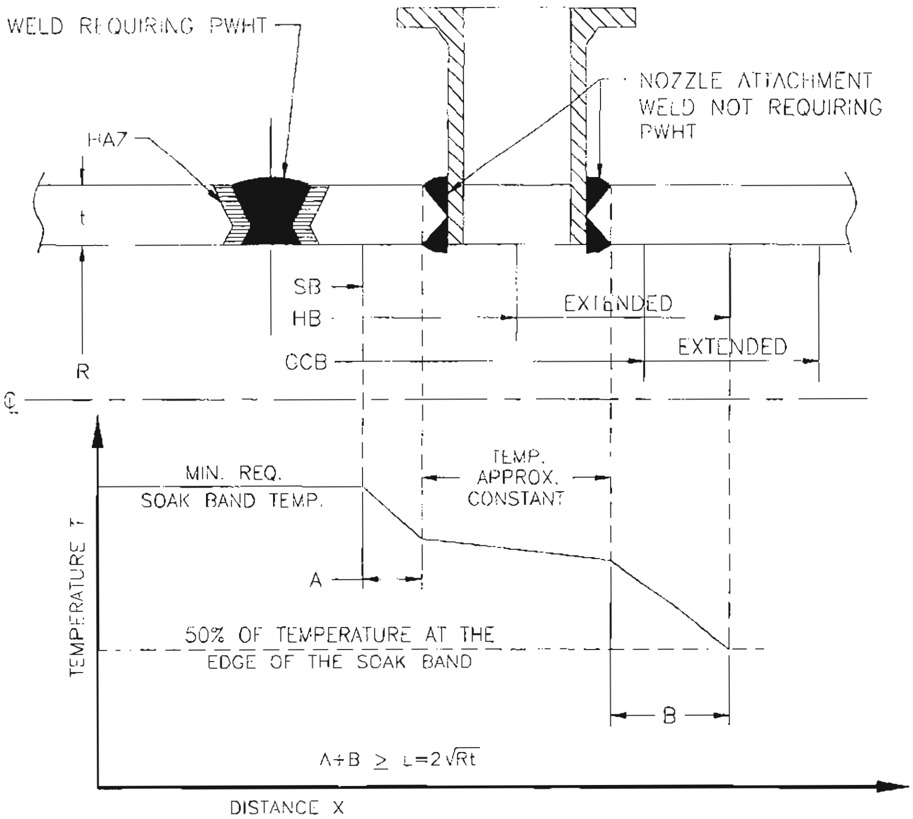
A safe practice is to maintain an approximately uniform temperature across these components. As a result, the soak band, heated band or gradient control band, whichever intersects, should be extended in the axial direction such that it ends beyond the weld on the opposite side connecting the nozzle, attachment or associated pad to the shell. In addition, the minimum distance, L, over which the temperature can drop to 50% of that at the edge of the soak band, should be achieved outside the region of intersection. Figure 4 provides an example of such an approach when the heated band from a weld requiring PWHT intersects a nozzle which does not require PWHT. Note that the total distance over which the temperature drops from that at the edge of the soak band to 50% ("A" plus "B") is greater than or equal to $L = 2\sqrt{Rt}$.

It is also recognized that based upon experience or analysis, larger temperature gradients across such nozzles or attachments may produce acceptable levels of distortion or residual stress.

5.7 Recommended PWHT Practices for Common Welds

The following recommended practices utilize the soak bands, heated bands and gradient control bands discussed above. Note that some practices are not currently recognized by fabrication codes and therefore may not be allowed. For repair codes, use of these alternate practices may be allowed based upon approval by the Authorized Inspector.

5.7.1 Weld in Shells or Heads: For welds (such as circumferential seams) in cylindrical shells, a



Nomenclature:

SB = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals a multiple of t on each side of the weld).

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

t = Nominal thickness of shell or head.

R = Inside radius of shell or head.

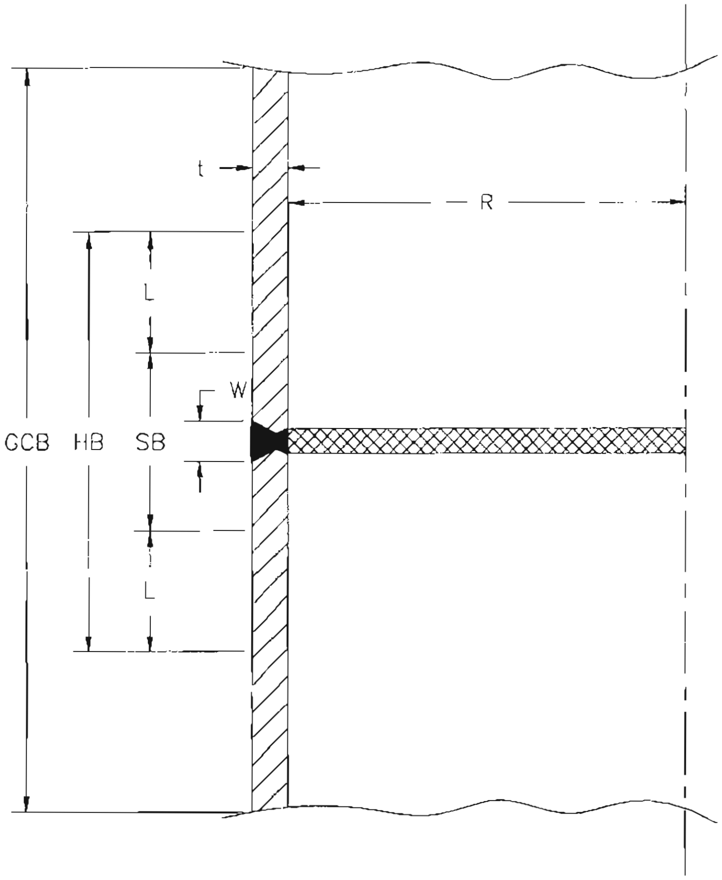
Fig. 4—Example of one approach when the heated band from a weld requiring PWHT intersects a weld not requiring PWHT.

uniform width circumferential band PWHT practice, as illustrated in Figure 5, is recommended. For welds (such as circumferential seams) in hemispherical heads or spherical vessels, a uniform width circumferential band PWHT practice, as illustrated in Figure 6, is recommended. Note that the practice described by Figure 6 is applicable when the soak band is located a minimum of 30 degrees from the vessel or head centerline. When the soak band is closer than 30 degrees from the vessel or head centerline, it is recommended that the soak band be extended to the centerline as shown in Figure 6.

5.7.2 Welds Connecting Nozzles or Other Attachments: For welds connecting nozzles or other attachments to cylindrical shells, a uniform width circumferential band PWHT practice, as illustrated in Figures 7 and 8, is recommended. For welds connecting nozzles or other attachments to hemispherical heads or spherical vessels, a practice similar to that shown in Figure 6 is recommended. An alternate approach for hemispherical heads or spherical vessels using circular "spot" heating is discussed in section 6.

5.7.2.1 Non-Uniform Temperature / Width Heating. Although existing fabrication codes only recognize uniform circumferential band practices, the following practices may be accepted by the Authorized Inspector for use with repair codes. Specifically, these practices may be used to exclude or minimize the need for heating nozzles or attachments whose welds do not require PWHT or when it is undesirable to heat the entire circumference to the full PWHT temperature.

These practices may be used when the vessel is sufficiently large in diameter to accommodate the requirements shown in Figures 9 and 10. Figure 9 describes a practice in which a circular soak band is utilized in conjunction with a full circumferential band heated to at least 70% of the temperature at the edge of the soak band. Figure 10 describes a practice



Nomenclature:

W = Widest width of weld.

SB = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t on each side of the weld).

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

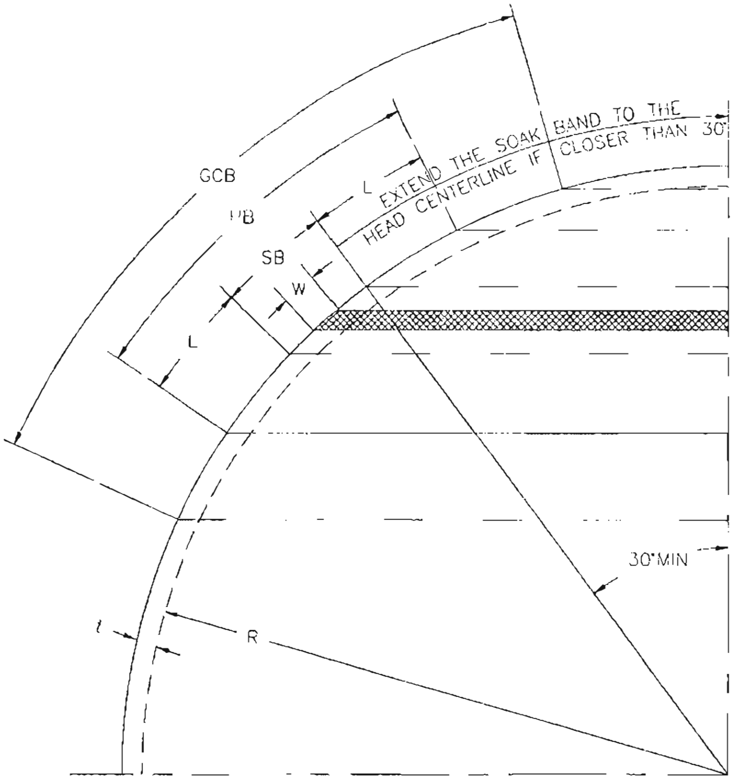
HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

t = Nominal thickness of shell or head.

R = Inside radius of shell or head.

Fig. 5—Example of uniform circumferential band without nozzles or attachments.



Note: If the soak band is closer than 30° to the vessel or head centerline, the soak band should be extended to the centerline.

Nomenclature:

W = Widest width of weld.

SB = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t on each side of the weld).

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

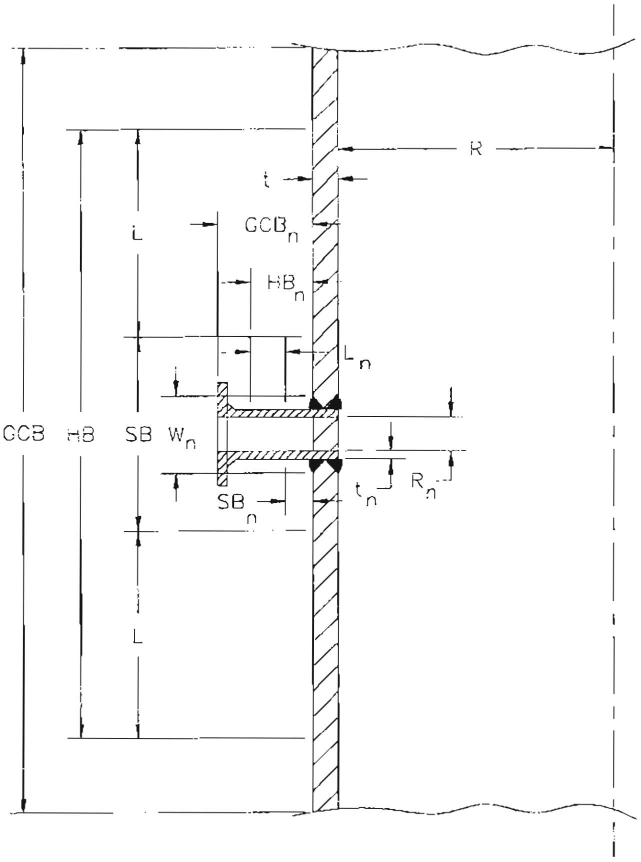
HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

t = Nominal thickness of shell or head.

R = Inside radius of shell or head.

Fig. 6—Uniform width circumferential band without nozzles or attachments for hemispherical heads or spherical vessels.



Nomenclature:

W_n = Widest width of nozzle attachment weld.

SB = Soak band on shell or head (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W_n plus a multiple of t on each side of the weld).

SB_n = Soak band on nozzle. The minimum width equals a multiple of t_N from the widest width of the weld.

L, L_n = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band ($L = 2\sqrt{Rt}$ and $L_n = 2\sqrt{R_n t_n}$).

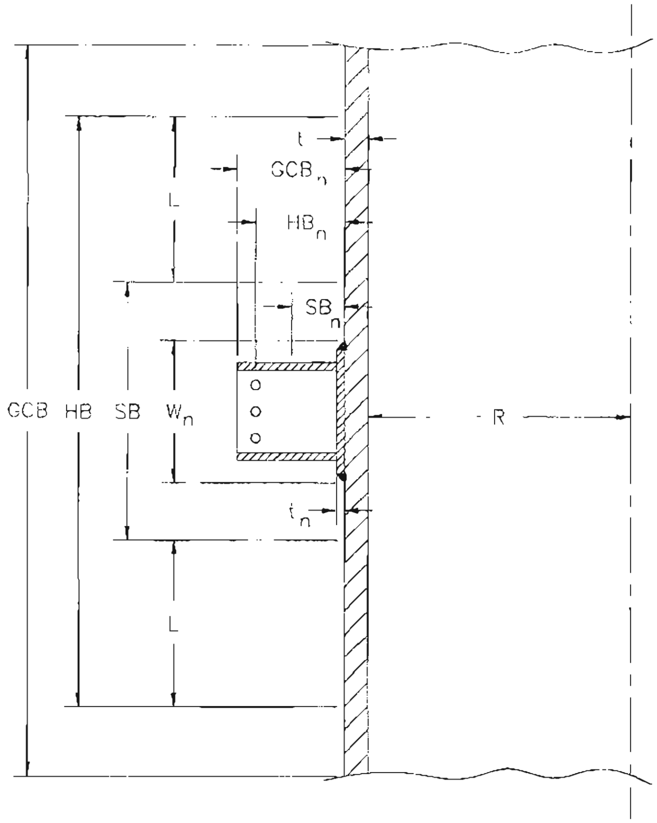
HB, HB_n = Heated band (width of heat source).

GCB, GCB_n = Gradient control band (minimum width of insulation and/or gradient heat source).

t, t_n = Nominal thickness of shell, head, or nozzle neck.

R, R_n = Inside radius of shell, head or nozzle neck.

Fig. 7—Uniform width circumferential band with nozzle.



Nomenclature:

W_n = Widest width of attachment weld.

SB = Soak band on shell or head (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W_n plus a multiple of t on each side of the weld).

SB_n = Soak band on structural pad/clip attachment. The minimum width equals a multiple of t_n.

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

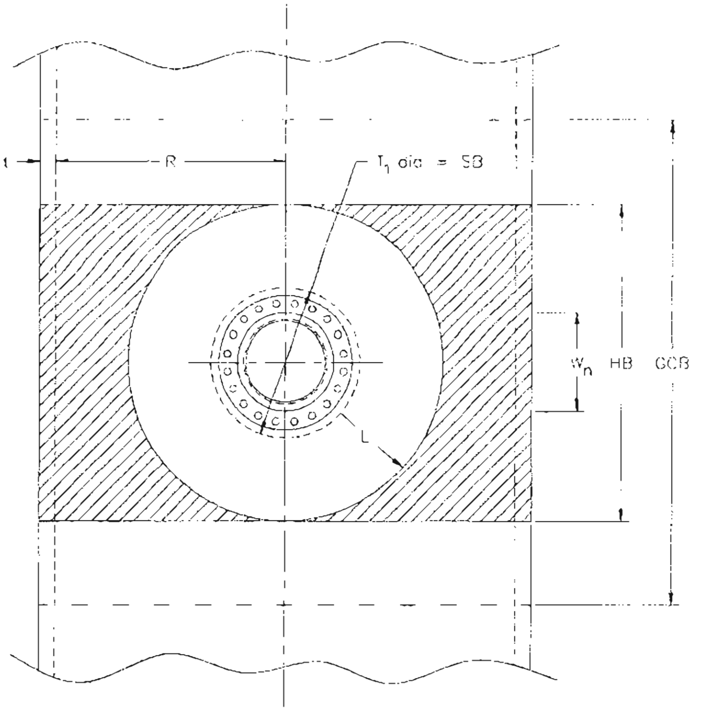
HB, HB_n = Heated band (width of heat source).

GCB, GCB_n= Gradient control band (minimum width of insulation and/or gradient heat source).

t, t_n = Nominal thickness of shell, head, or attachment.

R = Inside radius of shell or head.

Fig. 8—Uniform width circumferential band with structural pad/clip attachment.



Note: SB_n, L_n, HB_n and GCB_n are defined in Figure 7.

Nomenclature:

W_n = Widest width of attachment weld.

SB = Circular soak band on shell or head (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum diameter equals W_n plus a multiple of t on each side of the weld).

L = Minimum distance over which the temperature may drop to 70% of that at the edge of the soak band.

Shaded area = The region in which the temperature must be greater than or equal to 70% of that at the edge of the soak band.

HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

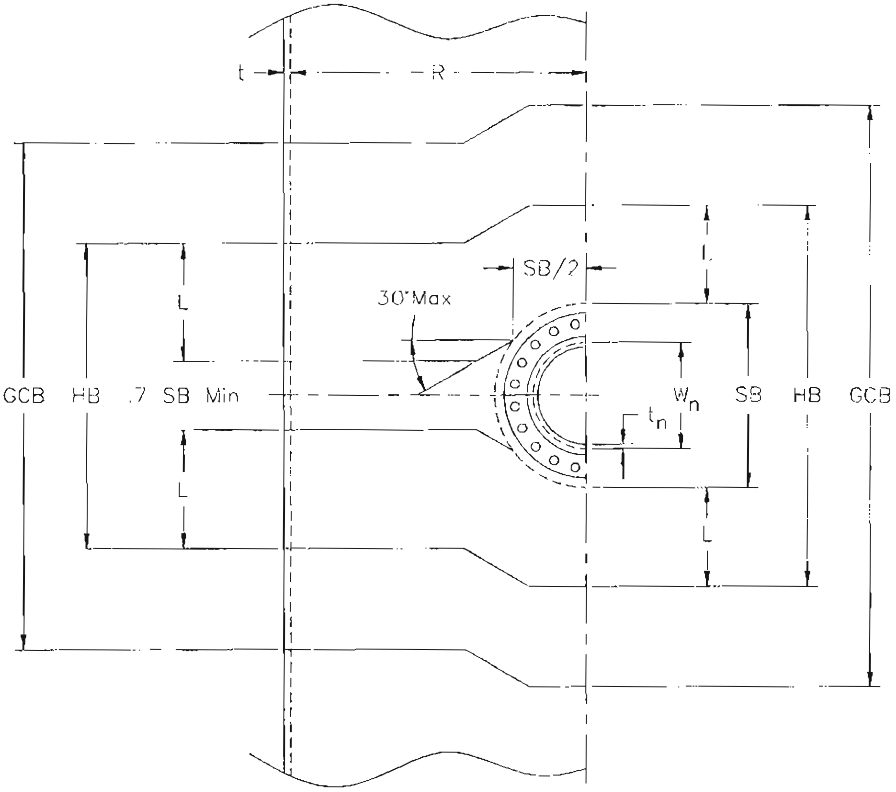
T_1 = Temperature at the edge of the soak band, meets or exceeds the minimum required.

T_2 = Temperature in the shaded region, greater than or equal to 70% of T_1.

t, t_n = Nominal thickness of shell or nozzle neck.

R, R_n = Inside radius of shell or nozzle neck.

Fig. 9—Uniform width, non-uniform temperature circumferential band with nozzle attachment.



Note: SB_n, L_n, HB_n and GCB_n are defined in Figure 7.

Nomenclature:

W_n = Widest width of attachment weld.

SB = Soak band on shell or head (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W_n plus a multiple of t on each side of the weld).

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

t, t_n = Nominal thickness of shell or nozzle neck.

R, R_n = Inside radius of shell or nozzle neck.

Fig. 10—Non-uniform width, uniform temperature circumferential band with nozzle attachment.

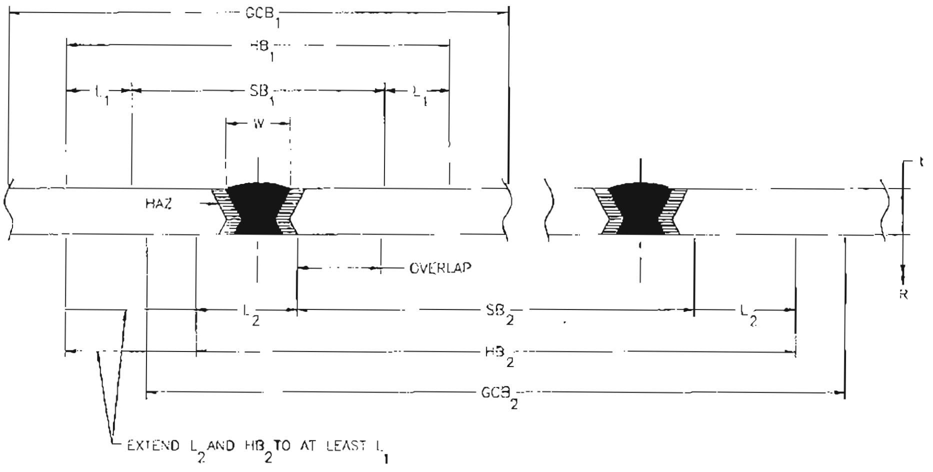
in which the width of the soak band around the vessel is reduced to 70% of that required at the attachment weld requiring PWHT.

5.7.3 Heating Large Sections, Overlapping Sections or the Entire Vessel: In certain situations, local heating of welds may be best accomplished by heating large sections, overlapping sections or the entire vessel. Some of the factors influencing a decision to heat a larger region than just the local area required for the weld might include the following:

1) proximity to attachments which results in a larger heated area;
2) costs for heating the larger area may be less; and
3) better control of induced stresses and/or distortion.

Section 16 provides additional discussion regarding this decision. The recommended approach for circumferential heating of sections would generally follow the practices described in Figure 5. However, for heating methods such as internal heating using high velocity heated air, the region heated to the soak band temperature would be extended to include essentially the entire region being heated.

Figure 11 provides a recommended approach for local heating using overlapping circumferential bands. ASME Sections III and VIII, BS 5500 and AS 1210 provide specific requirements for the overlap region when such heating is to be performed in a furnace. Although not explicitly stated in these codes, since the requirement is for furnace heating, it is assumed that the overlap applies to the soak band. ASME Sections III and VIII require that the overlap region be at least 5 feet (1,524 mm); BS 5500 requires that it be at least 1,500 mm (59.1 inches) or



Nomenclature:
W = Widest width of weld.
HAZ = Heat affected zone.
SB_1 = First soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t on each side of the weld).
SB_2 = Second soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum width equals W plus a multiple of t on each side of the weld).
L_1, L_2 = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.
HB_1, HB_2 = Heated band (width of heat source)
GCB_1, GCB_2 = Gradient control band (minimum width of insulation and/or gradient heat source).
Overlap = Region in which the two soak bands overlap.
t = Nominal thickness of shell or head.
R = Inside radius of shell or head.

Fig. 11—Example of local PWHT procedure using overlapping circumferential bands.

$5\sqrt{Rt}$, whichever is greater; and AS 1210 requires that it be at least 1,500 mm (59.1 inches). The need to heat such large overlap regions is not apparent. The objective for specifying such an overlap region is to insure that all material within the vessel achieves the minimum required soak band temperature and that heated band sizes and axial gradients are sufficient to limit induced stresses and distortion. A smaller overlap width could therefore be specified in combination with control of the heated band and the axial temperature gradient. For example, an overlap of 2 times the shell thickness (2t) might be appropriate for the approach described in Figure 11. Also note that in Figure 11 the heated band (HB_2) and the distance over which the temperature may drop to 50% of that at the edge of the soak band (L_2) for the second circumferential heating have been extended to avoid inducing stress in the weld which received PWHT first.

ASME Section VIII, Division 2, paragraph AF-410.2 requires that the cross section where the vessel projects from the furnace not intersect a nozzle or other structural discontinuity. Therefore, the approach described above to avoid inducing stress in the weld which received PWHT first should also be applied when an overlap region intersects a nozzles or other structural discontinuity.

Section 17 provides several case histories which describe heating large, bulkheaded sections using internal gas firing.

6. Local Non-Circumferential PWHT

Applications frequently arise where it may be more practical to apply local non-circumferential PWHT. Such PWHT generally involves heating a circular area and is therefore often referred to as "spot" PWHT. Due to highly restrained mechanical conditions during spot PWHT, two major concerns are present: thermal stresses at geometric discontinuities near and outside the heated band and the reactions of the weld region and weld residual stresses. The following section provides recommendations regarding the applicability of such PWHT practices.

6.1 Requirements in Fabrication and Repair Codes

ASME Sections III and VIII and BS 5500 do not provide an allowance for non-circumferential PWHT. AS 1210 provides specific requirements for PWHT of a local area around nozzles or attachments on spheres or dished ends. In summary, the AS 1210 requirements specify a circular soak band and that the temperature at a radial distance $2.5\sqrt{Rt}$ from the edge of the attachment weld is not less than one-half the PWHT temperature, (where R = inside principal radius of the sphere or end and t = the thickness). Further restrictions are imposed on the proximity of the half temperature location to the junction with the shell (for heads) or other attachments.

API 510 (para. 5.25) explicitly allows non-circumferential heating providing certain precautions and requirements are applied. In general, these precautions and requirements include:

1) review and development of a procedure by a pressure vessel engineer;
2) consideration of various factors such as expected strains/distortion, material properties, thermal gradients, etc.;
3) a minimum preheat temperature of 300°F (149°C);
4) monitoring by a suitable number of thermocouples; and
5) supplementary heating of intersected branch connections or attachments.

Although not explicitly stated in NBIC, alternative methods of postweld heat treatment per section RC-1103 (which are assumed to include non-circumferential heating) may be used if acceptable to the Authorized Inspector.

6.2 Bases for Current Practices

Early published work regarding non-circumferential PWHT appears to be limited to spherical vessels or heads [19]. Published and unpublished work generally utilize a circular heated region with sizing and temperature gradient control based upon a function of $\sqrt{Rt}$ as described above for AS 1210. Recent work [44, 49] performed on a case by case basis showed that, by considering detailed thermal stress interactions with weld residual stresses, both the temperature level and heated area size for spot PWHT may be significantly reduced from typical codes requirements to achieve desired weld residual stress reduction. From such analyses, it was shown that the reduction of weld residual stresses was mainly obtained by thermal compression effects ("hot compression") within the weld caused by spot PWHT. If such effects can be generalized in the new PVRC joint industry project [45], significant economic benefits for using spot PWHT procedures can be realized in terms of reduced spot heating area, hold time, and temperature level. In doing so, the likelihood of generating high thermal stresses at nearby geometric discontinuities should also be reduced. Any decision to reduce temperature must be made with a clear understanding of the objectives for PWHT. For example, if tempering is an objective, a lower temperature, even with adequate reduced in residual stress, may not be desirable.

At present, the application of generalized rules for non-circumferential local heating of non-spherical surfaces has not been recommended. Instead, each application involving non-circumferential local heating of a non-spherical surface must be evaluated on its own merit.

6.3 Recommended Practice for Spherical Heads or Vessels

Welds in hemispherical heads or spherical vessels may undergo PWHT using the practices described in Figure 12. Note that the edge of the soak band must be a minimum of 2 feet or $1.5\sqrt{Rt}$, whichever is greater, from the head to shell junction or other structural discontinuity. This practice has also been applied to the larger radius section of double curvature heads such that the edge of the soak band must be a minimum of 2 feet or $1.5\sqrt{Rt}$, whichever is greater, from the knuckle transition region between the larger and smaller radius sections. Multiple nozzle or attachment welds may undergo PWHT using this practice, provided that the soak band is increased in size to properly incorporate all of the welds.

6.4 Analysis to Justify Use in Non-Spherical Components

The acceptability of non-circumferential local PWHT to non-spherical components must be determined on a case-by-case basis. The approach outlined in API 510 provides a framework for performing an evaluation. It is recommended that such an evaluation be documented in writing and include consideration of all of the precautions and requirements of API 510.

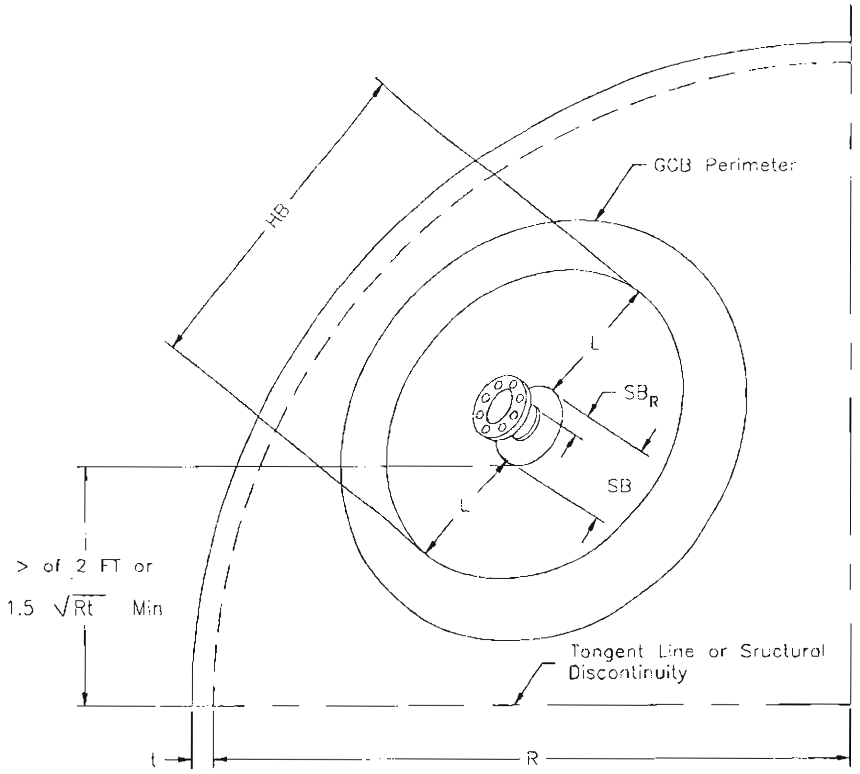
The analysis should include the effect of all significant or major structural discontinuities (such as nozzles, attachments, and head to shell junctions) and any mechanical loads which may be present during PWHT within the gradient control band.

If an elastic analysis is performed, it has been suggested that thermal stress be treated as a primary stress. It has further been suggested to consider only the contribution to membrane stress. As a result, a possible acceptance criteria for such an elastic analysis would be that the calculated membrane stress at any point be limited to the yield strength of the material for the temperature of that point.

Of course, elastic-plastic analyses can be performed to estimate strain and residual stress levels induced by spot PWHT. If such an analysis is to be performed, it is recommended that the weld residual stress state should also be considered [e.g., 43, 44, 48], since additional benefits can be demonstrated if the reduction of weld residual stresses is one of the objectives in applying spot PWHT. Acceptance criteria for such analyses would have to be based upon specific knowledge of the component and its service environment.

7. Measurement of Temperature

[Refer to Section 8 and Annex C of AWS D10.10/D10.10M: 1999 for additional information and recommendations.]



Note: SB_n, L_n, HB_n and GCB_n are defined in Figure 7.

Nomenclature:

W_n = Widest width of attachment weld (see Figures 7, 9, & 10).

SB = Circular soak band on shell or head (width of the volume of the material where the holding temperature equals or exceeds the minimum required. The minimum diameter equals W_N plus a radius, SB_R, which is a multiple of t from the edge of the weld attaching the nozzle or reinforcing plate).

L = Minimum distance over which the temperature may drop to one half of that at the edge of the soak band.

HB = Heated band (width of heat source).

GCB = Gradient control band (minimum width of insulation and/or gradient heat source).

t, t_n = Nominal thickness of shell, head, or nozzle neck.

R, R_n = Inside radius of shell, head or nozzle neck.

Fig. 12—Circular heating for nozzle attachment on hemispherical heads or spherical vessels.

It is necessary to measure temperature during heating operations. It is desirable and frequently required to produce a continuous permanent record of the temperature during a heating cycle. Although temperature can be measured using various methods, temperature-indicating crayons/paints and thermocouples are very common for local heating. The following section considers the applicability of using temperature-indicating crayons/paints or thermocouples and provides recommendations for their proper use.

7.1 Temperature-Indicating Crayons and Paints

Temperature-indicating crayons and paints are of compositions which melt when the temperature exceeds the value for which they were designed. If a crayon or paint mark melts, the temperature is above that for which the crayon or paint is rated, but one does not know by how much, unless several with different melting points are placed in close proximity. Some types of crayons or paint may not be able to indicate that this temperature is being maintained. By using a combination of such indicators, one can determine that the temperature is above the temperature of the mark which melts and lower than the rating of another mark which does not melt. The surface of the work must be accessible for the use of these materials. As a result, this generally limits the applicability to preheat/interpass heating.

While it is possible to use such a manual approach if proper attention is exercised, it must be recognized that the likelihood of measurement lapses and associated temperature excursions is greatly increased compared with methods that utilize automatic measurement and control. In addition, the use of temperature indicating crayons or paint does not enable production of a continuous permanent record of temperature during the heating cycle. Therefore, the use of temperature indicating crayons or paint is not recommended.

7.2 Thermocouples

If the ends of dissimilar wires are in contact with each other and also with a hot (hot junction) and a cold (cold junction) surface, a voltage difference between the two junctions is created with one wire serving as a positive electrical lead, and the other as the negative lead. These voltage differences are proportional to the differences in temperature. Therefore, a properly calibrated instrument connected to the cold junction to measure the voltage difference can translate voltages into temperature readings at the hot junction. However, each combination of wires requires a separate calibration and an instrument designed for that combination.

A more complete discussion of thermocouples and their use is given in ASTM manual MNL 12 [20] and ANSI standard MC96.1 [21]. Of the seven combinations of thermocouple wire classified and discussed in these documents, three are commonly selected for local heating operations. Their classification, nominal composition, upper temperature limits, and color coding are shown in Table 7. The letter designation applies only to the temperature-voltage relationship and not to the material. This is done to eliminate the use of proprietary names.

Thermocouple wires are available in different gauges. Due to the lower thermal mass of the junction and leads, thinner wire can have a faster response in some applications. In selecting a wire gauge, one must consider the response time as well as the durability, loop resistance of the circuit, chemical corrosion, radiation effects, and stability. Larger diameter wires exhibit better long term stability at high temperatures. Further discussion of thermocouple materials can be found in the ASM Handbook [22]. The size of wire commonly used in local heating is #20 American Wire Gage (AWG), which has a diameter of 0.032 in (0.81 mm).

The wires must be electrically insulated from each other and from any other conductor, such as the metal being heated, except at the junction. Such separation is accomplished by an insulation sheath, ceramic beads, or similar systems. It is important that the thermocouple and insulation material and construction withstand the temperatures and environments to which they will be exposed.

Table 7—Thermocouple Data

Type	*Nominal Composition*	*Normal Upper Temperature Limit*	*Positive Color*	*Negative Color*
J	Iron—Constantan	1,400°F (760°C)	White	Red
E	Chromel—Constantan	1,600°F (870°C)	Purple	Red
K	Chromel—Alumel	2,300°F (1,260°C)	Yellow	Red

7.3 Thermocouple Extension Wires

Usually, the temperature-measuring instrument is farther from the heated area than the length of the thermocouple, requiring a thermocouple extension wire to connect the thermocouple and the instrument. Thermocouple extension wires are either of the same composition as the thermocouples (sensor grade) or designed to be compatible with the thermocouple system (extension grade). Extension grade wire differs from sensor grade wire in that extension grade accuracy (compared to National Institute of Standards and Technology [NIST] standards) is within acceptable limits only at low temperatures (32 to 390°F [0 to 199°C]) [22]. In the ANSI designation system, thermocouple extension wires have the letter "X" included in their designation. For example, thermocouple Type J (iron-constantan) uses thermocouple extension Type JX.

Care must be taken to connect the positive side of the thermocouple to the positive side of the extension lead and the negative to the negative. To facilitate correct polarity connections, the color red is used for the covering on the negative side of both thermocouples and extension leads, regardless of the thermocouple type.

In designing the extension cable system, the engineer must select an extension cable wire gauge that will minimize the loop resistance for a given length of wire. For further discussion of this issue, refer to section 7.7.2 or manufacturer's literature [23].

To maintain the correct temperature-voltage relationship, thermocouple extension wires should be protected from mechanical damage, moisture, and excessive heat. Care should also be taken to prevent short radius bends, cold working, and excessive flexing.

Both the positive and negative leads must be exposed to the same thermal conditions, and thus should be paired at all times. Furthermore, to reduce the effects of signal noise, the pair should be twisted at a minimum of 6 twists per foot. A shield system with an integral drain wire is also recommended. The drain system must only be grounded at one location to prevent ground loops [24].

7.4 Potentiometers

The potentiometer balances the voltage it receives from the thermocouple system against a standard voltage within the instrument. This standard voltage is obtained from either a standard cell or a regulated constant voltage power supply. In the case of a portable instrument, there is a standard cell and a battery. The battery is calibrated against the standard cell and then used to determine temperatures. Such calibration should be performed not only when the instrument is first used, but also at regular intervals. See section 15.6 regarding control of inspection, measuring and test equipment.

Stray alternating current, especially high frequency currents, can cause errors. These errors can be reduced by AC rejection filters in the input circuit of the instrument.

7.5 Thermocouple Installation

Any recording or controlling instrument reads the temperature at the junction (short) between the thermocouple wires closest to the instrument. Therefore, the wires must "touch each other" or be made common only where the temperature is to be measured. At all other locations, the wires must be insulated from each other and from the pressure vessel being heated.

The hot junction must be at the same temperature as the surface whose temperature is being measured. This requires that (1) it be insulated from external radiant heat (this may require application of insulating putty), (2) the thermocouple wire be kept under insulation for approximately 8 in. (200 mm) to prevent heat conduction along the wire (the effect is expected to be minor for thin gauge wire), (3) the thermocouple be protected from corrosive media, and (4) the hot junction must be in intimate contact with the surface whose temperature is being measured. Note that large errors can be caused if there is no intimate contact or the wires contact each other outside the hot junction.

Several of the issues discussed above depend upon the type of thermocouple and attachment method. For example, the use of putty may not be necessary for capacitor discharge attached thermocouples. If these thermocouples are prepared by "pushing back" the insulation instead of stripping it, the insulation can be moved back to cover the bare wire after installation and thereby mitigate the effect of the heat source on the thermocouple. In general, it is reported [12] that capacitor discharged welded thermocouples with or without the use of ceramic putty provide accurate temperature measurement at the junction. However, for heavier thermocouple wire (sheathed, etc.) not directly attached to the surface, the use of putty may be important to avoid inaccurate temperature readings.

Several methods are used to attach the thermocouple to the surface. The recommended method is to attach each wire separately to the surface by capacitor discharge welding, with the wires in close proximity (~ ¼-inch [6 mm]) to each other. ASTM Manual MNL 12 specifically recognizes the directly attached, separated junction method (paragraph 9.2.2.2 and Figure 9.3) and states "This type of junction has been shown to be more accurate than a bead junction [20]."

When using mechanically attached thermocouples (such as sheathed, twisted wire end, welded end, with or without insulation), the measurement accuracy depends on heat transfer from the workpiece to the bead junction. With thermocouples directly attached by capacitor discharge welding, the hot junction is integral to the workpiece, and as such, heat transfer is generally not a concern. Temperatures of mechanically attached thermocouples which were ~130°F greater than that of a thermocouple attached by capacitor discharge welding and reading 1,292°F have been reported [25].

Thermocouples attached by capacitor discharge welding provide positive feedback to the instrument in case a wire breaks or contact is lost at the junction. Both ASME Section III, Division 1, Subdivision NB (para.4311.2) and ASME Section VIII, Division 1 [para. UW-37 (h)] provide a special allowance for attachment of thermocouples by low energy (usually limited to 125 W-sec.) capacitor discharge welding without requiring a welding procedure or a welder performance qualification.

After capacitor discharge welding, the thermocouple welds should be carefully inspected for proper attachment before insulation is applied to the junction. Slight pulling on the attached thermocouple wires is an effective way to insure that they are secure. In addition, it is also good practice to secure the thermocouple to the workpiece so as to minimize stress on the point of thermocouple attachment (hot junction).

Installation of a spare thermocouple at each location offers a means to address thermocouple failures which may occur during the heating cycle. This is especially important for PWHT where the higher temperatures preclude access during heating. Duplex thermocouple wire/extension wire is available and can be used such that two thermocouples are installed at each location and connections brought back to the control/recording equipment. While only one would be connected at any given time, the spare will be readily available in case of a problem.

7.6 Thermocouple Readings to Control and Record Temperatures

The voltages produced by the thermocouples are sent to two types of instruments:

1) temperature controllers, which have been programmed to shut off the heating source at a specific temperature or follow a specific heating rate, holding temperature and time, and cooling rate, and
2) recorders, which document the actual temperature at specific times during the heating cycle.

In addition to strip chart type recorders, data acquisition systems enable capture of data on electronic media. Use of thermocouple/extension wires and recorders with traceability to national standards, such as those maintained by the NIST, provides a recognized means to document, for quality assurance and other purposes, various heating cycles. Quality assurance issues are discussed further in section 15.

7.7 Accuracy of Thermocouple Temperature Measurements

A number of factors determine the overall accuracy of a temperature measuring system. They include sensor, system connections, and instrumentation error contributions. This discussion is based upon the assumption that a type K thermocouple is attached to the work piece by means of capacitor discharge welding. The type K thermocouple is best suited for PWHT applications not exceeding 2,300°F. The lead extending from the sensor to the measuring or controlling instrument will be of thermocouple extension lead and not simply compensation lead, and interconnecting plugs and sockets will also be made of the type K material.

7.7.1 Sensor Error: The total error for the sensor will be the sum of the errors resulting from the following factors: Initial Calibration, Stability, Intermediate Metals, Green Rot, Cold Work, Noise, and Thompson Effect.

Initial Calibration—The initial calibration is a measure of the effect of the deviation of the stabilized thermocouple wire (as supplied from the manufacturer) from NIST standards. This error is expressed as a deviation from NIST standards. The deviation results from a variation in the material composition and or inhomogeneity of the wire. Many manufacturers offer a 'premium' grade wire which has a typical tolerance of ±2°F (±1.1°C) or ±0.4% of the temperature reading, whichever is greater. When using the premium wire at a typical PWHT temperature [1,150°F (621°C)], the inaccuracy due to wire composition is ±4.6°F (±2.55°C).

Stability—Extended exposure of standard type K wire to temperatures of 1,000°F (538°C) or more can lead to a shift of +6 to +9°F (+3.3 to +5°C). This is due to the aging of the positive element of the type K thermocouple. Many manufactures offer 'stabilized' wire to reduce this effect. An aged, stabilized type K thermocouple reading will increase by 1.35°F (0.75°C) after 200 hours at 1,000°F (538°C). After 1000 hours, the offset reduces to 0.9°F (0.5°C). For a worst case scenario, +1.35°F (0.75°C) will be assumed.

When installing and routing thermocouples and extension lead, good, practical low voltage wiring practices are desirable. In fact, poor installation and routing practices could represent the greatest source of error, if present. The remaining factors (Intermediate Metals, Green Rot, Cold Work, Noise, and Thompson Effect) are not expected to be significant if good installation and routing practices are followed and normal local heating conditions are encountered.

7.7.2 System Connections Error: The total error for the connection to the instrument will result from the same factors as stated above with the addition of loop resistance. When specifying thermocouple extension lead, the allowable loop resistance of the system must be determined. This value, along with the length of lead required, is used to determine the proper gauge of wire. A typical rule of thumb is not to exceed 600 ft (182.9 m) of 20 gauge type K extension wire. Although this is dependent on the instrument, a slight error, in the order of 0.2°F (0.1°C), may be induced. The effects of the remaining factors (Initial Calibration, Intermediate Metals, Stability, Green Rot, Cold Work, Noise, and Thompson Effect) can again be neglected.

7.7.3 Instrumentation Error: The instrument, in most cases, is a temperature recorder or data logging device. The accuracy of the instrument depends on factors such as reference junction compensation (RJC) circuitry, ambient effects on the instrument, and noise considerations. When using a strip chart recorder, print head positioning must also be factored into the final accuracy.

The chart paper from a strip chart recorder provides the final record of the thermal cycle, documenting that the temperature/time requirements have been met. A typical accuracy for the printing function of a strip chart recorder is 0.3% of span. A recorder setup for PWHT temperatures will likely have a span of 0 to 2,000°F (−18 to 1,093°C). This produces an accuracy ±6°F (±3.3°C). Assuming that the instrument is operated according to the manufacturer's specifications, and that good wiring technique has been utilized, the overall accuracy of the recorder can be ±6.5°F (±3.6°C).

7.7.4 Total System Error: The worst case error of the thermocouple and extension lead up to, but not including the instrument is +6.15°F, −3.45°F (+3.42°C, −1.92°C). In order to achieve these extreme values, all errors must occur in a positive or negative direction. A more likely value can be calculated by using the root of the sum of the squares (RSS) technique. Neglecting the zero valued factors, this method yields ±4.79°F (±2.66°C). This is a typical error value on a type K thermocouple prior to connecting to an instrument. The RSS value for the entire system, including a typical temperature recorder, is ±8°F (±4.44°C).

7.7.5 Improving Total System Accuracy: The system can be improved by properly maintaining and calibrating the strip chart recorder. This requires that a calibration device be utilized which has an accuracy 4 times greater than that of the recording instrument. An instrument of ±1.5°F (±0.83°C) accuracy is acceptable. The calibration instrument is to be connected to the recorder with a thermocouple extension lead of no longer than 12 inches (304.8 mm). After calibration, the accuracy of the recorder can theoretically be reduced to that of the calibrating instrument, ±1.5°F (±0.83°C). The overall accuracy of the system would then be reduced to ±5°F (±2.78°C).

7.8 Location of Thermocouples

Regardless of other considerations, the ability of thermocouples or any other method to adequately reflect temperature is dependent upon measurement at appropriate locations. There are two purposes for locating thermocouples: control or monitoring.

The location of control thermocouples must be based upon the nature of the heat source, location(s) of heat source(s), and the component being heated. The objective of control thermocouples is to assure that appropriate heat is supplied to regions or zones to achieve the temperatures required in these regions or zones. For example, for a circumferential band of electric resistance heaters centered on the weld, control thermocouples would most likely be placed along the centerline of the weld.

Monitoring thermocouples should be placed to insure that all of the parameters specified to control the local heating operation are being achieved. Thermocouples should be placed to measure the maximum and minimum anticipated metal temperatures and to delineate the axial temperature gradient. To achieve this, thermocouples should be placed at the centerline of the weld, the edge of the soak band and at the edge of the heat source to determine the axial thermal gradient. It is always a good practice, if possible, to locate thermocouples on the surface opposite to that of the heat source for one sided heating, to insure that the required temperatures are achieved throughout the thickness.

ASME Sections III and VIII and BS 5500 do not provide any specific guidance with regard to the placement of thermocouples or other measuring devices. AS 1210 requires the use of thermocouples at not less than three sections for circumferential band PWHT to check the peak and one-half peak temperature. For PWHT of pipe-to-nozzles welds less than $5\sqrt{Rt}$ from the shell, AS 1210 requires thermocouples at not less than three sections on the nozzle and four sections on the shell. For local circular PWHT of welds connecting nozzles or attachments to spherical heads or vessels, AS 1210 requires thermocouples at not less than three sections on the nozzle and four sections on the spherical head or vessel.

The following constitutes minimum recommended monitoring thermocouple locations for the local PWHT practices discussed in section 5.7. The use of monitoring thermocouples represents a cost effective means to assure that specified parameters for local heating are achieved. Therefore, the use of more than the recommended minimum number of monitoring thermocouples should be considered, especially when unusual circumstances or uncertainties are present. In addition to the monitoring thermocouples, controlling thermocouples would be required, with the number and location dependent upon the heating method as discussed above.

First, thermocouples should be placed at the centerline of the weld. Second, thermocouples should be placed at the two planes representing the edges of the required soak band. Third, thermocouples should be placed at the two planes representing the edges of the heated band in order to measure the axial temperature gradient. If additional control of the axial temperature gradient is required, two additional planes of thermocouples could be located midway between the edges of the soak and heated bands. The number of thermocouples in each plane would depend upon the specific component size, configuration and geometry. Figures 13 through 18 provide recommended monitoring thermocouple locations for the heating practices described in Figures 3 through 12.

8. Insulation

One aspect of local heating shared by all methods discussed in this publication is that of heat loss to the cooler, adjacent environment. Heat is lost by conduction through the heated structure itself, by radiation, by convection via moving air within the pressure vessel (the chimney effect), and by conduction, radiation and convection from the outer surface through the insulation to the surrounding air.

Conduction heat losses through the structure are primarily addressed by the use of supplemental heat sources and to a lesser extent by insulation. Heat losses due to internal convection (chimney effect) are best addressed by closing off the ends of the pressure vessel as discussed in section 9.4. Insulation is therefore generally utilized to minimize heat losses from the outside surface to the surrounding air and to minimize axial temperature gradients. Whenever possible, insulation should be placed on the inner surface of the pressure vessel to reduce the through-thickness temperature gradient and radiant heat losses.

8.1 Classification of Insulation

Fibrous insulation, such as commonly used for local heating, is generally classified by the type of fibers, construction, and their density. Physical properties of insulation such as thermal conductivity and maximum usage temperature are dependent upon these attributes. Therefore, specification of insulation requirements to control heat loss must include fiber type, construction, density and thickness.

Health and safety issues regarding insulation have become very significant in recent years. Specifically, the type of fiber, its size characteristics, concen-

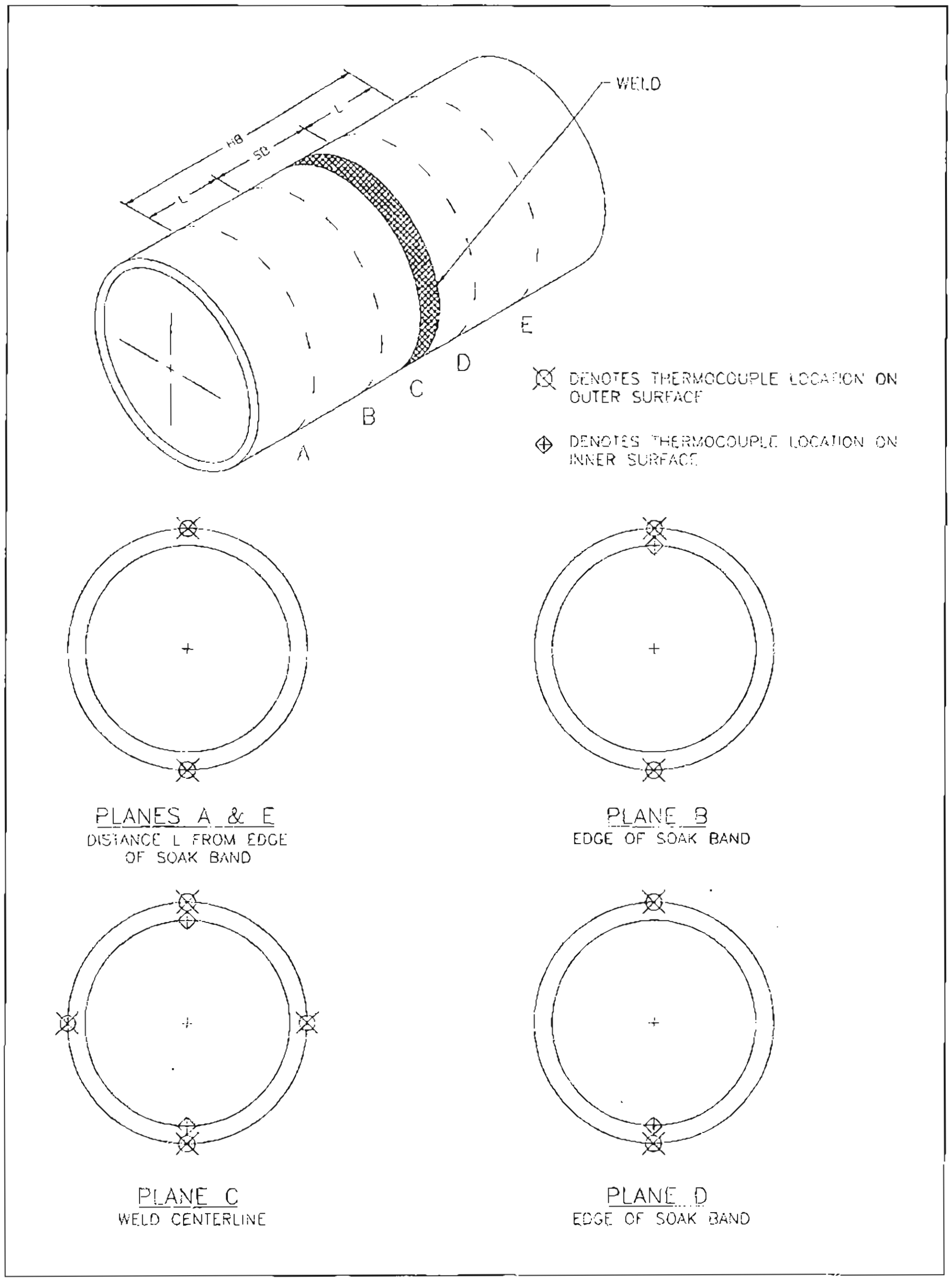


Fig. 13—Minimum number of monitoring thermocouples recommended when heating a cylindrical shell in accordance with Figure 5.

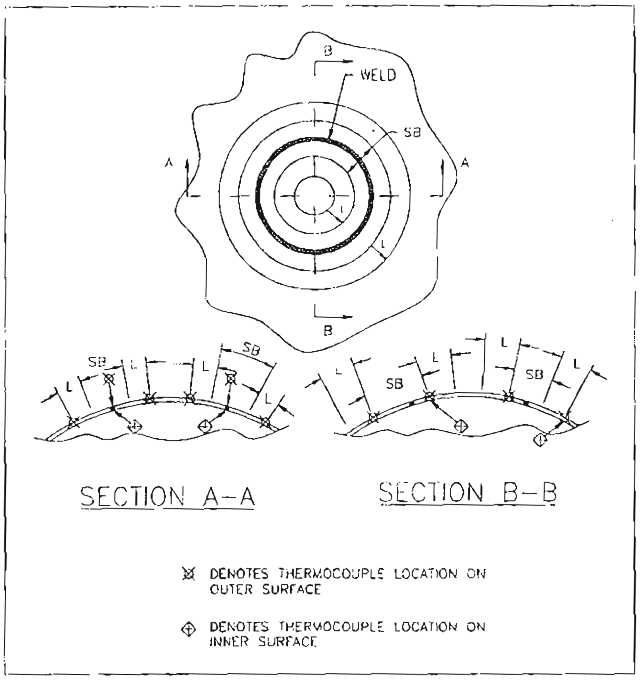


Fig. 14—Minimum number of monitoring thermocouples recommended when heating a double curvature shell or head in accordance with Figure 6.

tration of fibers and phase changes to crystalline form are important with regard to these health and safety issues. TIMA (formerly the Thermal Insulation Manufacturers Association and now referred to as NAIMA, the North American Insulation Manufacturers Association) has issued a publication [26] which provides standard nomenclature for describing/classifying man-made vitreous fibers.

8.1.1 Man-Made Vitreous Fibers: The first level in TIMA's classification system differentiates between man-made and natural fibers. For example, asbestos is classified as a natural, inorganic, crystalline fiber. Man-made, inorganic, nonmetallic, vitreous fibers are the type commonly used today for insulation. These are generally referred to as man-made vitreous fibers (MMVF). The term vitreous is important because it indicates that the fibers are amorphous or exist in a glassy, non-crystalline state. This characteristic is important and will be discussed further.

MMVF can be further subdivided based upon the fiber manufacturing method. Fiber manufacturing processes can be classified as continuous or discontinuous. As the name implies, the continuous drawing process produces continuous filament fibers. Various discontinuous processes such as rotary, blowing, wheel centrifuge, spinning, etc. are used to produce fiber segments. The term wool is often used to describe fibers manufactured by one of the discontinuous processes

Historically, continuous filament fibers have been used for textile applications, while the wool fibers have been used for insulation. However, in recent years, the availability of insulation made from continuous filament fibers has increased. One significant aspect of the continuous process is that greater control of fiber diameter can be achieved. The significance of this will be discussed further.

The final characteristic of fibers is their composition. Insulation fibers are typically silicates, i.e. the principal constituent is silicon dioxide (SiO_2) with varying amounts of other oxides. Variation of the composition has a significant effect upon the properties of the fibers.

In summary, the fibrous insulation materials commonly used today for local heating can be classified as silicate MMVF produced by continuous or discontinuous manufacturing processes.

8.1.2 Fiber Respirability: Three issues appear to be important with regard to selection of insulation. These include: thermal characteristics such as conductivity and maximum use temperature; health and safety characteristics relating to respirability; and cost. As a result of health and safety concerns associated with asbestos, the issue of respirability (ability to enter the lungs) has become very significant. Usage of insulation which contains respirable fibers can result in the need to use special personnel

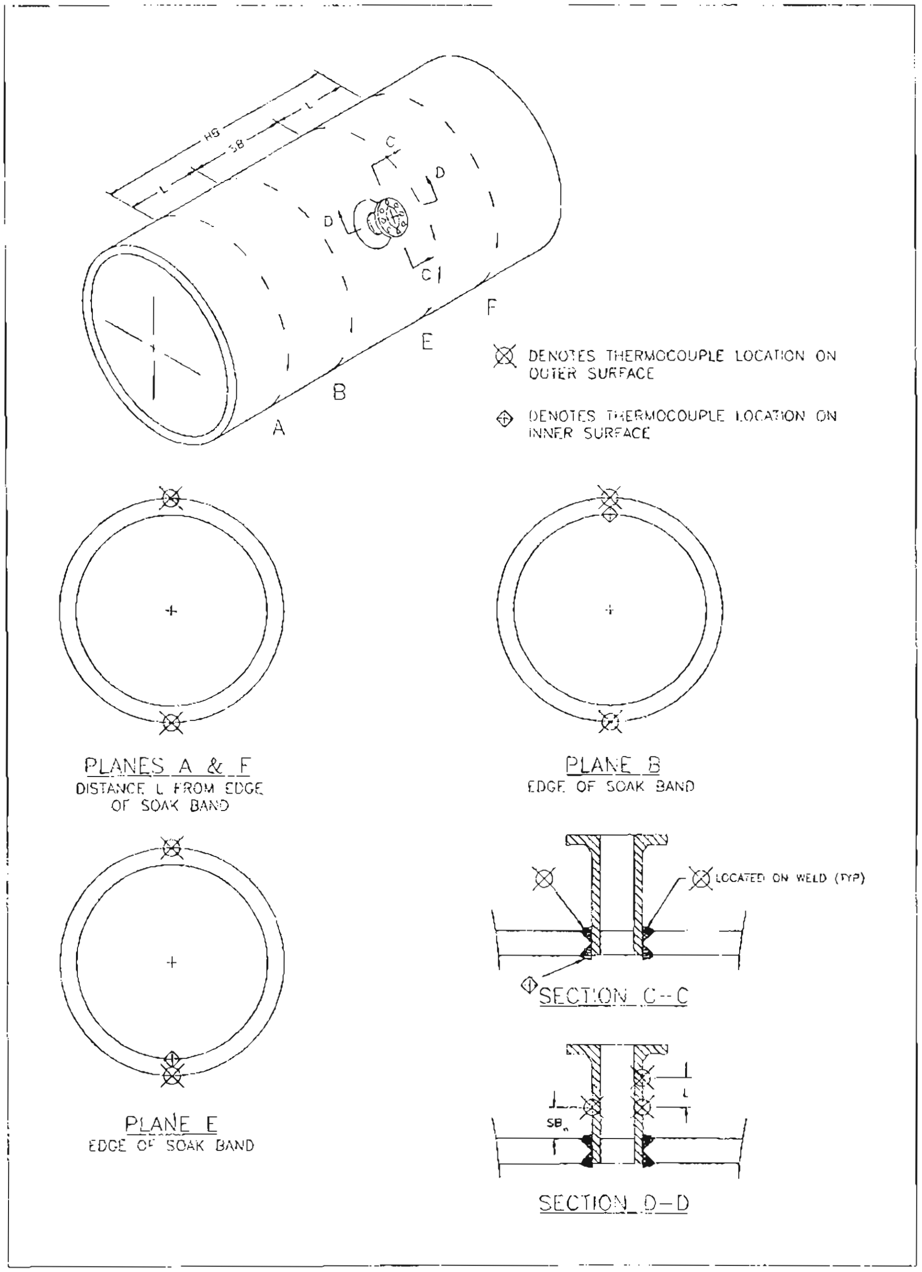


Fig. 15—Minimum number of monitoring thermocouples recommended for a nozzle or attachment when heating in accordance with Figures 7, 8, & 10.

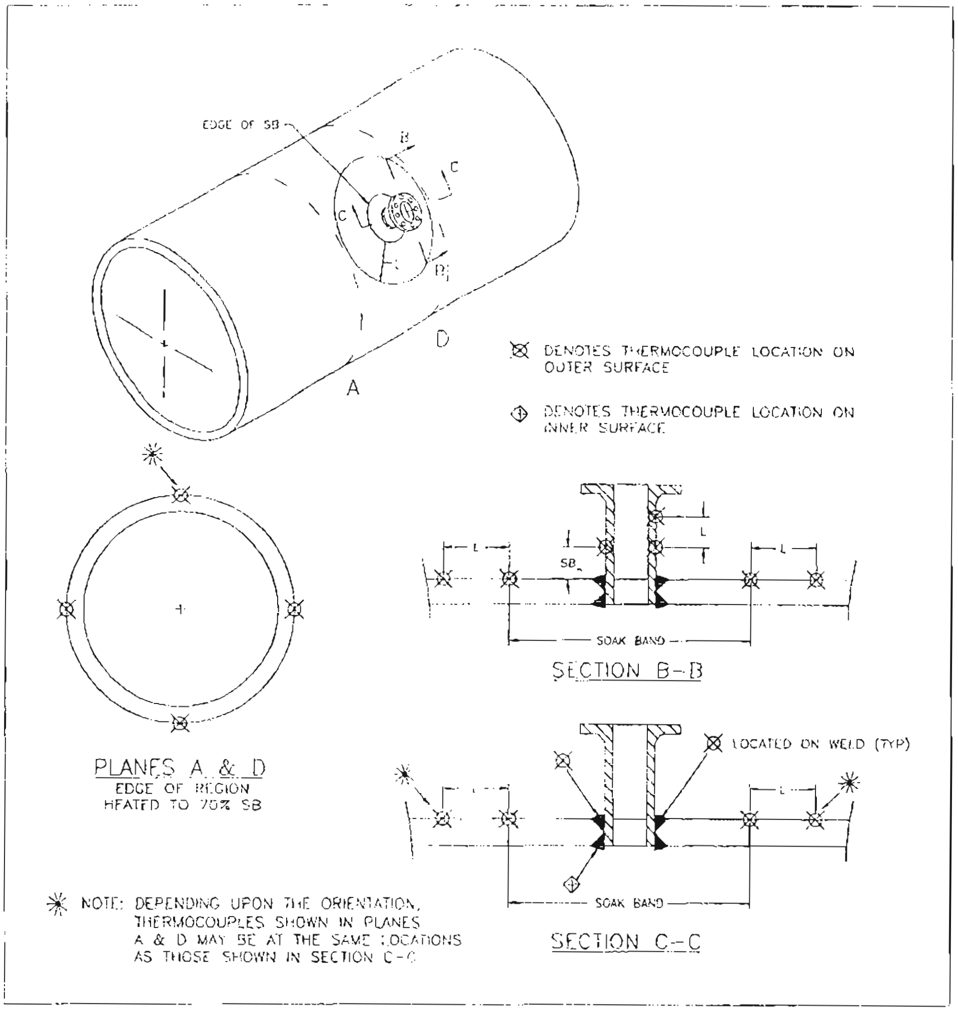


Fig. 16—Minimum number of monitoring thermocouples recommended for nozzle when heating in accordance with Figure 9.

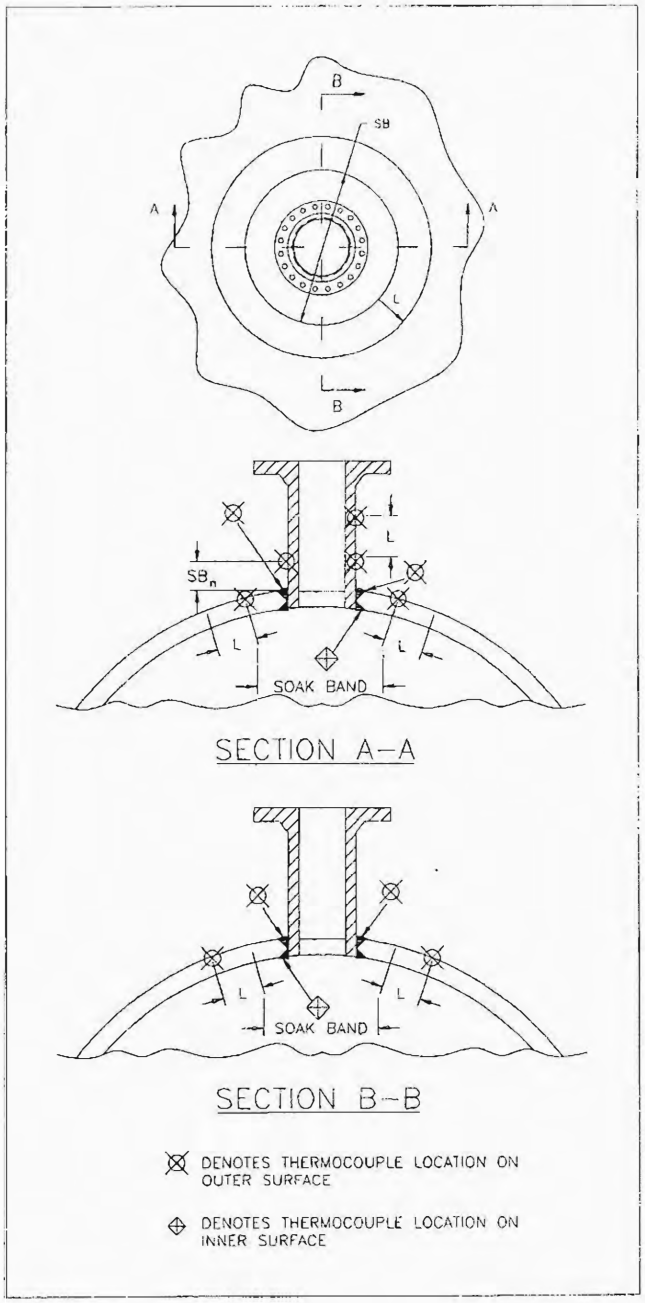


Fig. 17—Minimum number of monitoring thermocouples recommended for nozzle attachments on hemispherical heads or spherical vessels when heating in accordance with Figure 12.

protection equipment such as respirators, and to follow special handling and disposal requirements. As a result, additional costs can be incurred when utilizing insulation with respirable fibers.

It is beyond the scope of this document to discuss the biological effects of fibers once they enter the lungs. However, it is appropriate to discuss issues relating to the size of fibers in context with respirability. Because the definition of a respirable fiber varies between various governing organizations, specific requirements will not be discussed other than to indicate that diameter, aspect ratio (length:diameter) and overall length are considered.

One of the more important characteristics affecting the respirability of MMVF is the amorphous state. As a result of existing in the amorphous state, MMVF exhibit conchoidal fracture properties in which they fracture across the diameter and do not split longitudinally. This means that the diameters during usage generally remain the same as when manufactured, unless the transformation temperature from amorphous to crystalline has been exceeded. Manufacturers should be consulted for recommendations regarding the maximum usage temperature to avoid this transformation.

Crystalline fibers such as asbestos can fracture longitudinally and as a result, adversely change their diameter and aspect ratio. MMVF textile fibers, can be produced with diameters well in excess of that considered respirable. Control of the manufacturing process is such that even when considering variation, fiber diameters can be larger than those defined to be respirable. Therefore, by limiting the usage temperature (below transformation), MMVF textile fibers can remain non-respirable during usage.

MMVF produced by discontinuous manufacturing processes have a wide range of diameters. Typically, a significant portion of the sizes present are considered respirable. Although these fibers are also amorphous, with manufactured diameters expected to remain stable during usage below the transformation temperature, this does not mitigate the presence of respirable fibers.

Manufacturers should be consulted for specific information regarding the size of fibers in their products, the relationship between concentration of fibers and health effects, safe usage temperatures and recommendations regarding personnel protection equipment, handling and disposal.

8.2 Types of Insulation

Insulation materials commonly used in local heating include: glass wool, mineral wool, refractory ceramic fiber, and, recently, continuous filament fiber. Asbestos is no longer used nor recommended. The following sections provide an overview of each of

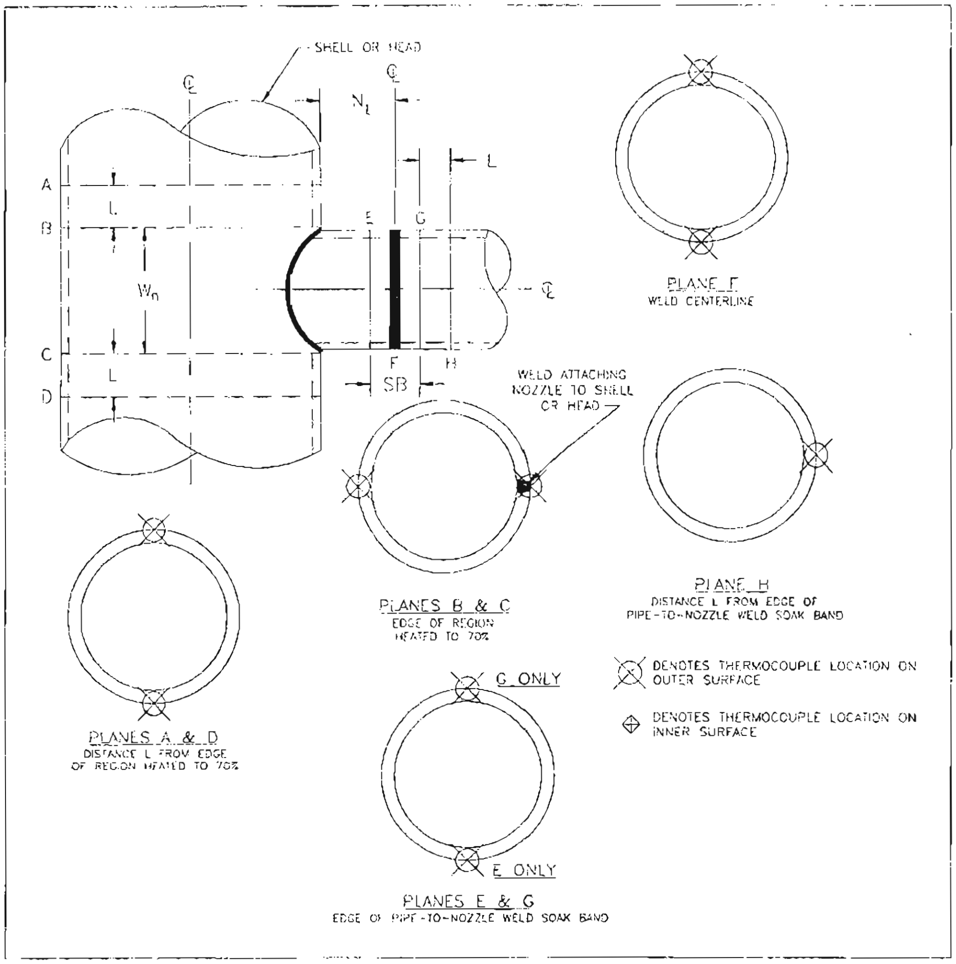


Fig. 18—Minimum number of monitoring thermocouples recommended for pipe-to-nozzle welds when heating in accordance with Figures 3 and 5.

the commonly used types. Table 8 provides a summary of the important characteristics of these materials.

8.2.1 Glass Wool: Fiber glass wool is a silicate MMVF manufactured by a discontinuous process. Its composition has specifically been adjusted to allow formation at a lower temperature. A binder is usually present to hold the fibers together. Heating deteriorates this binder and generally results in individual fibers which can readily become airborne. The softening point of the fibers is reported to be 1,200°F (650°C), with a maximum recommended use temperature of 840°F (450°C) [26].

The application of glass wool insulation can be cost

Table 8—Comparison of the Characteristics of Commonly Used Insulation Materials

Type	*Respirable Fibers*	*Max. Usage Temp.*	*Crystalline Transformation Temperature*	*Thermal Conductivity*	*Relative Cost*
Glass Wool	Present due to mfg. process & if transformation to crystalline state with subsequent fracture into smaller size; loss of binder facilitates fibers being airborne	840°F (450°C)	Above Max. Usage	>mineral wool & RCF	Low Cost Outer Layer
Rock & Slag (Mineral) Wool	Present due to mfg. process & if transformation to crystalline state with subsequent fracture into smaller size; loss of binder facilitates fibers being airborne	1200°F (650°C)	1337–1517°F (725–825°C)	<glass wool; >RCF	Lowest
Refractory Ceramic Fiber (RCF)	Present due to mfg. process & if transformation to crystalline state with subsequent fracture into smaller size	2000°F (1093°C)	1832°F (1000°C)	<glass & mineral wool	>glass or mineral wool
Continuous Filament Fiber	Mfg. process allows production of non-respirable fibers; respirable fibers can be present if transformation to crystalline state with subsequent fracture into smaller size	2012°F* (1100°C)	1832°F (1000°C)	depends upon composition	expensive; multiple use important

*Assumes high purity silica.

effective for outer layers of insulation and along the pressure vessel away from the heat sources. However, glass wool insulation should not be allowed to be in contact with the heat source or any material which has a temperature approaching the softening point. Thermal conductivity for glass wool is generally higher than that of mineral wool or refractory ceramic fiber.

8.2.2 Rock and Slag Wool: Rock and slag wool are silicate MMVF manufactured by a discontinuous process. As the name implies, rock or blast furnace slag are melted to produce fibers. These fibers are also referred to as mineral wool. A binder is usually present to hold the fibers together. Heating deteriorates this binder and generally results in individual fibers which can readily become airborne. The maximum continuous service temperature is approximately 1,200°F (650°C), with devitrification (transformation from amorphous to crystalline) beginning above 1,337 to 1,517°F (725 to 825°C) [26]. Mineral wool is typically less expensive than either glass wool or refractory ceramic fiber, while its thermal conductivity generally is between that of glass wool and refractory ceramic fiber.

8.2.3 Refractory Ceramic Fiber: Refractory ceramic fiber (RCF) is silicate MMVF manufactured by a discontinuous process. Up to approximately 50% alumina (Al_2O_3) and for certain types 15% zirconia (ZrO_2) are added to improve high temperature performance. Although the name may seem to imply a crystalline structure, these fibers are fully amorphous in the as-manufactured condition. RCFs are reported to crystallize or devitrify at temperatures above 1,832°F (1,000°C) and begin softening in the range 3,164 to 3,272°F (1,740 to 1,800°C) [26]. The maximum continuous use temperature is approximately 2,000°F (1,093°C). RCFs are more expensive than glass or mineral wool, but generally have the lowest thermal conductivity.

8.2.4 Continuous Filament Fiber: Continuous filament silicate MMVF can be manufactured in a range of compositions from approximately 50% to approaching 100% silica. As a result, thermal and other characteristics vary accordingly. For high purity silica fibers, the maximum use temperature reported is 2,012°F (1,100°C), with devitrification beginning at 1,832°F (1,000°C) [26]. Variation of these temperatures with purity is noted [26]. Continuous filament fibers can be used to produce knitted or needled-felt type insulation products. The knitted products have a higher strength, and neither type uses binders. As a result, the knitted products tend to remain integral longer, and therefore may be capable of a greater number of reuses.

Because continuous filament fibers are considerably more expensive than those produced by a discontinuous manufacturing process, the number of reuses becomes an important cost consideration. By limiting usage temperature to below that where devitrification occurs, savings can be derived from avoidance of more restrictive personnel protection equipment, handling and disposal. Depending upon composition, density and construction (knitted verses needled-felt), thermal conductivity should have a range comparable to that for glass wool, mineral wool and refractory ceramic fiber.

8.3 Attachment of Insulation

Ideally, insulation pieces should be cut so that the ends butt against themselves when the piece(s) are wrapped around the pressure vessel. No gaps should be permitted in the insulation layer, and any inadvertent gaps should be filled with insulation. Such wrapped insulation is commonly held in place with insulation pins which are capacitor discharge welded to the pressure vessel. Other attachment techniques such as banding and magnetic clamping may be used depending upon the circumstances. Banding would not be applicable on the inner surface and may not be appropriate on large diameter vessels. For magnetic clamping, the temperature at the location of the magnet should be well below the Curie temperature (temperature at which ferromagnetisim is lost). Multiple layers of insulation are typically used when the hold period temperature is over 1,200°F (650°C).

As discussed in sections 5.3 and 5.4, the insulation should normally extend well beyond the edge of the heated band to diminish heat losses and assure the required axial temperature gradient from heated to unheated sections.

9. Other Considerations

Additional issues to consider when performing local heating include support, buckling and distortion, the presence of internal liquids, chimney effect, and thermal expansion.

9.1 Support During Heating

Support for pressure vessels may be necessary when heated to elevated temperature, since they lose strength. When heated without sufficient support, there may be permanent distortion of an undesirable nature. For example, the weight of spans may be great enough to cause permanent bending when heating to typical PWHT temperatures if the weight is not properly supported. It is best to accomplish adequate support without the use of attachments welded to the pressure vessel.

When a pressure vessel is being heated in the horizontal position, saddle type supports are generally used. An analysis is normally performed to determine the adequacy of the basic saddle design and the spacing between saddle supports.

9.2 Buckling and Distortion

When a pressure vessel is being heated in the vertical position, the combined stresses from the axial dead weight load and bending moments from eccentric and wind loading, should be less than the allowable buckling stress. Obviously, the taller the pressure vessel and the lower the point of local heating, the greater the concern regarding buckling and distortion. Structural integrity analysis should be performed to determine the acceptability of the heating procedure with regard to buckling and distortion criteria.

It is imperative to accommodate vessel thermal expansion during PWHT by disconnecting all external attachments which would inhibit growth, and to modify supports to enable translation. Specifically, pipe attachments should be decoupled and saddle supports placed on roller-plate assemblies.

9.3 Internal Liquids

The presence of liquids, even in small amounts, can prevent the weld from reaching the desired temperature. It is necessary, therefore, to remove internal liquids and prevent the flow of liquids or gases inside the pressure vessel while being heated. However, adequate venting should be used to assure that there is no pressure build-up within the vessel. All venting should be damped to prevent air from flowing through the pressure vessel, causing undesirable cooling.

9.4 Chimney Effect

Natural convection can cause the flow of hot gases within the pressure vessel. Such flow can result in undesirable convective heat losses on the inside surface of the pressure vessel. It is therefore desirable to close valves and manways, erect bulkheads, and use other means to prevent such gas circulation.

9.5 Thermal Expansion

Depending upon the service temperature, pressure vessels are normally designed to accommodate some degree of thermal expansion. However, it is desirable to verify whether the pressure vessel will be able to accommodate the expansion associated with the local heating cycle. To the extent possible, the pressure vessel should be free to expand in all directions (axially, radially, and circumferentially). For example, a carbon or low alloy steel pressure vessel with a diameter of 10 ft (3,048 mm), will grow in diameter by approximately 1 in (25.4 mm) when heated from 70 to 1,100°F (21 to 593°C). If the pressure vessel contains supports, they must be free to expand. It may be necessary to release or modify such existing supports to accommodate expansion.

10. Thermal Cycle

[Refer to Section 11 of AWS D10.10/D10.10M: 1999 for additional information and recommendations.]

It is important to control three aspects of the thermal cycle associated with heating operations (both furnace and local). These include the heating rate above a specified temperature, the specified hold temperature and time, and the cooling rate above a specified temperature. Control of heating and cooling rates are typically associated only with PWHT, since the temperatures for bake-out, preheat/interpass heating and postheating are normally below the specified temperature which triggers control requirements. ASME Sections III and VIII require heating and cooling rate control above 800°F (427°C), while BS 5500 and AS 1210 require control above 400°C (752°F) for carbon and low alloy steels.

The cited pressure vessel fabrication codes limit heating and cooling rates during PWHT to restrict stresses produced by nonuniform expansion or contraction. The temperature gradient through the wall of the pressure vessel causes stress.

Whenever heat is applied to only one surface, there will be a gradient through the thickness. As thickness increases, the gradient will increase for a given heat input. Although slow heating or cooling rates can not totally eliminate this gradient, such reduced rates do lessen the magnitude of temperature differences and associated stresses. The size of the heated band can also be extended to reduce the through-thickness gradient in the vicinity of the weld. When possible, the placement of insulation on the surface opposite to that of heating should be used to lessen the through-thickness temperature gradient, as previously discussed in section 5.2.2.

The effects and benefits produced during bake-out, postheating, and PWHT (stress relaxation, tempering, and hydrogen removal) are time-temperature dependent. Temperature is the more important variable. Unless code requirements limit the selection of temperature, it is more desirable to select a temperature such that the desired effects are produced in reasonably short time periods. This helps to limit the variability of the outcome as opposed to selection of longer times at lower temperatures. Further discussion of the issues associated with the use of longer PWHT times at lower temperatures can be found in section 10.2. The effects and benefits from preheating/interpass heating (drive off moisture, slow the cooling rate, and increase hydrogen diffusivity) while deriving some benefit from time, are primarily dependent upon temperature.

It is recognized that the time-temperature dependent nature of stress relaxation and tempering associated with PWHT can be represented by a parameter for carbon and low alloy steels. The Holloman-Jaffe or Larson-Miller parameter, H_p or LMP respectively, is commonly used to represent the time-temperature relationship during the hold period for tempering or relaxation of residual stress by creep [3,27]. This parameter, which is described in equation (2), provides a convenient means for establishing equivalent PWHT time-temperature combinations during the hold period.

$$H_p \text{ or LMP} = T(C + \log t) \times 10^{-3} \qquad (2)$$

where: T = hold period temperature (°K or °R)
t = hold period time (hr.)
C = constant, approximately 20 for carbon and low alloy steels

It should be cautioned that different authors use different temperature scales when calculating this parameter. As an example of the possible difference, one hour at 1,110°F (593°C) would have the following LMPs based upon degrees Kelvin and Rankine respectively, 17.33 and 31.20. Another caution relates to the fact that metallurgical reactions, such as precipitation, are highly dependent upon temperature. Therefore, in situations where such reactions occur, it may not be appropriate to apply this parameter over a broad temperature range. Suggestions have been made to limit application of the parameter to temperatures within ± 72°F (± 40°C).

Work [28] sponsored by the Pressure Vessel Research Council (PVRC) which examined tempering of the HAZ of welds in ASTM A 516 material cautions that care must be exercised in the selection of an appropriate constant, C, for this relationship. It appears that near the end of completion of tempering, much smaller constants may be appropriate. In addition, a much larger constant may be appropriate to describe tempering of the HAZ of high heat input welds. The constant did appear to be close to 20 for low heat input welds and/or high carbon content. Other researchers have reported [29] a constant C of 17.5 for tempering Cr-Mo and Cr-Mo-V steels. This is in agreement with the PVRC sponsored work which concluded that material with a higher hardness has a lower constant C.

In addition to the hold period, the heating and cooling periods also contribute to the time-temperature effect. This contribution becomes more important for large components which have longer heating and cooling periods. A calculation has been developed to represent an additional equivalent time at the hold temperature for the heating and cooling periods [27]. The method to calculate these equivalent heating and cooling hours, t_h and t_c respectively, is shown in equation (3). The heating and cooling rates are assumed to be linear. Although linear rates are unlikely in practice, the assumption is expected to provide reasonable accuracy [27].

$$t_h \text{ or } t_c = T/[2.3k(C - \log k)] \tag{3}$$

where: T = hold period temperature (°K or °R)
k = heating or cooling rate (°K/hr or °R/hr)
C = constant, approximately 20 for carbon and low alloy steels

The equivalent hours for the heating and cooling periods can be combined with equation (2) to produce a parameter, LMP_{cycle}, which represents the entire thermal cycle (heating, hold, and cooling). This parameter is shown below in equation (4).

$$LMP_{cycle} = T[C + \log (t_h + t + t_c)] \times 10^{-3} \tag{4}$$

where: T = hold period temperature (°K or °R)
t_h, t_c = equivalent heating/cooling time (hr.) = $T/[2.3k(C - \log k)]$
k = heating or cooling rate (°K/hr or °R/hr)
t = hold period time (hr)
C = constant, approximately 20 for carbon and low alloy steels

The parameter, LMP_{cyclc}, offers a method for fabrication codes to specify allowable PWHT time-temperature combinations. If the parameter were used in conjunction with an allowable temperature range for each material grouping, it would assure adequate relaxation yet provide flexibility for fabricators to chose time-temperature combinations.

The parameter also offers a means to represent the cumulative effects of various times at different PWHT temperatures. The ability to represent such cumulative effects is important for large components which experience multiple PWHT cycles such as pressure vessels. This could be accomplished by converting all cycles to equivalent times at one temperature and then summing the equivalent times. This follows the same approach as done using equation (4) where the equivalent heating, hold and cooling times are summed. Equation (5) provides a useful formula for calculating the equivalent hold time t_2 to give the same Holloman-Jaffe parameter at the temperature T_2 as t_1 hours at a temperature of T_1.

$$t_2 = 10^{[(T_1/T_2)(C + \log t_1) - C]} \tag{5}$$

where: T_1, T_2 = hold period temperatures (°K or °R)
t_1, t_2 = hold period times (hr)
C = constant, approximately 20 (with caution noted)

Note that the times used in this calculation could be the total cycle equivalent times which include the effects of heating, hold and cooling.

The research work [28] sponsored by the PVRC has examined the effectiveness of longer PWHT times at lower temperatures for tempering the HAZ of ASTM A 516 welds. A part of this work examined the contribution of the heating portion of the thermal cycle. Results confirm that slow heating rates can have a significant contribution to the effects produced by the hold period and that equation (3) provides a reasonable approach to describe the effect [28]. For example, a heating rate of 78°F/hr (43.3°C/hr) to a maximum temperature of 1,100°F (649°C) was reported [28] to be equivalent to a hold time of approximately 0.5 hours at the maximum temperature. It was also reported [28] in this work that the degree of HAZ softening remained fairly constant at slightly over 80% for heating rates above 100°F/hr (55.5°C/hr). However, at slower heating rates, the percentage of softening dramatically increased.

The results of a study to estimate the relaxation of welding residual stresses in 2-1/4Cr − 1Mo steel has been reported [30]. A significant degree of stress relaxation was shown to occur during the heating portion of the PWHT cycle. In addition, the magnitude of stress relaxation during the heating period was shown to increase at a slower heating rate. Others [31] have reported similar results using the previously developed method [30] to estimate stress relaxation. This study concluded [31] that at the start of the hold period, the stress state is most influenced by the rate of heating. As a result of these findings, it was stated [31] that "consequently doubts arise about any need for extending the period of heat treatment in relation to an increase in the joint thickness."

The above results [28,30,31] strongly suggest that by using a sufficiently slow heating rate, which assures relatively uniform temperature through the thickness, a significant amount of the effects desired from PWHT (tempering and stress relaxation) could be completed with minimal hold time required. Since such slow rates of heating are common with large pressure vessels, the net effect would be to reduce the PWHT cycle time required to achieve desired effects and thereby reduce costs. The ability to reduce the PWHT cycle time will also benefit materials for which there are concerns regarding deterioration of properties with long hold times.

10.1 Heating Rate

The rate of heating during PWHT can affect the temperature difference between the outside and inside surfaces. With an external heat source, the existence of a radial thermal gradient produces hoop stresses, with the outer fibers in compression and the inner fibers in tension, as the outer layers attempt to expand but are restrained by the cooler material below. The stresses are proportional to the temperature difference between the outside and inside surfaces. As the heating rate increases, the temperature difference increases. However, if an acceptable level of distortion and/or no cracking results, high rates of heating may be tolerable since associated residual stresses are relaxed during the hold period.

Table 9 compares the maximum allowed rates of heating during PWHT for ASME Sections III and VIII, BS 5500 and AS 1210. In cases where code requirements do not limit the rate of heating, faster rates than these could be considered if experience or analysis demonstrate that acceptable distortion or levels of residual stress result.

It should be realized that the maximum possible rate of heating for a large, heavy wall pressure vessel may be much less then the maximum rates allowed by the applicable code. In addition, the previously discussed contribution of the heating portion of the PWHT cycle to stress relaxation and tempering should also be considered. As a result, while slow heating rates may be a necessity, if the contribution of the heating portion of the PWHT cycle is accounted for, such slow rates offer the potential for reduced PWHT cycle time, costs and property deterioration.

10.2 Hold Temperature and Time

Achievement of specific hold temperatures and times must occur to meet the objectives of the heating operations described in this document. However, as discussed above, it is important to include the contribution of the heating portion of cycle to the hold period.

As previously discussed, the cited fabrication codes do not provide any guidance with regard to bake-out and minimal guidance with regard to postheating. Minimum preheat/interpass temperatures are provided as a function of material type and thickness for the cited fabrication codes.

PWHT hold temperature and time requirements are based upon material type and thickness. For certain material types, BS 5500 and AS 1210 provide different temperature ranges for optimization of creep properties versus tempering to soften.

The concept of hold time as a function of thickness is directly applicable for both bake-out and postheating. This is due to the fact that thickness determines the diffusion path. As discussed above, the desired effects of PWHT (tempering and stress relaxation) are a function of both time and temperature, with temperature being the more important variable. For PWHT, hold time as a function of thickness is primarily relevant to insure that the full thickness achieves the minimum required temperature. While it is recognized [32] that thickness and the overall structure may influence stress relaxation due to constraint effects, the primary consideration for associating PWHT hold time with thickness is to insure achievement of the minimum temperature through the wall thickness.

ASME Sections III and VIII treat PWHT time as a step function related to thickness. For thicknesses over 2 in (50.8 mm), the requirement is typically 2

Table 9—Comparison of Maximum Rates of Heating and Cooling During PWHT

Fabrication Code	*Maximum Rate of Heating*	*Maximum Rate of Cooling*
ASME Section III, Subsection NB	400°F/hr (222.2°C/hr) divided by the thickness in inches above 800°F (427°C); 100°F/hr (55.6°C/hr) minimum.; 400°F/hr (222.2°C/hr) maximum.	400°F/hr (222.2°C/hr) divided by the thickness in inches above 800°F (427°C); 100°F/hr (55.6°C/hr) minimum.; 400°F/hr (222.2°C/hr) maximum.
ASME Section VIII, Divisions 1 & 2	400°F/hr (222.2°C/hr) divided by the thickness in inches above 800°F (427°C); 100°F/hr (55.6°C/hr) minimum.; 400°F/hr (222.2°C/hr) maximum.	500°F/hr (277.8°C/hr) divided by the thickness in inches above 800°F (427°C); 100°F/hr (55.6°C/hr) minimum.; 500°F/hr (277.8°C/hr) maximum.
BS 5500	Depending upon complexity of vessel, material and thickness, rates can vary from 6000°C/hr (10,800°F/hr) divided by the thickness in mm to 200°C/hr (360°F/hr) above 300°C (572°F)	Depending upon complexity of vessel, material and thickness, rates can vary from 6000°C/hr (10,800°F/hr) divided by the thickness in mm to 200°C/hr (360°F/hr) above 300°C (572°F)
AS 1210	Depending upon material and thickness, rates can vary from 5000°C/hr (9,000°F/hr) divided by the thickness in mm to 200°C/hr (360°F/hr) above 400°C (752°F)	Depending upon material and thickness, rates can vary from 6250°C/hr (11,250°F/hr) divided by the thickness in mm to 250°C/hr (450°F/hr) above 400°C (752°F)

hours plus 1/4 hour for each inch (25.4 mm) over 2 in (50.8 mm). BS 5500 and AS 1210 specify linear functions of time per unit thickness. It may be possible that with the proper selection of temperature, shorter hold times than currently specified can be used once all required material is at the minimum temperature. The ability to use shorter hold times may also be justified when the effect of the heating portion of the thermal cycle is accounted for as described above. Since codes do not currently recognize the ability to account for the heating portion of the PWHT cycle or to specify hold time independent of thickness, the most likely approach is to develop data and seek approval from the Authorized Inspector.

It is recognized that for certain materials, prolonged time at PWHT temperature can reduce tensile and yield strength and increase the charpy transition temperature. AS 1210 accounts for this by placing a maximum limit on the total time. ASME Sections III and VIII require that test coupons be heat treated such that the total time at temperature is 80% of the total time at temperature during all actual heat treatment of the product. When determining the total expected time, manufacturers attempt to account for that normally associated with manufacturing, repairs during manufacturing, and an allowance for repairs and/or modifications after the vessel is in service. It also appears very likely that the unfired pressure vessel code being developed by the European Committee for Standardization (CEN) will contain detailed requirements for assessing the effect of PWHT on material properties

In addition to total time, it may also be necessary to account for multiple PWHT cycles at different temperatures. An approach, based upon the Larson-Miller parameter, for determining a single test specimen PWHT cycle equivalent to several at different temperatures is reported [33].

Unexpected repairs during manufacturing and/or service may cause the total time at temperature to encroach upon the total time at temperature of the test coupon. As a result, justification for using shorter hold times, such as accounting for the effects of heating as discussed above, may be highly desirable in these situations.

ASME Sections III and VIII allow longer times at lower temperatures for PWHT of certain materials, while BS 5500 and AS 1210 allow it only with agreement by the purchaser. Concern has been expressed because the allowed lower temperatures and longer times do not appear equivalent based upon the Larson-Miller relationship described above. The appropriateness of using longer times at lower temperature should always be assessed based upon the objectives and service environment. While the results of the cited PVRC research [28] indicate that significant tempering does occur at lower temperatures for longer times, it is apparent, as expected, that there is not equivalency. In addition, this work also indicates a dependency upon the rate of heating. For rates of heating below 100°F/hr (55.5°C/hr), the difference in HAZ hardness between a weld which received PWHT for 1 hour at 1,100°F (593°C) and 10 hours at 950°F (510°C) began to increase more quickly. For heating rates above 100°F/hr (55.5°C/hr), the difference remained relatively constant at 23–25 diamond pyramid hardness (DPH), while at slower rates it increased dramatically, approaching a difference of 45 DPH.

Whenever hardness reduction is targeted, for example due to the service environment, care must be exercised when using the PWHT time-temperature ranges provided in the fabrication codes. For example, it may be necessary to use the upper end, and in some cases, exceed the temperature range provided in a fabrication code, in order to reduce hardness below a maximum target level.

10.3 Cooling Rate

Stresses induced during heating are likely relaxed during the hold period, while those induced during cooling tend to remain. As a result, there is generally more concern regarding the effect of the cooling rate.

The cooling rate may also affect mechanical properties such as hardness and ductility. For subcritical PWHT, cooling rate can affect the final hardness due to the contribution of equivalent hold time as previously described. However, as discussed above, the contribution from the heating portion appears to provide a more significant contribution.

In some instances, procedures have specified slower cooling rates because of a desire to insure greater hardness reduction. Since the effect is based upon hold time equivalency, a more desirable and controllable approach is to simply increase the hold time. Based upon the work reported above, it may actually be best to decrease the rate of heating.

For certain materials such as ferritic stainless steels, slower cooling rates can result in longer exposure time to temperature ranges which cause embrittlement, thereby reducing toughness.

Since the natural cooling rate is highest at higher temperatures, it may be necessary to continue applying heat during the early stages of cooling in order not to exceed the specified cooling rate. The insulation is generally not removed until the temperature is below that where control is required.

Table 9 compares the maximum allowed rates of cooling during PWHT for ASME Sections III and VIII, BS 5500 and AS 1210. In cases where code requirements do not limit the rate of cooling, faster rates than these could be considered if experience or analysis demonstrate that acceptable distortion or levels of residual stress result. However, it should be realized that the maximum possible cooling rate for a large, heavy wall pressure vessel may be considerably less than that allowed by the applicable code.

11. Response to Deviations

Although various deviations may occur during local heating operations, those listed below are most common. As a result, the possibility of their occurrence should be considered and plans made to enable appropriate response.

11.1 Thermocouple Failure

The ideal way to respond to a thermocouple failure is the use of a spare, with its own extension wire. The response under such circumstances can be made immediately, without any impact. It simply involves disconnecting the lead from the primary thermocouple and connecting the lead for the spare thermocouple. In the less likely event of a double failure (i.e. failure of both the primary and spare), adjacent thermocouples may have to be used to estimate temperature. If access is possible, a thermocouple located on the opposite surface from the point of double failure provides a good source for such comparative data.

11.2 Heat Source Failure

Depending upon the nature of the heat source, it may or may not be feasible to make a replacement without discontinuing the heating operation. The temperature of the heating operation will also impact the ability to make such a replacement. In general, it is desirable to have spare equipment for those cases where replacement is feasible. It also may be possible that the operation of adjacent heat sources can be modified to partially or fully compensate for the failed heat source.

Although it can't help after the fact, proper equipment maintenance and operational check-out before use will likely prevent many failures.

11.3 Interruption During Heating

An interruption during heating consists of either exceeding the maximum heating rate while above the threshold temperature for control, or loss of temperature due to a heat source failure. The response to exceeding the maximum heating rate is to first correct the cause of the interruption. Heating can then be restarted at the heating rate appropriate to the temperature at restart. As previously discussed, the principal concern with regard to exceeding the maximum heating rate is distortion. An assessment of the distortion would have be made at the completion of the PWHT cycle, after returning to ambient temperature. Remedial action to address distortion is beyond the scope of this document.

The response to a temperature loss during heating is to first correct the cause of the interruption. Heating can then be restarted at the heating rate appropriate to the temperature at restart. Generally, the response will not be dependent upon whether the temperature is above or below that requiring heating/cooling rate control, other than to utilize the heating rate required at the restart temperature.

11.4 Interruption During Hold Period

An interruption during the hold period consists of the temperature either dropping below the minimum or exceeding the maximum required soak temperature.

When the temperature drops below the minimum for soak before the end of the required hold time, the first response must be to correct the cause of the interruption. Heating is then restarted at a rate appropriate for the temperature of the pressure vessel at restart. Once at or above the minimum soak temperature, hold is resumed and maintained for a period of time such that the summation of all time periods at or above the minimum soak temperature must be equal to or greater than the minimum required.

When the temperature exceeds the maximum for the soak period, the first response must be to correct the cause of the interruption. For carbon and low alloy steels, the subsequent response depends upon whether the lower and upper critical transformation temperatures have been exceeded. It is generally possible only to estimate the transformation temperature based upon either data for material groups/specifications or a knowledge of composition and use of an empirical formula. Table 129.3.2 in ASME B31.1 [34] provides a convenient source of data by material P-No, while work reported by Andrews [35] is a well known source for empirical formulae. However, such information is generally not available at the time of the temperature excursion.

If it is suspected that the lower critical temperature has been exceeded, the recommended practice is to reduce the temperature to the soak range at a cooling rate no greater than the maximum allowed and to hold for the full required period, regardless of the time already at temperature. This is done to assure adequate tempering of any material which may have experienced hardening due to transformation. A full assessment of the deviation would then have to be made subsequent to cooling to ambient temperature. Such an assessment may include hardness measurements, surface replication and/or other tests to determine the condition of the material.

If the temperature does not exceed the lower critical temperature, reduce the temperature to the soak range at a cooling rate no greater than the maximum allowed and hold for the remaining required time. All time above the minimum temperature, including that above the maximum temperature, can be used to determine the total time at temperature.

11.5 Interruption During Cooling

An interruption during cooling can consist of either exceeding the maximum cooling rate or failing to exceed the minimum cooling rate while at or above the threshold temperature for control. The more commonly encountered situation is exceeding the maximum cooling rate. As previously discussed, concern with regard to exceeding the maximum cooling rate is associated with distortion and/or introduction of residual stress. Remedial action regarding distortion is beyond the scope of this document.

The following response addresses concerns regarding the introduction of residual stress. The first response must be to correct the cause of the interruption. Heating should be restarted with a heating rate appropriate to the temperature of the pressure vessel at restart. Heating should continue until the minimum soak temperature is achieved. Holding at or above the minimum soak temperature should then occur for a sufficient period of time to relax the induced stress. A conservative approach would be to repeat the originally required hold period time. However, since a significant contribution to stress relaxation occurs as a result of immediate yield strength reduction at temperature, holding for one hour may be sufficient. After completion of this additional hold period, the thermal cycle can be completed as specified, i.e. cool at a rate not exceeding the maximum allowed.

For certain material, a minimum cooling rate may be required to avoid embrittlement or other undesirable metallurgical reactions. The remedial response may be similar to that described above, i.e., heating should be restarted with a heating rate appropriate to the temperature of the pressure vessel at restart. Heating should continue until the minimum soak temperature is achieved. Holding at or above the minimum soak temperature would then be required. However, careful selection of the soak temperature and time would be required to assure elimination of the undesirable material condition. Once the required time at temperature has occurred, cooling at or above the minimum required rate should be applied.

12. Considerations Related to Service Environment

The cited fabrication codes generally do not recognize the service environment. Instead, the user is expected to apply engineering judgment based upon knowledge of the service environment. The user is able to obtain guidance from recommended practices which relate to the specific service environment. The practices cited in this document, NACE RP0472, NACE RP0296, NACE 8X194 and API 945, consider such environments as wet H_2S, caustic and amine.

ASME Sections III and VIII do not provide guidance regarding service environment, other than with respect to brittle fracture considerations. As previously discussed, BS 5500 and AS 1210 recognize the need for different PWHT thermal cycles for creep service or to achieve greater softening when tempering. Both BS 5500 and AS 1210 also recognize that local PWHT may not provide the same degree of immunity from stress corrosion cracking as heating the entire pressure vessel in a furnace.

AS 1210 additionally notes that where residual stresses must be kept to a minimum, the distance to the edge of the heated band should be increased beyond $2.5\sqrt{Rt}$. AS 1210 also includes a requirement that PWHT be performed, regardless of thickness, on vessels intended for service with any substance liable to cause stress corrosion cracking.

12.1 Appropriateness of Local PWHT

As discussed above, there is concern with regard to the use of local PWHT when stress driven failure mechanisms such as stress corrosion cracking are operative in the service environment. Recommendations to perform PWHT in a furnace or increase the size of the heated band for local PWHT are found in fabrication codes. As discussed in sections 5.2 and 5.4, the heated band size and axial temperature gradient can be used to reduce the magnitude and shift the peak induced stress axially away from the weld centerline (for circumferential local PWHT). It must however be noted that to estimate the effect of increasing the heated band size or decreasing the axial temperature gradient on induced stress requires more sophisticated thermo-plastic analyses [43, 44] than typical linear elastic evaluations. Precise knowledge of the stress thresholds associated with the failure mechanisms is generally not available. Finally, it must be noted that while the magnitude of the peak stress induced by local PWHT can be reduced, a stress peak of some magnitude is expected axially some distance from the weld centerline, typically in the adjacent base metal. As a result, a point of diminishing return is likely, beyond which increasing the heat band size or decreasing the axial temperature gradient does no more than move the stress peak further from the weld centerline.

All of these considerations must be weighed when deciding if it is appropriate to use local PWHT and how to properly select the associated parameters. It can be argued that by shifting the peak induced stress, it is moved out of the weld metal and HAZ where there is a greater likelihood of crack initiation sites being present. Without accurate estimates of the level of induced stress or the stress threshold for failure, prior experience with specific local PWHT parameters in similar service environments appears to offer the most practical source of guidance regarding acceptable practices. Admittedly, such prior experience may not be available and/or difficult to interpret regarding the success or failure or the outcome.

The following recommended practices are therefore offered as a result of the above considerations. They are listed in descending order of preference.

1. Whenever possible consider heating the entire structure or section. Techniques for PWHT of such large areas would typically involve internal heating using high velocity heated air as discussed in sections 16 and 17.
2. If heating the entire structure or section is not possible, consider heating a full circumferential

band. Perform an analysis using available techniques to estimate the induced stress resulting from the proposed parameters and compare to the estimated threshold values for cracking. If such an analysis is not possible, consider extending the heated band size to the soak band plus $6\sqrt{Rt}$.

3. If heating a full circumferential band is not possible, consider heating a circular local area for a spherical head or shell. Perform an analysis using available techniques to estimate the induced stress resulting from the proposed parameters and compare to the estimated threshold values for cracking. If such an analysis is not possible, consider extending the heated band size to a diameter of the soak band plus $6\sqrt{Rt}$.
4. If circular local heating of a non-spherical surface is being considered, an analysis or similar previous experience should be used to establish acceptable practices.

12.2 Exemption from PWHT

Fabrication codes typically provide exemptions from PWHT based upon thickness, preheat/interpass heating, composition, diameter and weld type/size. The concept of exemption from PWHT is important to understand as it relates to the service environment. Generally, exemption from PWHT is not valid when environmental cracking is operative.

The greater restraint associated with heavier wall thickness can result in plane strain conditions such that it is desirable to assure adequate tempering and stress relaxation to preclude unstable crack propagation. When designing to avoid such failure conditions, exemption from PWHT based upon thickness is reasonable.

However, in certain service environments, failure mechanisms such as alkaline stress corrosion cracking (ASCC) or hydrogen stress cracking (HSC) may be operative. These failure mechanisms can be driven by factors such as residual tensile stress and/or hardened microstructure. As a result, exemption from PWHT based upon thickness is not relevant when such environments are present.

Exemption from PWHT based upon composition relies upon limiting the amount of carbon and elements which can cause a hardened microstructure after welding. Carbon equivalent formulas can be used to quantify the effects of various elements and thereby provide a means to establish requirements. For example, NACE 8X194 discusses the possible use of carbon equivalent in order to control base metal composition and thereby limit the potential hardness of the HAZ. Exemption from PWHT based upon composition may be appropriate when environmental cracking mechanisms associated with a hardened microstructure are operative. However, it appears from the surveys cited in NACE 8X194 that the most effective use of composition limits is when combined with other approaches (limiting hardness of production weld metal and following recognized welding, fabrication and heat treatment practices) to control HAZ hardness. Exemption from PWHT based upon composition is clearly not appropriate when stress driven cracking mechanisms are operative.

Exemption from PWHT based upon preheat/interpass heating is generally used in conjunction with thickness, weld size or type. For example, in ASME Section VIII, PWHT is not mandatory for P-No. 1 carbon steel over 1-1/4 to 1-1/2 inch (31.75 to 38.1 mm) nominal thickness if a 200°F (93°C) minimum preheat temperature is used. While preheat/interpass heating does slow the cooling rate during welding and thereby help to control hardness and to some extent reduce residual stresses, it is most effectively used in combination with several approaches to mitigate environmental cracking as described above for composition control. It is therefore not appropriate to consider preheat/interpass heating as the only justification for exemption from PWHT when environmental cracking is operative.

Exemption from PWHT based upon diameter, weld type or size is not appropriate when environmental cracking is operative.

12.3 Tempering and Stress Relaxation Objectives

It is important that the user understand the needs imposed by a service environment to insure that appropriate PWHT is applied. Beyond the recognition that PWHT may be required independent of exemptions based upon thickness or other factors as described in section 12.2, careful attention must be paid to insure that the appropriate degree of tempering and/or stress relaxation occurs. With regard to tempering, this generally involves recognition that minimum code time-temperature requirements may not be sufficient to produce the desired hardness. As a result, higher temperatures and minimum hold times must frequently be specified. NACE 8X194 discusses this issue.

With regard to stress relaxation, the soak band must be large enough to accommodate the regions where tensile residual stresses are present. NACE RP0472 (para. 6.1) cites concern that tensile residual stresses may be present up to 2 inches (50 mm) from the weld. There is also concern that local PWHT may induce stress as previously discussed in section 12.1. NACE RP0472 (para. 6.4.2) specifically recommends that heating bands larger than required by codes be used for welds in piping with diameters greater than 10 inches (25 cm). It is assumed that this recommendation is referring to the use of a larger heated band.

In addition, longer times at lower temperatures are not recommended. For example, both API 945 (para. 4.6) and NACE RP0472 (para. 4.3.3 and 6.4.1) contain recommendations that PWHT at lower temperature and longer time not be used. NACE 8X194 cites survey results which indicate that almost no users have employed PWHT temperatures lower than 1,125°F (607°C).

Another important concept is that multiple failure mechanisms may be operative. For example, both HSC and ASCC may be operative. As a result, the need to achieve both adequate levels of tempering and stress relaxation may be necessary.

Another factor which may be overlooked is the presence of inadvertent arc strikes or temporary attachments. Although such areas may appear innocuous after grinding, the effects of the thermal cycle remain. It is important to insure that areas exposed to such thermal cycles receive adequate tempering and/or stress relaxation. Concern is greatest when such areas occur on the inner surface with direct exposure to the process environment. However, external attachments which generate through-wall residual stresses are also of concern. In such cases, the size of the soak band for local PWHT may have to be increased to incorporate these areas.

12.4 Hardness Testing

Hardness testing of production welds is commonly used as a quality control tool to insure that adequate PWHT has occurred. Such testing may be specifically aimed at insuring that adequate tempering has occurred (as measured by weld metal macrohardness) during PWHT to mitigate HSC. NACE 8X194 reports survey results and states that "This (hardness) testing has been shown to identify gross misuse of welding consumables and/or fabrication techniques." It also must be clearly understood that hardness testing is not an appropriate method to assess the level of residual stress present. Therefore, it is not appropriate to use hardness testing as a means to assess the ability of a weldment to perform in an environment where stress driven cracking mechanisms are operative.

In some cases, hardness testing may be used to determine that PWHT is not required because the as-welded hardness is adequate. The use of hardness testing for such purposes must be based upon recognition of its limitations.

To insure reasonable accuracy, portable field hardness measurements should be performed in accordance with recognized industry standards. ASTM A 833 – 84 [36] provides requirements for Brinell hardness testing by comparison methods. NACE RP0472 requires the use of this ASTM practice and provides (in Appendix A) suggested guidelines for such testing related to control of environmental cracking.

Portable field hardness testing is recognized as applicable to the weld metal, but not the HAZ of production weldments. NACE 8X194 states "There does not presently exit a practical hardness testing method for use on the actual HAZs of production weldments." This is due to the fact that such testing is frequently made using a portable Brinell hardness tester. The large size of the indentation in relation to the small HAZ or localized hard areas makes it difficult or impossible to obtain readings which are not composites of two or three regions (weld metal, HAZ and base metal) and hard and soft areas. As a result, such composite readings are not representative of the peak HAZ hardness. Although methods such as rebound hardness testing use smaller indenters than that used for Brinell, the resultant indentations are not considered to have sufficient spatial resolution, especially for the narrow HAZ associated with low heat input welds.

TWI is currently engaged in a second group sponsored project [37] to assess the ability of ultrasonic contact impedance (UCI) hardness testing to assess the HAZ hardness of production welds. The UCI testing method utilizes a Vickers diamond pyramid indenter, which provides the spatial resolution required. Although the UCI testing method addresses the issue of spatial resolution, other concerns exist. These concerns include dependence upon operator skill, adequate surface preparation, probe orientation and indentation spacing, and the need for a large number of measurements, with statistical assessment of data. The principal objective of the TWI project is to develop ancillary equipment to facilitate surface preparation and hardness measurements.

As a result of these limitations, the user must evaluate the appropriateness of hardness testing for the intended application. It may be that weld metal hardness testing in combination with one or more HAZ mitigation techniques, including control of base metal composition, PWHT and/or qualification of a specialized welding procedure, is necessary. Qualification of the welding procedure may include modification of preheat/interpass heating and welding heat input to produce the required hardness. Hardness testing of welding procedure qualification test specimens is discussed in NACE 8X194. Such testing utilizes multiple microhardness traverses using laboratory equipment.

It is also desirable to perform hardness testing both before and after PWHT, if there is not a concern with regard to brittle fracture. Since the indentation associated with field hardness testing is frequently made using an impact load, there may be some concern regarding brittle fracture. It is therefore advisable to discuss the appropriateness of hardness testing before PWHT with the user.

Hardness testing before PWHT can help in the selection of time-temperature parameters. For example, testing before PWHT may identify an unexpected weld metal and/or material condition such that higher temperatures are required to achieve the maximum target hardness. In general, hardness testing before PWHT can make a significant contribution to avoiding undesired outcomes after PWHT.

13. Repair of Service Exposed Material

The first step in any repair activity involving service exposed components should be a determination of the root cause of the failure, including an assessment of the material condition. Such a determination/assessment not only allows selection of the proper repair and mitigation techniques, but prevents actions which can be harmful. For example, application of heating may cause crack propagation from defects or blisters which were not removed.

For certain service environments, it may be important to remove any residue before the application of heat. This is due to the fact that a cracking mechanism may become operative above a threshold temperature. For example, API 945 (para. 4.6) recommends removal of residual amine before heat treatment.

As previously discussed, it may be necessary to perform bake-out, before welding, if hydrogen has been introduced during service. Such bake-out should be sufficient to remove hydrogen from an area around the weld to prevent weld metal or HAZ cracking.

High levels of restraint are often associated with repair welds [49–51]. As a result, higher preheat/interpass heating temperatures are frequently used.

The need to consider postheating is primarily dependent upon the sensitivity of the material to hydrogen cracking, the hydrogen potential of the welding consumables, the practicality/cost effectiveness of maintaining the preheat/interpass temperature, and whether or not PWHT is to be applied.

The need to apply PWHT and issues relating to the methods and objectives of the process are of course dependent upon the specific service environment. The discussion of considerations relating to service environment in section 12 are therefore applicable and need not be repeated.

14. Welding Without Postweld Heat Treatment

In recent years there has been increased interest in the use of welding methods in lieu of PWHT. Such methods have been allowed by ASME Sections III and VIII. The NBIC (Part RD-1000) repair code provides requirements for three such methods. Various issues which must be considered when applying such methods have been reported [38]. As noted in NBIC and reported [38], the application of such alternatives to PWHT must be carefully considered for use in highly stressed areas, certain service environments such as those where ASCC and/or HSC are operative, materials subject to hydrogen embrittlement, and materials operating in the creep range.

The use of minimum preheat/interpass temperatures, a maximum interpass temperature, and postheating are required by NBIC when using the alternative welding methods. The methods for materials without notch toughness requirements provide specific minimum preheat/interpass temperatures and maximum interpass temperatures. The method for materials with notch toughness requirements does not specify the minimum preheat/interpass temperatures or maximum interpass temperatures. Instead, the procedure must be qualified such that preheat/interpass temperatures in conjunction with welding heat input produce cooling rates required to achieve the desired toughness.

Two of the three methods provide soak band sizing requirements for preheat/interpass heating of 4 in (102 mm) or four times the material thickness, whichever is greater, on either side of the weld joint. Two of the methods provide specific requirements for postheating when using either the SMAW or FCAW processes.

It should be recognized that the local heating associated with these alternative welding methods plays an important role in attempting to achieve desired as-welded properties. Therefore, greater care must be exercised to insure that the heating is performed properly and without significant interruption during the required periods. Inherent to such consistent heat application is the use of automatic heating and control methods.

15. Quality Assurance System

[Refer to Section 14 and Annexes F and G of AWS D10.10/D10.10M: 1999 for an additional information and recommendations.]

In order to insure that local heating operations are performed in accordance with various codes, standards, practices or specifications, it is desirable to perform such heating in accordance with an established quality assurance system. ANSI/ASQC Q9002 [39] provides an appropriate model for such a system.

Although it is recognized that other temperature measurement techniques may be used as described in section 7, thermocouples are referenced in the following discussions.

15.1 Quality System

All work should be performed in accordance with a written quality assurance system. Such a written description is generally available in a Quality Assurance Manual and should define the organizational structure, responsibilities, procedures, processes and resources for implementing quality management. The written description of the quality assurance system should be available for review. It is desirable that the user audit the supplier of local heating services to determine compliance with the written quality assurance system.

15.2 Process Control

Although written procedures are not always used in local heating operations, the use of such procedures and associated drawings provides greater assurance that requirements will be met. NACE 8X194 cites survey results which indicate that many users have required such procedures to obtain better control of the PWHT process. As a minimum, the use of general procedures and informal sketches should be considered. The procedure should include the steps below and be used in conjunction with a drawing/sketch which specifies placement of thermocouples, heat sources (including control zones) and insulation.

1) Match procedure/drawings to work piece, including: verification of work piece identifica-

tion number and checking the appropriateness of specified thermal cycle to material.
2) Installation and testing of power/control equipment, including: power supply, temperature controllers, and temperature recorder.
3) Verify validity of temperature recorder calibration.
4) Install thermocouples, heat sources and insulation per drawing/sketch.
5) Verify specified (per drawing/sketch) placement of thermocouples, heat sources and insulation before the start of heating. The user's inspector is frequently involved in such verifications.
6) Verify operation of all thermocouples and heat sources before the start of heating. One common problem which may be detected by this step is reversed thermocouples.
7) Perform periodic checks during heating, including: equipment operation (thermocouples and heat source) and adherence to thermal cycle.
8) Verify that the required region achieved the minimum temperature for the required time before the start of cooling. The user's inspector is frequently involved in such verifications.
9) Deactivate power/control equipment after required temperature-time profiles have been attained and verified. This normally occurs at a temperature below that where cooling rate control is required (below 800°F [427°C] for ASME Section VIII).
10) Remove all equipment after the temperature is safe for personnel.
11) Complete and submit appropriate records.

15.3 Response to In-process Deviations

Various deviations can occur during the course of local heating operations as discussed in section 11. The supplier's procedures should contain specific actions to be taken in response to such deviations.

15.4 Testing

A common testing method associated with local heating is hardness testing. Such testing should be performed in accordance with an established procedure. Since hardness testing associated with local heating is frequently performed using a portable Brinell tester, ASTM A 833 – 84 [36] and NACE RP0472, Appendix A provide appropriate guidelines, as previously discussed in section 12.3.

Hardness testing both before and after PWHT can make a valuable contribution by verifying the correct condition of welds before and after PWHT if there are no concerns regarding brittle fracture.

15.5 Documentation

The most important documentation associated with any heating is a record of the thermal cycle. Currently, such a record is typically provided by a strip or disk chart from a recorder. However, use of other data acquisition methods may result in such information being available on electronic media. The record of the thermal cycle should be submitted upon the completion of local heating. As a minimum, the record of the thermal cycle should contain the following information:

1) Date and time
2) Identification of contractor/personnel performing the work
3) Identification number of the work piece (material type & dimensions optional)
4) Temperature and time scales
5) Correspondence of thermocouple numbers between chart & drawing/sketch
6) Heating rate above specified temperature
7) Hold period temperature and time
8) Cooling rate above specified temperature
9) Appropriate signatures (contractor/inspector) verifying in-process inspections

Copies of the procedures, drawings/sketches, thermocouple/extension wire Certificates of Conformance, temperature recorder calibration records, and hardness test results (if applicable) should be submitted along with the record of the thermal cycle.

15.6 Control of Inspection, Measuring and Test Equipment

The most important aspect of any quality assurance system relating to heating involves the measurement and recording of temperature. Use of equipment which conforms to specific requirements and has been properly calibrated and maintained is vital. ANSI/NCSL Z540-1 [40] provides requirements for controlling the accuracy of measuring and test equipment.

All thermocouples/extension wire and recorders must be traceable to national standards, such as those maintained by NIST.

Hardness test bars must be traceable to Certificates of Conformance and be used such that the proper spacing is maintained between successive indentations.

15.7 Training

Training programs should provide personnel with the knowledge and skills relating to safety, calibration, maintenance, processes, and inspection associated with local heating. Documentation of such training should be maintained.

15.8 Servicing

All equipment should be serviced at appropriate intervals to insure proper performance. Documentation of such servicing should be maintained.

16. Comparison of Heating Methods

Various methods can be used to accomplish local heating of pressure vessels. Possible heat sources include: low or high voltage electric resistance heaters (contact pads or radiation elements supported on a structure); combustion burners (high velocity gas and luminescent flame); induction coils, and quartz lamps. Induction coils and quartz lamps are the least common and, therefore, will not be discussed. Low voltage electric resistance and high velocity gas combustion are common methods in the United States for local heating of pressure vessels. Low voltage electric resistance heating pads are used in contact with the weldment for conduction heat transfer. High velocity gas combustion is generally used in conjunction with a temporary furnace. An entire vessel can become its own furnace by simply covering its exterior surface with thermal insulation and using the turbulent heated air of a combustion heating system to convectively heat the vessel shell. In a similar fashion, sections of a vessel can be heated by employing insulated bulkheads internally to create an isolated heat chamber. Alternatively, a temporary furnace can be constructed around a vessel.

High voltage electric resistance heaters offer similar advantages to combustion heating of large vessel sections. They can be placed a fixed distance from the weldment surface, as in a temporary furnace constructed within or on the outside of a pressure vessel, for radiant and convective heat transfer. These elements are usually connected in star (wye) formation to take advantage of the increased voltage with this type of connection with 3-phase electric power. A neutral connection at the star point of each circuit allows individual control of each element in the star. However, it is not common to run a neutral with a 3-phase supply in the United States. As such, the use of internally bulkheaded electric resistance temporary furnaces is more common outside of the United States. Wider utilization in the United States appears to be limited due not only to the inability to achieve individual element control, but also to safety concerns relating to the use of high voltage. In addition, installation and equipment requirements are greater for high voltage heaters compared to internally fired high velocity gas combustion.

However, high voltage electric resistance does offer many benefits when compared to low voltage electric resistance heating. Specifically, avoiding the use of transformers results in lower secondary amperage for the same energy output, and hence lower rated contactors and other components. In addition, the number of heating elements may be reduced for the same energy output because of the higher voltage. Typically, the elements used for high voltage electric resistance heating are more robust than those used for low voltage.

Luminescent flame combustion can be used for direct internal heating (i.e., a temporary furnace with insulation on the outer surface of the pressure vessel) with primarily radiant and some convective heat transfer. It is most suited to vessel configurations such as spheres where the flame can be centrally located to achieve symmetrical distances for radiant heat transfer. Luminescent flame is not amenable for use with distribution tubes, as is high velocity gas. As such, luminescent flame is not a desirable method for vessels with large axial length to diameter ratios or for situations where it is necessary to direct heated air into regions where stagnant air layers are present. Therefore, the use of luminescent flame appears to be limited to certain pressure vessel geometries.

A detailed discussion of various heat sources is provided in a related American Welding Society (AWS) document [41] which addresses local heating in piping and tubing. The following sections provide brief descriptions of local heating using low voltage electric resistance heaters and high velocity gas combustion burners. Additional information regarding electric resistance and gas-fired techniques has been reported [25, 42] elsewhere.

16.1 Electric Resistance

Electric resistance heating can be performed using elements placed either externally or internally. When performing external heating, the use of low voltage flexible ceramic pad (FCP) type heaters, placed in contact with the outer surface is most common. When internal electric resistance heating is used, elements are normally mounted on bulkheads or other structural support. High voltage heaters are frequently used for such internal bulkhead heating.

A heated band can be created by using FCP heaters, with each heater developing 3.6 kW of thermal power when connected to an 80 Volt, alternating current circuit of a power source. Because of conductive heat losses into the adjacent unheated shell sections and convective and radiate heat losses from the heated weldment assembly, the actual heated band must be wider than the required soak band. This concept was discussed previously in section 5.2.

The heated band may be comprised of one or more bands of FCP heaters with multiple control circuits, or zones, depending on the diameter and thickness of a given weldment assembly. A standard 80 volt FCP has a surface area of approximately 120 in^2 (0.077 m^2), producing approximately 30 W/in^2 (46.8 kW/m^2) and is available in a variety of combinations of length and width. In addition, 60 and 40 volt FCP heaters are available with similar power density, and special configuration heaters can be fabricated. Heater selection is made to minimize circumferential gaps between heaters, and thus optimize surface coverage, in order to create a uniform heated band width sufficient to maintain temperature uniformity across the soak band. Typically, heater spacing up to the wall thickness or 1 in (25.4 mm), whichever is less, can be accommodated without detrimental heat loss.

16.2 High Velocity Gas Combustion

Heating of pressure vessels by direct internal firing, with high velocity gas burners offers many advantages. Good temperature uniformity is obtained due to the forced convective mode of heat transfer. High velocity heated air is amenable to the use of distribution tubes to direct flow into regions of stagnant air, to enhance turbulent convective heat transfer. Where suitable external insulation exists on a pressure vessel, the installation time for an internal combustion heating system is much less than required for the attachment of heaters and insulation to the vessel's outer surface.

Direct internal firing can be used to heat the whole pressure vessel or sections, depending upon local heating needs. When sections are to be heated, insulated bulkheads are erected to limit the area being heated. As previously discussed, the decision to heat a larger section than the required local area can be driven by several factors. It may be easier and less expensive to bulkhead a section and use direct internal firing as opposed to external heating with electric resistance heaters. As previously discussed in section 5.6, it is common for nozzles or other attachments not requiring PWHT to intersect the region to be heated. The resultant need to heat an even larger section to insure an allowable gradient across these attachments further enhances the advantages of cost and time savings from direct internal firing.

The use of bulkheads to isolate sections of a vessel for heating a weldment or repair is particularly appropriate in cases where the area to be heated is sufficiently large (e.g., a cluster of several nozzles, etc.) to preclude the less cost-effective use of FCP heaters. In those instances, bulkheads are typically erected beyond each edge of the required soak band at a distance based upon the heated band width requirements as discussed in section 5.2. The resultant volume between bulkheads creates an internal furnace, or heat chamber. Insulation is installed on the hot face of each bulkhead and on the external surface of the pressure vessel shell opposite the heat chamber, typically extending past the bulkheads a distance based upon gradient control band requirements as discussed in section 5.3. The volume between the bulkheads can be heated with a high velocity combustion system in the same manner as with complete vessel heating, which is described below.

There are cases when it is necessary to heat an entire vessel in situ. In each of these instances, the vessel is insulated externally and heated internally, thus turning the vessel into its own furnace. The combustion heating system used for such heating consists of at least one burner and high volume air blower, supported by at least one control console, or gas train, with its essential piping, valving, and electronic instrumentation, for safety and precise control of temperature and heating and cooling rates, etc.

The burner(s) are directed into appropriate openings, such as manway(s), etc. It may be necessary to attach a special distribution tube to each burner to direct heated air flow to areas which would otherwise be difficult to heat using burners alone. Generally, each distribution tube is custom-designed. For example, certain applications require a distribution tube that incorporates a discharge tee to force heated air in opposing directions. Often the tee will be fitted with compressed air tubing for analog control of heated air flow rates, in an effort to achieve temperature uniformity throughout a vessel with limited access openings.

The gas flow into the system can be controlled manually or automatically by the gas train's microprocessor. To achieve precise control of heating and cooling rates and temperature distribution throughout the system, gas flow input, air input and exhaust dampers are adjusted. Burners are typically available in sizes from 1/2 MBtu/hr (0.15 MW) to 10 MBtu/hr (2.9 MW). The output of some burners can be adjusted to as little as 1% of their maximum rated power. Each burner is fitted with a spark ignition device, and the flame is monitored by an ultraviolet flame sensor coupled to an automatic gas safety shut off valve, to provide a fail-safe process. In addition, each burner is coupled to an adjustable high volume air blower via flexible ducting, to provide a discharge velocity of up to 450 ft/s (137.2 m/s). This establishes a turbulent flow of heated air within the vessel, and thereby enhances convective heat transfer and temperature uniformity.

The combustion system's heated air is exhausted through a dedicated opening(s), such as an existing nozzle, and may be modulated with a damper plate. The temperatures of sections or attachments with thicknesses which significantly differ from the bulk of the shell should be monitored to ensure conformity with the vessel shell at all times. In fact, supplemental electric heating should be used on nozzles, skirt welds, and other attachments of relatively large thickness, in order to achieve heating in concert with the rest of the vessel, and thereby prevent harmful temperature gradients.

One of the biggest obstacles preventing more widespread use of direct internal firing is a lack of understanding of the process. In many cases, safety concerns are raised regarding the use of a combustion heating technique, especially in a refinery or petrochemical plant environment. While it is critical to insure the safe operation of combustion heating systems in such environments, it should also be realized that electric resistance heating equipment must also be carefully controlled since it typically utilizes contactors which create sparks when opening and closing.

16.3 Considerations For Choosing The Appropriate Heating Method

Obviously, the first issue to consider when choosing which of several available heating methods to use is the ability to meet the technical requirements. Low voltage electric resistance and high velocity gas combustion can generally provide satisfactory results if correctly applied with an understanding of their limitations. For example, electric resistance heating is better suited to heat small local areas, especially where achievement of adequate gas flow might be difficult. Therefore, it is common to use both methods together: supplemental electric heaters on heavy wall attachments in conjunction with gas firing of a large section.

The need for non-uniform temperature heating, as described in section 5.7.2.1 and figure 9, provides an important example where the combined use of electric and gas firing techniques is well suited. In this situation, electric resistance heaters can be used to achieve the soak band temperature, while high velocity gas is used to heat a circumferential band of adjacent shell metal to a percentage of the soak band temperature. As previously discussed in section 5.7.2.1, this provides a means to balance thermal expansion, while limiting the net section strength loss at elevated temperature. This is frequently an important consideration when heating sections of vertical vessels in which buckling or distortion due to wind, dead weight or other loads is a possibility.

Because of the ability to utilize individual zones of control, electric resistance heaters are also better suited to provide gradient heating. However, as the number of electric resistance heaters increases, the number of control zones, power/control consoles and total power requirements can become excessively large. A minimum diameter of approximately 4 ft (1.2 m) is generally required for proper application of high velocity gas combustion to prevent direct flame impingement, unless distribution tubes are used. This minimum diameter also appears to coincide with the size where high velocity gas combustion begins to gain a cost advantage, depending on the length of the heated region.

The advantages of one method over the other emerge as specific dimensions and requirements are considered. In general, as the size of pressure vessel and/or area to be heated increases, it becomes more likely that high velocity gas combustion will be more advantageous. Therefore, when not constrained by other issues, it is desirable to evaluate the cost and time requirements of each approach to insure efficient use of resources.

The following example highlights a situation where high velocity gas combustion was more advantageous than electric resistance. PWHT was required for six nozzles being attached to a DEA-absorber column. The electric resistance method required five separate heat cycles over 6 ten-hour shifts in which two nozzles were heat treated together and the others separately. Direct internal firing of bulkheaded sections required only three separate heat cycles over 4.5 ten-hour shifts in which 3, 2 and 1 nozzle were heated at a time. As a result, the price of the high velocity gas combustion approach was approximately 40% of the electric resistance approach. Since this price difference does not reflect the impact on the plant's schedule, inclusion of down-time costs would further increase the advantage of high velocity gas combustion.

17. Case Histories

The following case histories generally reflect practices based upon interpretation of current code requirements and/or direct implementation of owner requirements. As such, band sizes (soak, heated and gradient control), axial temperature gradients, and thermocouples (number and location) may differ from some of the earlier recommendations. The information which follows was extracted directly from the written procedures and drawings used to perform the work. Since parts of drawings were extracted, all referenced notes, etc., are not present. Please note that thermocouple locations are denoted in the drawings by a circle with an "x" through it (⊗).

17.1 Shell

Case histories are provided for PWHT of a shell circumferential seam weld and hydrogen bake-out and PWHT of repairs to base metal.

17.1.1 Internal Gas Firing of a Circumferential Seam Weld: Figure 19 illustrates the burner and thermocouple layout for an ASME Section VIII, Division 1 PWHT of a circumferential seam weld on an SA-516 grade 70 carbon steel de-ethanizer vessel, joining a 1-7/8 in (47.6 mm) thick upper section to a 1-13/16 in (46 mm) thick lower section. The PWHT procedure specified a gas-fired combustion heating system to internally heat a section of the vessel, defined by two specially constructed bulkheads to include the girth weld and an adjacent manway, while insulated externally with a 2 in (50.8 mm) layer of 8 lb/ft^3 (128.1 kg/m^3) density mineral wool extending 2 ft (0.6 m) beyond each bulkhead. In addition, supplemental electrical heating elements were used on the 20 in (508 mm) diameter manway.

The lower and upper bulkheads were installed at tray locations. The bulkheads were constructed of wire mesh and a 2 in (50.8 mm) thick layer of 8 lb/ft^3 (128.1 kg/m^3) density refractory ceramic fiber insulation. The gas-fired combustion heating system consisted of a 3 MBtu/hr (0.88 MW) burner fired through the manway into a 6 in (152.4 mm) diameter 'T' distribution pipe. Exhaust gases were vented out of the inlet/exhaust bonnet adapter onto which the burner was mounted.

Thermocouples were placed on the outer surface of the pressure vessel in a pattern which enabled monitoring of temperature gradients in any 15 ft (4.6 m) length. In addition, control thermocouples were used for each supplemental electric resistance heating zone.

17.1.2 Electric Resistance Heating of Base Metal Repairs: Figures 20 and 21 illustrate heater and thermocouple layout for hydrogen bake-out and PWHT of two shell repair patch welds and one head nozzle attachment weld in a cylindrical refinery vessel. The vessel's shell and upper head were

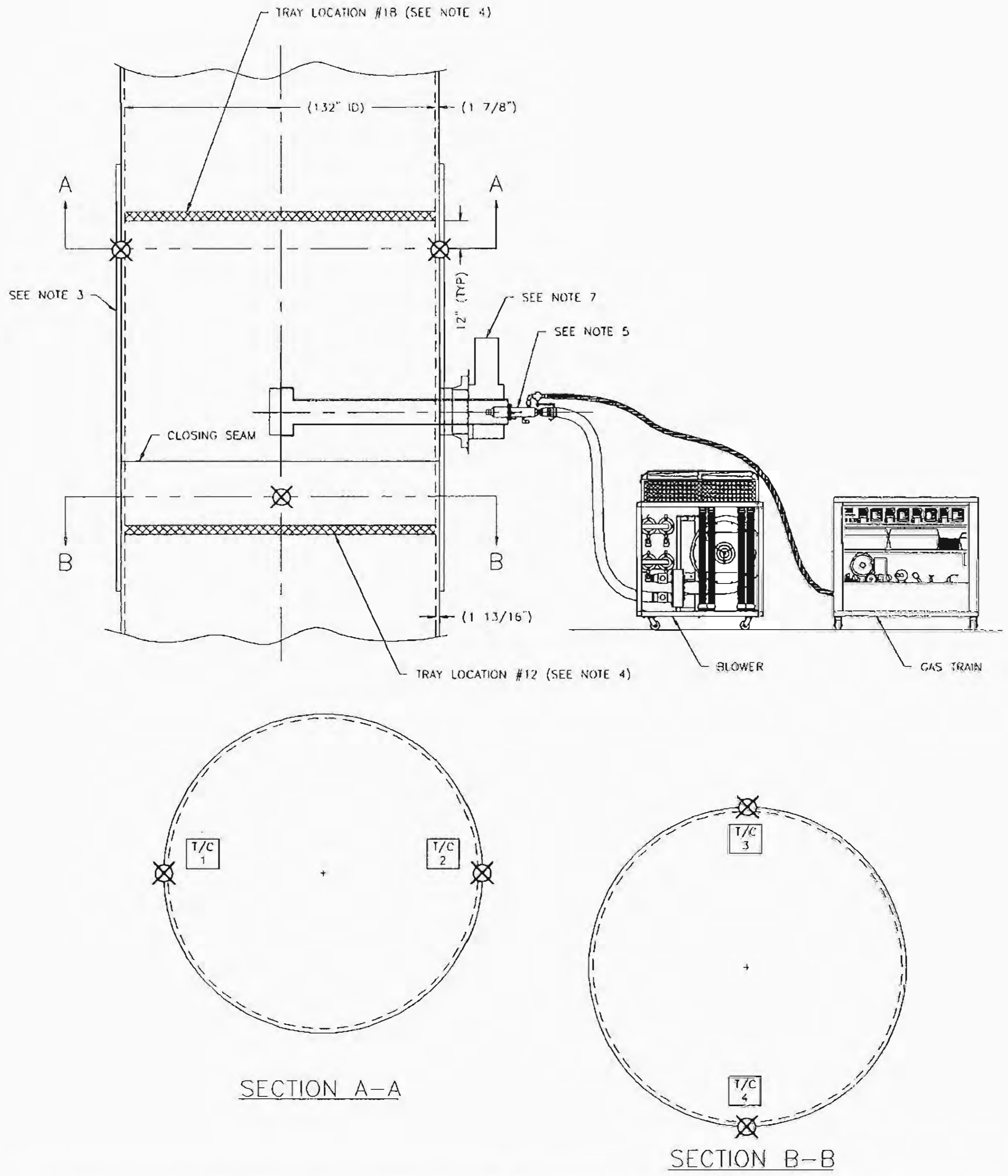


Fig. 19—Burner and thermocouple layout for case history described in section 17.1.1 in which internal gas firing with supplemental electric resistance heating was used for full circumferential PWHT of a circumferential seam weld in a de-ethanizer vessel.

constructed of 3/8 in (9.5 mm) thick carbon steel. The upper patch was 24 in (609.6 mm) wide by 26 in (660.4 mm) tall, with its top edge on the upper shell-to-head tangent weld seam. The second patch was 48 in (1,219.2 mm) wide by 10 in (254 mm) tall, and was located 4 in (101.6 mm) below the upper patch. The upper head nozzle was a 3 in (76.2) nominal pipe size (NPS), with a 3-1/2 in (88.9 mm) outer diameter and a standard schedule thickness of 0.216 in (5.5 mm).

The PWHT minimum soak temperature, circumferential soak band width, and heating and cooling rates specified by this procedure were in accordance with the requirements of ASME Section VIII, Division 1. However, the head PWHT soak band and the hydrogen bake-out requirements were in accordance with client specifications.

Hydrogen bake-out involved heating the shell and/or head in the immediate vicinity of the cut opening by placing a heated band of nominal 6 in (152.4 mm) width directly around or over the edge of the opening. PWHT, on the other hand, involved a

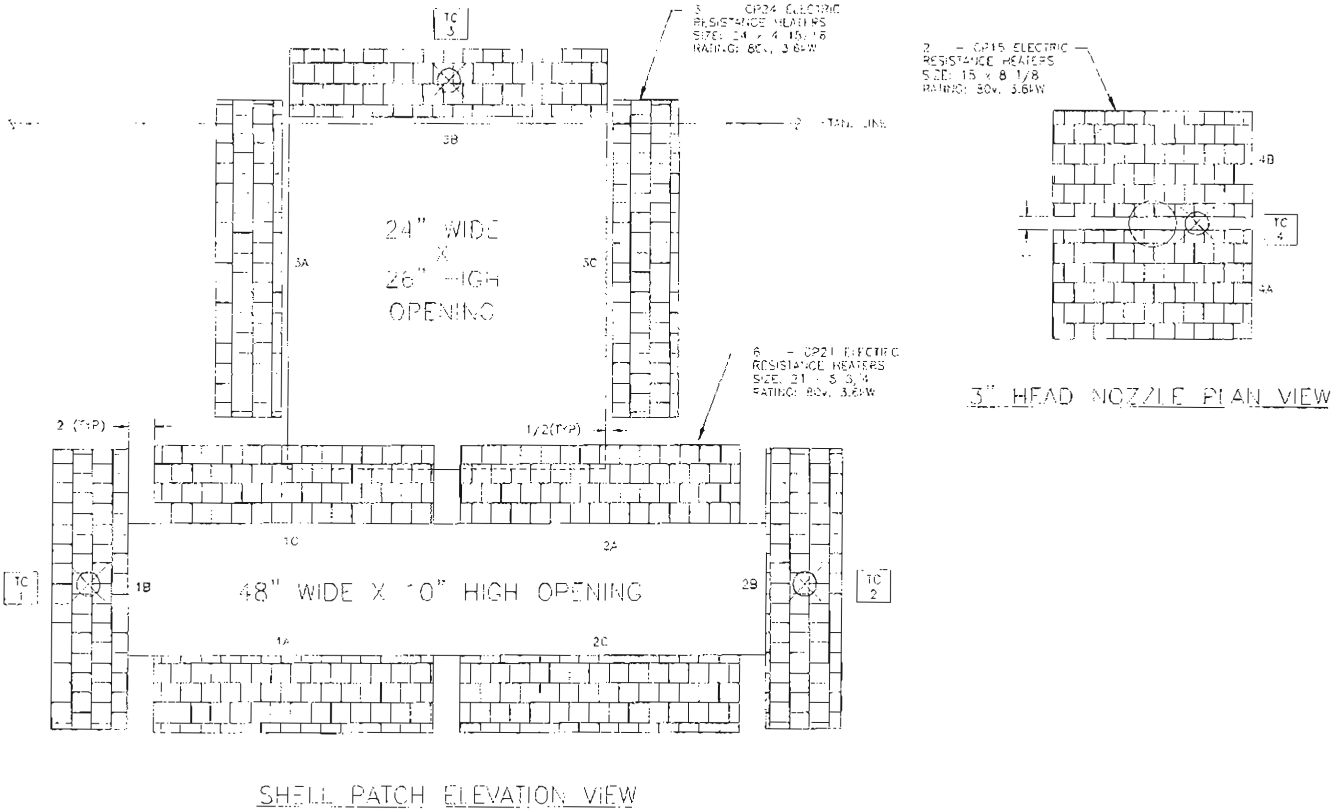


Fig. 20—Heater and thermocouple layout for case history described in section 17.1.2 in which electric resistance heating was used for hydrogen bake-out of base metal shell repairs and a head nozzle attachment to a cylindrical refinery vessel.

full circumferential heated band around the vessel and head to avoid harmful circumferential temperature gradients at the much higher PWHT soak temperature.

The arrangement of heaters, thermocouples, and insulation for hydrogen bake-out and PWHT is illustrated in Figures 20 and 21, and is briefly described below. Heated bands for hydrogen bake-out and PWHT were composed of FCP heaters which were attached to the exterior surface of the shell and head by capacitor discharge welded insulation stud pins and retaining clips.

The hydrogen bake-out for the shell patch openings was achieved by placing a ring of six CP21 (21 x 5-3/4 in [533.4 x 146.1 mm]) heaters around the lower rectangular opening, and a ring consisting of one CP21 heater along each of the remaining three sides of the upper rectangular opening. In addition, the nominal 3-1/2 in (88.9 mm) hole in the center of the upper head was covered with two CP15 (15 x 8-1/8 in [381 x 206.4 mm]) heaters. The heaters surrounding the rectangular patch openings were arranged into three 3-heater zones, and the heaters over the head opening were arranged into a single 2-heater zone.

PWHT was accomplished by encircling the top 4 ft (1.2 m) of shell length with three circumferential bands of FCPs, and by completely covering the upper head with approximately five concentric bands of FCPs. Each of the three 15 in (381 mm) wide shell circumferential bands was composed of 35 CP8 (8 x 14-3/4 in [203.2 x 374.7 mm]) heaters with nominal 3/16 in (4.8 mm) circumferential spacing, arranged into eleven 3-heater zones and one 2-heater zone. Axial spacing between the band of FCPs on the shell was approximately 1 in (25.4 mm).

The upper head was completely covered with five concentric bands of FCPs, composed of the following:

A. Eleven CP21 heaters forming the outer band, arranged into three 3-heater zones and one 2-heater zone.
B. Ten CP18 (18 x 6-1/2 in [457.2 x 165.1 mm]) heaters forming the 2nd band, arranged into two 3-heater zones and two 2-heater zones.
C. Nine CP15 heaters forming the 3rd band, arranged into three 3-heater zones.
D. Six CP12 (12 x 9-3/4 in [304.8 x 247.7 mm]) heaters forming the 4th band, arranged into two 3-heater zones.
E. Two CP12 heaters, one on either side of the center nozzle, each riding approximately 3 in (76.2 mm) up the nozzle neck, arranged into a single 2-heater zone.

Each zone, or circuit, had its own control thermocouple, with each thermocouple having a spare located within 1/2 in (12.7 mm), and all thermocouples being attached by means of capacitor discharge welding.

A total of 4 control thermocouples were used during hydrogen bake-out. A single control thermocouple was placed beneath the center of the middle

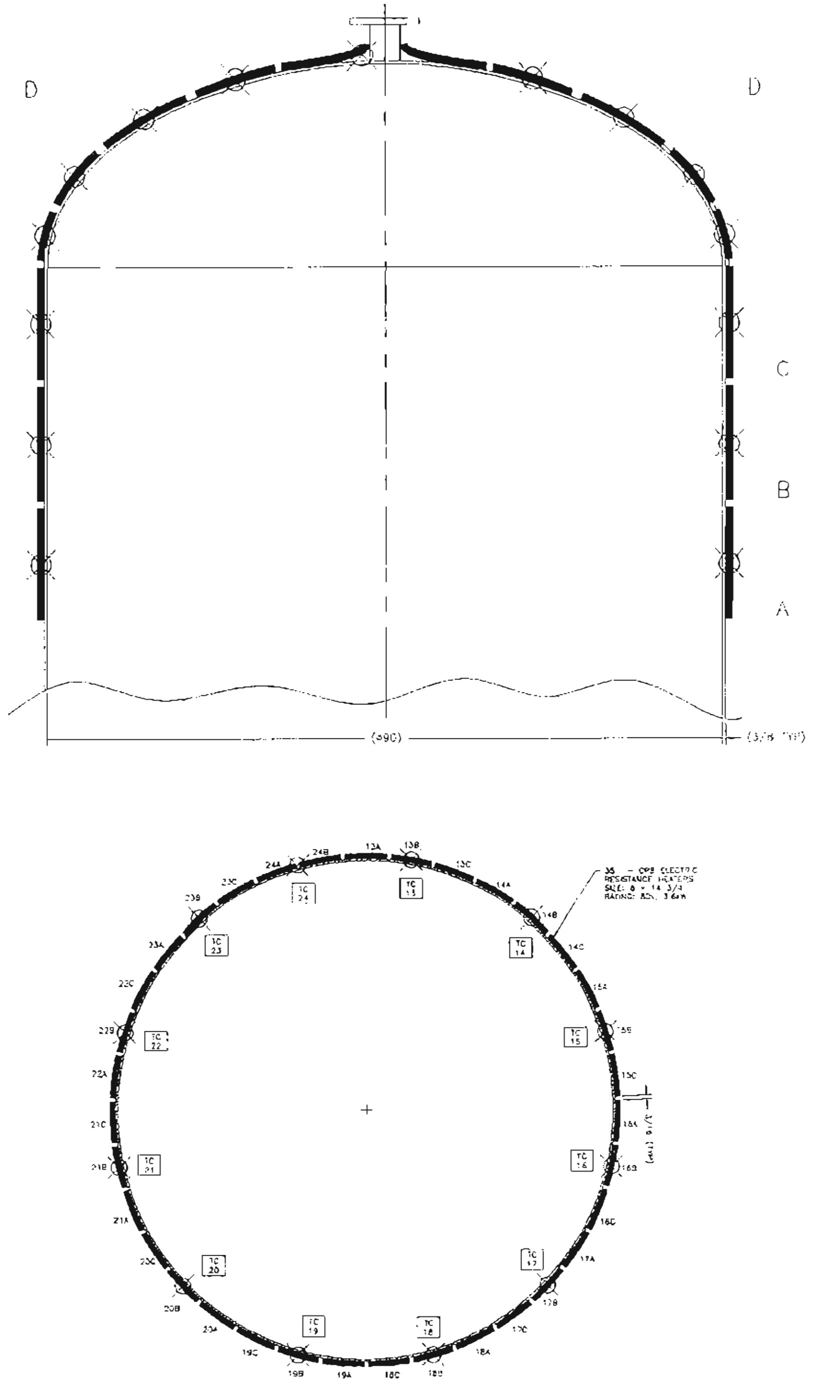


Fig. 21—Heater and thermocouple layout for case history described in section 17.1.2 in which electric resistance heating was used to PWHT base metal shell repairs and a head nozzle attachment to a cylindrical refinery vessel.

heater for each of the three 3-heater zones on the shell, and in the space between heaters for the single 2-heater zone on the upper head.

Twelve control thermocouples were used for each of the three circumferential bands of FCPs around the cylindrical shell, and fourteen control thermocouples were used for the full complement of five concentric bands of FCPs covering the upper head. Each 3-heater zone had its thermocouple placed beneath the middle of the center heater, and each 2-heater zone had its control thermocouple placed in the space between heaters.

Insulation was attached to shell and head surfaces by means of capacitor discharge welded insulation stud pins and retaining clips. For the hydrogen bake-out, both exterior and interior surfaces were covered with a 1 in (25.4 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation, extending 2 ft (0.6 m) past all heaters. For PWHT, both exterior and interior surfaces of the heat zone were covered with a 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation, extending 2 ft (0.6 m) past all heaters.

17.2 Nozzles

Case histories are provided for PWHT of nozzles using full circumferential band and spot heating.

17.2.1 Full Circumferential Band Electric Resistance Heating: Figure 22 illustrates heater and thermocouple layout for a case history in which electric resistance heating was used for PWHT of the weld attaching a nozzle to an acid settler tank. Specifically, a 3 in (76.2 mm) ANSI B16.5 Class 300 nozzle, having a 4-5/8 in (117.5 mm) outer diameter was added to the shell of a 156 in (3,962.4 mm) inner diameter cylindrical acid settler tank at a distance of 15 ft, 10 in (4.8 m) from the nearest shell-head tangent line. The 1-1/2 in (38.1 mm) thick shell was constructed of SA-516, Grade 70 carbon steel.

PWHT was performed in accordance with ASME Section VIII, Division 1, which requires a circumferential soak band of a prescribed width around the part of the settler tank shell containing the attachment weld. PWHT was performed in situ, with the vessel supported in a horizontal orientation in the same manner as during its normal operation. However, provisions were made to accommodate the longitudinal elongation of the tank during PWHT. Specifically, the support saddles were unbolted from their bases and placed on slide plates which were coated with a lubricant to facilitate longitudinal translation as the vessel elongated approximately 1/2 in (12.7 mm) during PWHT. Similarly, all nozzles that attached to the tank in the region between the area being heated and the nearest end experienced this nominal 1/2 in (12.7 mm) longitudinal displacement. Therefore, each nozzle had its flange bolts removed to enable unconstrained movement.

ASME Section VIII, Division 1 requires that an attachment weld undergo PWHT with a circumferential soak band whose width extends beyond the weld a minimum distance equal to six times the maximum vessel wall thickness at the weld (6t).

The heated band consisted of two adjacent bands of FCPs. Heaters were held in place through the use of capacitor discharge welded stud pins, and the axial space between adjacent bands of FCPs was less than 1 in (25.4 mm).

Specifically, each of the two bands of FCPs was composed of 81 CP6 (6 x 19-1/2 in [152.4 x 495.3 mm]) heaters, with a nominal 3/16 in (4.8 mm) space between each heater, and arranged into 27 power circuits or zones of temperature control. Therefore, the heated band was approximately 40 in (1,016 mm) wide and required nine 6-Way power sources to supply its 54 temperature zones. The four heaters which were adjacent to the nozzle attachment weld were positioned to have their edges ride up along the nozzle neck, to ensure heating of the attachment weld.

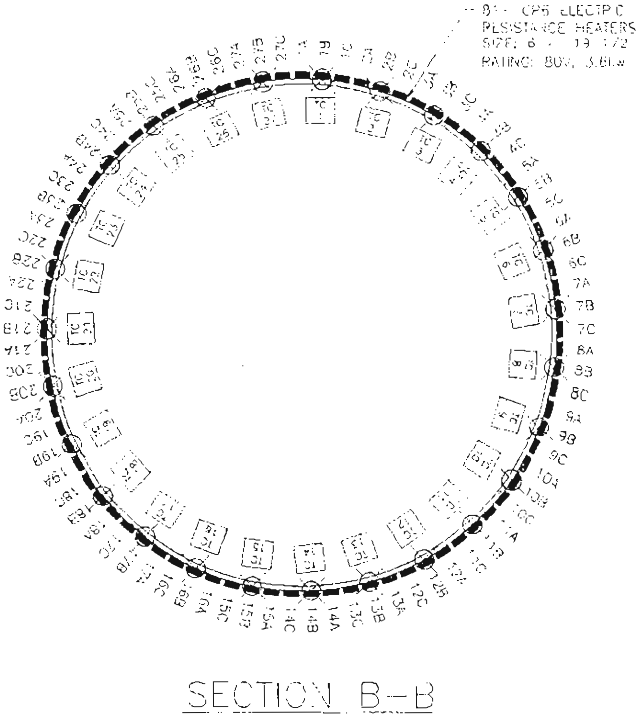


Fig. 22—Heater and thermocouple layout for case history described in section 17.2.1 in which external electric resistance heaters were used for full circumferential PWHT of a nozzle attachment to an acid settler tank.

A single thermocouple was used to control the temperature of each of the 54 control zones. Each control thermocouple was placed beneath the center heater of its 3-heater zone. The two bands of 27 thermocouples were located a distance of approximately 20-3/4 in (527.1 mm) apart, centered over the 3 in (76.2 mm) nozzle attachment. In addition, a monitor thermocouple was placed on the attachment weld to ensure attainment of soak temperature. All thermocouples had a spare attached to the vessel within a distance of 1/2 in (12.7 mm), and all thermocouples were attached by means of capacitor discharge welding.

All heaters were covered with a 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation, which extended a distance of at least 2 ft (0.6 m) past the heaters in all directions, and was attached by means of capacitor discharge welded stud pins. In addition, the internal surface of each shell was similarly covered, and the outer surface of the 3 in (76.2 mm) nozzle was wrapped with identical insulation.

17.2.2 Circular Spot PWHT on a Spherical Shell: Figure 23 illustrates the heater and thermocouple layout for electric resistance circular spot PWHT of a nozzle attachment weld on a butylene storage sphere. Although Figure 23 describes only the PWHT, heating during this repair also included hydrogen bake-out and pre-heat for the nozzle attachment weld and a replacement patch seam weld on

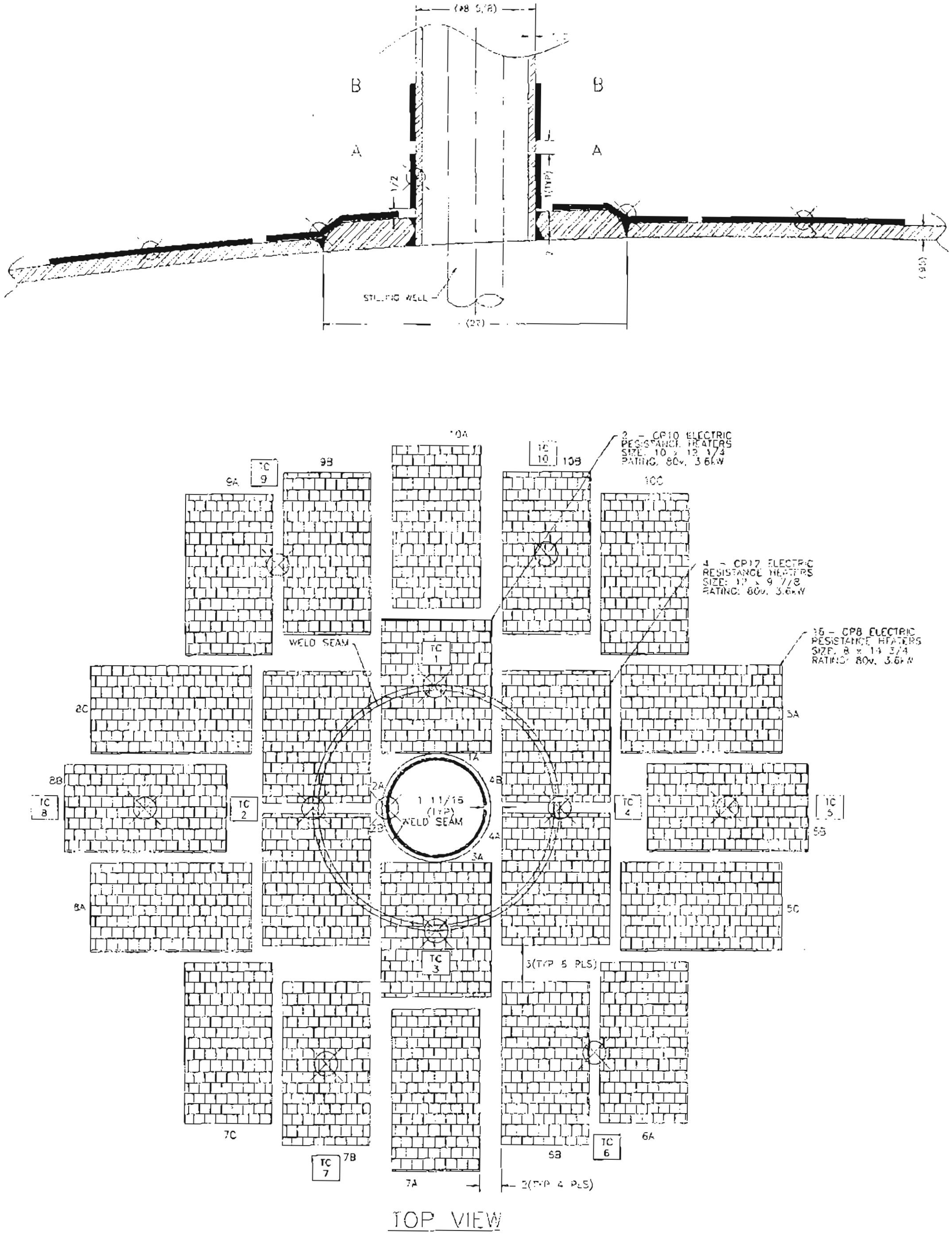


Fig. 23—Heater and thermocouple layout for case history described in section 17.2.2 in which external electric resistance heaters were used for circular spot PWHT of a nozzle attachment to a butylene sphere.

the upper dome of the spherical shell. Specifically, three 2 in (50.8) diameter nozzles were removed from the upper hemisphere of the 69 ft (21 m) inner diameter sphere, by having a 22 in (558.8 mm) diameter circular patch cut from the shell surrounding the three nozzles, for which a hydrogen bake-out was required. A replacement patch, containing an 8-in (203.2 mm) diameter nozzle, was then welded to the shell, for which pre-heat and PWHT was required.

The sphere was constructed of 0.95 in (24.1 mm) thick SA-516, Grade 70 carbon steel. The 8 in (203.2 mm) schedule 80 nozzle was made of SA-333, Grade 6 carbon steel having an 8-5/8 in (219.1 mm) outer diameter and a 1/2 in (12.7 mm) wall thickness. The replacement patch was made of 2 in (50.8 mm) thick SA-516, Grade 70 carbon steel, with it's thickness reduced to 0.95 in (24.1 mm) around its perimeter.

The PWHT soak temperature, time, and band width, along with heating and cooling rates were in accordance with ASME Section VIII, Division 1. Specifically, nozzle attachment weld PWHT required a soak band width extending at least 6t from the edge of the attachment weld, and the circular patch seam weld PWHT required a soak band width extending at least two shell thicknesses (2t) beyond the weld edge. In addition, the PWHT shell thermal gradient was in accordance with client requirements.

The removal of hydrogen from the spherical shell in the vicinity of the intended patch was achieved by placing three CP12 heaters in a row along each side of the existing three 2 in (50.8 mm) nozzles. A single control thermocouple was placed beneath the center of the middle heater for each of the two 3-heater circuits, and the heaters were covered with a 1 in (25.4 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation.

After the replacement patch was secured in position, CT120 (1 x 120 in [25.4 x 3,048 mm]) heaters were used to cover the surface of the sphere surrounding the 8 in (203.2 mm) nozzle, leaving approximately 2 in (50.8 mm) of space between the edge of the heater and the edge of the weld. Similarly, various sizes of FCP heaters were placed around the outer perimeter of the 22 in (558.8 mm) diameter weld path, again remaining 2 in (50.8 mm) from the edge of the weld. All heaters were covered with a single 1 in (25.4 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation, extending only to the edge of the heaters, so as to not interfere with welding. The heaters were controlled to maintain the minimum preheat temperature prior to and throughout the entire welding operation.

The PWHT heated band consisted of a core soak band surrounded by a gradient control band. The core soak band was composed of 6 FCP heaters on the patch and shell surrounding the replacement nozzle, and 2 FCP heaters around the nozzle neck. The 6 heaters on the patch and shell consisted of two CP10 (10 x 12-1/4 in [254 x 311.2 mm]) heaters placed 180° apart on either side of the replacement nozzle, each as a single-heater zone, or circuit, and four CP12 heaters arranged into two 2-heater zones on opposing sides of the replacement nozzle. These heaters were attached to the patch and shell via capacitor discharge welded insulation pins, with 1 in (25.4 mm) lateral spacing between adjacent heaters. The heated band on the nozzle neck consisted of 2 CP29 (29 x 4 in [736.6 x 101.6 mm]) heaters strapped in parallel bands, 1 in (25.4 mm) apart, arranged into a single 2-heater zone.

The gradient control band was composed of 16 CP18 heaters arranged in radial fashion surrounding the core soak band. The heaters were arranged into four 3-heater zones and two 2-heater zones. These heaters were attached to the shell via capacitor discharge welded insulation pins, with nominal 1 in (25.4 mm) lateral spacing between adjacent heaters.

Each zone, or circuit, had its own control thermocouple. The four soak band control thermocouples on the patch/shell surface were placed on the centerline of the 22 in (558.8 mm) diameter patch weld, 90° apart. The control thermocouple on the nozzle neck was placed beneath the lower heater. Each of the eight gradient control thermocouples was placed as close to the center of its respective heater zone as possible. Each of the 11 thermocouples had a spare located within 1/2 in (25.4 mm), and all thermocouples were attached by capacitor discharge welding.

A 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation, extending 6 ft (1.8 m) from the nozzle centerline was placed on the exterior and interior surfaces of the heated patch/shell area, and around the nozzle neck. The insulation on the patch/shell surfaces was secured via capacitor discharge welded insulation pins, and the insulation on the nozzle neck was secured by means of metal banding.

17.3 External Attachments

Case histories are provided for PWHT of walkway and nozzle attachment welds using overlapping electric bands and internal gas fired PWHT of a trunnion attachment weld. While it is important to examine the concept of overlapping bands, the most significant lesson to be learned by comparing these two case histories is the desirability of using internal gas firing for heating large sections.

17.3.1 PWHT of Attachments Using Overlapping Electric Heating: Figure 24 illustrates heater and thermocouple layout for a case history in which overlapping electric resistance heating was used for PWHT of walkway and nozzle attachment welds on an MEA absorber vessel. The use of electric resistance heating was dictated by a prohibition from using gas combustion. The need for overlapping bands resulted from the limited amount of equipment and power available at site. This case history provides an extreme example of where internal gas combustion would have been much more economical than electric resistance.

PWHT of an unspecified number of nozzle and walkway attachment welds was performed on the upper portion of an MEA absorber tower, having an outer diameter of 9-ft, 4-7/8 in (2,867 mm). The absorber was constructed of 2-7/16 in (61.9 mm) thick SA-515, Grade 70 carbon steel.

PWHT was in accordance with ASME Section VIII, Division 1. Therefore, each attachment weld PWHT required a circumferential soak band with a width extending beyond the weld a minimum distance equal to six times the maximum vessel wall thickness at the weld (6t). In addition, the client required that each of the three overlapping heated band widths be 19-ft, 8 in (6 m), and that the heated band be located immediately below the upper dished head of each absorber.

PWHT was performed in situ, with the vessel supported in a vertical orientation in the same manner as during its normal operation. The 19-ft, 8 in (6 m) long heated band consisted of a series of

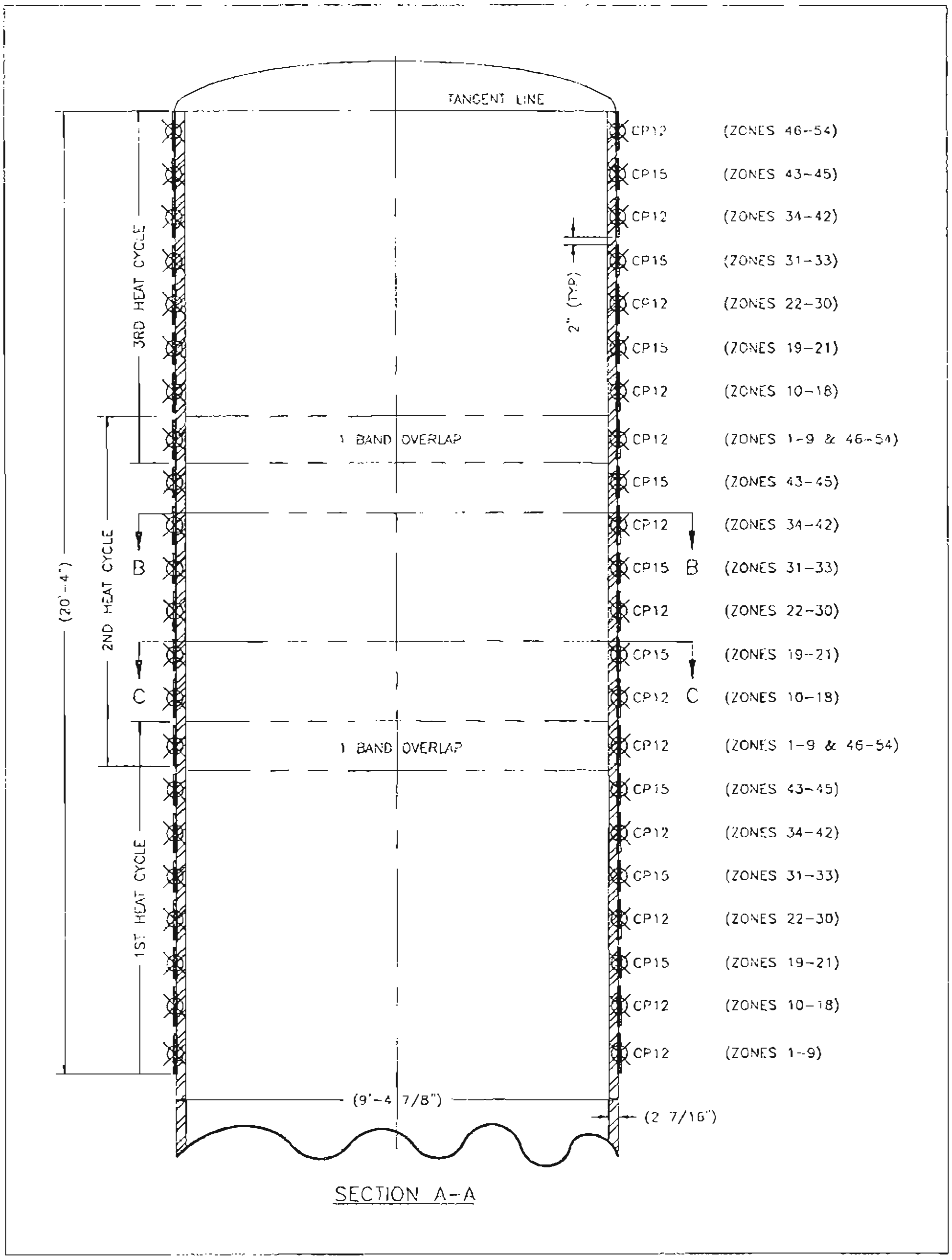


Fig. 24—Heater and thermocouple layout for case history described in section 17.3.1 in which overlapping external electric resistance heaters were used for circumferential PWHT of walkway and nozzle attachment welds to an MEA absorber.

adjacent circumferential bands of FCPs. All heaters were attached to the vessel either by capacitor discharge welded stud pins or metal strapping.

In order to maximize vessel surface area coverage per available power/control console, FCPs were arranged in combination of parallel and series-parallel circuits, with the former producing a thermal power density of 30 W/in^2 (46.8 kW/m^2), and the later producing 7.5 W/in^2 (11.7 kW/m^2). Each of the three PWHT heating stages consisted of an identical arrangement of 8 circumferential bands of FCPs, in which 3 bands of series-parallel heater circuits were placed alternately between 5 bands of parallel heater circuits.

Each of the five parallel circuit bands per PWHT heating stage consisted of 27 CP12 heaters, arranged into 9 circuits, or control zones, of three heaters each, with approximately 1-3/16 in (30.2 mm) circumferential space between adjacent heaters. Each of the three series-parallel circuit bands per PWHT heating stage consisted of 22 CP15 heaters, arranged into 11 parallel pairs of heaters, with each pair consisting of two heaters in series. These heaters were arranged into 2 control zones of 4 heater pairs each, and one zone of 3 heater pairs, with approximately 1-3/16 in (30.2 mm) circumferential space between heaters. In addition, a 2 in (50.8 mm) vertical space between bands of FCPs, and an

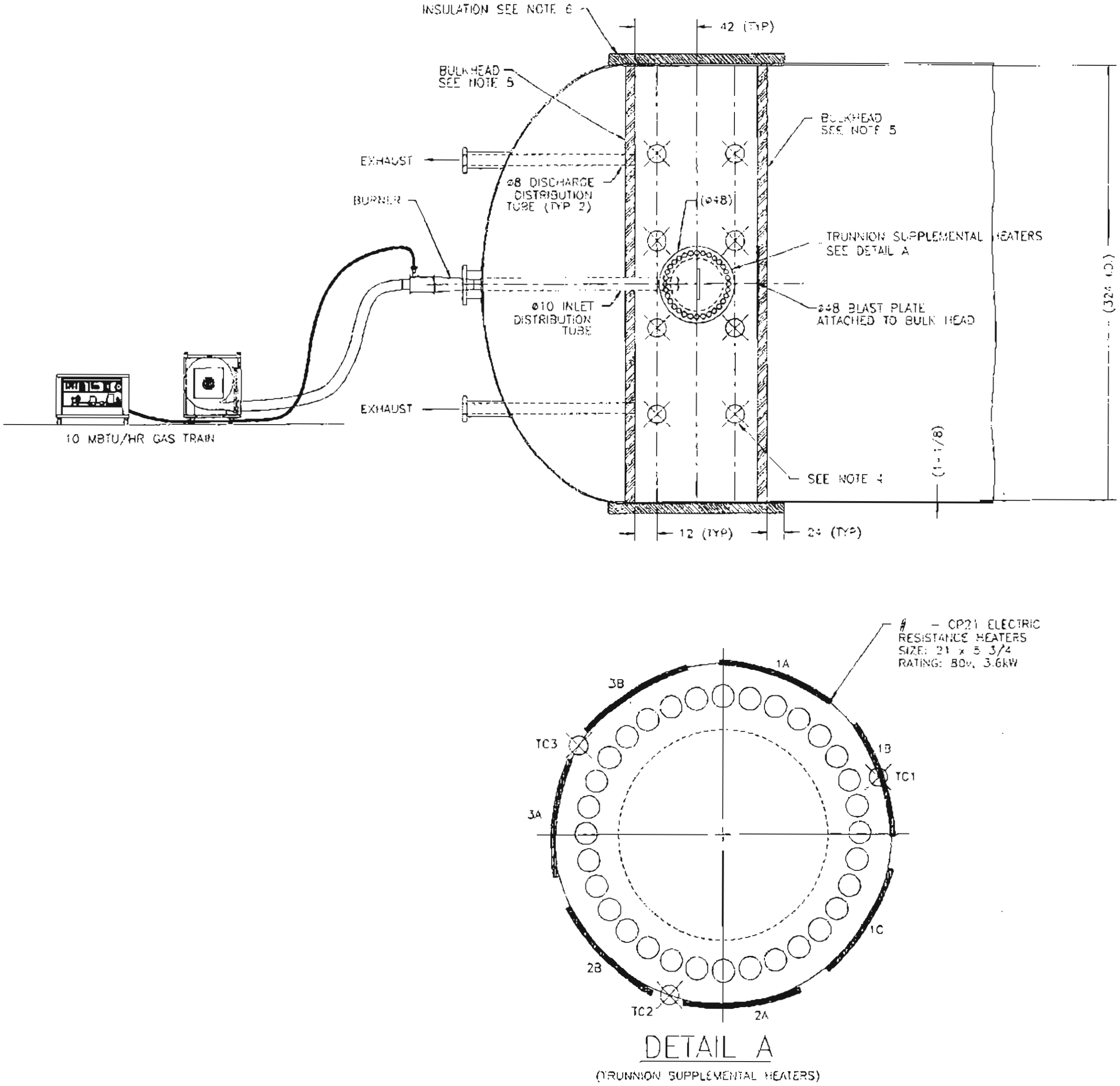


Fig. 25—Burner, heater and thermocouple layout for case history described in section 17.3.2 in which bulkheaded internal gas firing with supplemental electric resistance heating was used for full circumferential PWHT of two trunnion attachment welds to a coke drum shell.

overlap of one CP12 heater band (9-3/4 in [247.7 mm]) between subsequent PWHT heating stages was used.

A single thermocouple was used to control the temperature of each of the 54 control zones for each of the three PWHT heating stages. Specifically, there were 9 thermocouples for each of the 5 parallel circuit heater bands, and 3 thermocouples for each of the 3 series-parallel circuit heater bands. Each thermocouple had a spare attached within a distance of 1/2 in (12.7 mm), and all thermocouples were attached by means of capacitor discharge welding.

A 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber insulation covered the heaters and the inside surface during each PWHT heating stage, extending for a distance of 2 ft (0.6 m) past the heated band. Insulation was attached to the vessel by capacitor discharge welded stud pins.

17.3.2 PWHT of Trunnion Attachment Weld Using Combustion & Electric Heating: Figure 25 illustrates the burner, heater and thermocouple layout for PWHT of the attachment welds of two trunnions, 180° apart on a cylindrical shell section of a coke drum in which bulkheaded internal gas firing with supplemental electric resistance heating was used employed. Each trunnion had a 48 in (1,219.2 mm) outer diameter, and was constructed of 3/4 in (19.1 mm) thick SA-387, Grade 11, Class 2 low alloy steel. The shell had an internal diameter of 27 ft (8.2 m), and was constructed of 1-1/8 in (28.6 mm) thick SA 387, Grade 11, Class 2 low alloy steel having a 7/64 in (2.8 mm) thick layer of SA-240 Type 410S internal cladding. The PWHT soak temperature was in accordance with client requirements.

ASME Section VIII, Division 1 requires that the attachment welds undergo PWHT with a circumferential soak band whose width extends beyond the weld a minimum distance equal to six times the maximum vessel wall thickness at the weld. This soak band was accomplished by erecting two insulated bulkheads within the coke drum approximately 7 ft (2.1 m) apart, centered over the trunnions, insulating the coke drum outer surface surrounding the enclosed chamber, and heating the chamber with a gas-fired combustion heating system. In addition, supplemental electric heating elements were used to form a soak band around each trunnion to ensure uniform heating in concert with the circumferential heated band. PWHT was performed while the vessel was supported horizontally on a series of saddle supports which enabled unencumbered thermal expansion of the trunnion region during heating.

Each bulkhead was constructed of 2 x 2 x 1/4 in (50.8 x 50.8 x 6.4 mm) angle iron and 2 x 1/4 in (50.8 x 6.4 mm) flat stock welded or bolted into a rectangular grid of nominal 18 in (457.2 mm) centers. The grid was covered with 6 x 6 x 1/8 in (152.4 x152.4 x 3.2 mm) road mesh to which the thermal insulation was attached and sandwiched between an outer layer of road mesh, and wired together into a secure assembly. The insulation consisted of a 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density mineral wool covered by a 1 in (25.4) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber.

Each 27 ft (8.2 m) diameter circular bulkhead was installed in the coke drum at a distance of 3-1/2 ft (1.1 m) from the trunnion centerline. Accounting for typical temperature differentials across the thickness of each bulkhead, this 7 ft (2.1 m) wide chamber provided a uniform temperature heated band of at least 5-1/2 ft (1.7 m) wide across the trunnions, in accordance with code requirements.

The bulkhead closest to the top head of the coke drum was equipped with a 10 in (254 mm) diameter center hole to allow for the insertion of a 10 in (254 mm) diameter distribution tube. The tube was attached to a special blanking flange for the center nozzle of the top head, to which a 10 MBtu/hr (2.9 MW) burner was mounted. The opposing bulk head, farthest from the top head was equipped with a 1/4 in (6.4 mm) thick, 6 ft (1.8 m) diameter steel blast plate at its center, to protect its insulation from impingement of the burner's high velocity heated air. In addition, two 8 in (203.2 mm) diameter holes in the bulkhead provided access for insulated exhaust ducts from the heated chamber, to nozzles in the coke drum head.

To ensure that the soak band temperature was achieved at the two attachment welds, each trunnion was wrapped with 7 CP21 heaters. The heaters were arranged into one 3-heater zone and two 2-heater zones.

In addition to the 3 control thermocouples for the supplemental electric heat around each trunnion, 8 thermocouples were equally spaced around the drum at a distance of 1 ft (0.3 m) from each bulkhead. This thermocouple pattern enabled the monitoring of temperature gradients in any 15 ft (4.6 m) length along the entire area being heated.

In addition to the bulkhead insulation, the drum outer surface was covered with a 2 in (50.8 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber for a distance of 2 ft (0.6 m) past the bulkheads.

17.4 PWHT of Skirt and Cone Welds

Figure 26 illustrates the burner, heater and thermocouple layout for the PWHT of skirt and cone welds on a coke drum, in which bulkheaded internal gas firing with supplemental electric heating was employed. Specifically, PWHT was performed on the following:

An 8 ft (2.4 m) long skirt of 27 ft (8.2 m) internal diameter, made of 3/4 in (19.1 mm) thick SA-387, Grade 11, Class 2 low alloy steel;

A 19 ft (5.8 m) long 30° half-angle cone, made of 1-1/4 in (6.4m) thick SA 387, Grade 11, Class 2 low alloy steel having a 7/64 in (2.8 mm) thick layer of SA-240 Type 410S internal cladding {The discharge flange and 29-1/4 in (743 mm) of its nominal 3 ft (0.9 m) long, 5 ft (1.5 m) diameter discharge neck were excluded from PWHT]; and

The girth weld between the skirt and the 1-1/4 in (31.8 mm) thick shell of SA 387, Grade 11, Class 2 low alloy steel having a 7/64 in (2.8 mm) thick layer of SA-240 Type 410S internal cladding.

The PWHT soak temperature was in accordance with client requirements. PWHT was performed while the vessel was supported horizontally on a series of saddle supports, and was achieved by installing three insulated bulkheads to create an isolated internal chamber of girth weld and upper cone section, as well as an annular chamber between the cone and skirt. Each chamber was covered with external insulation and heated utilizing a gas-fired combustion heating system. Thus, each chamber was a furnace, providing heat to the skirt, its girth weld, and the upper section of cone. In addition, electric heating elements were used to form a supplemental heated band around the girth weld, to ensure uniform heating in concert with the two heated chambers.

Each bulkhead was constructed of 2 in (50.8 mm) wide by 1/4 in (6.4 mm) thick carbon steel angle iron and flat stock, welded or bolted into a rectangular grid of nominal 18 in (457.2 mm) centers. The grid was covered with road mesh, which was constructed of 1/8 in (3.2 mm) diameter (12 gauge) carbon steel wire welded into a grid of nominal 6 in (152.4 mm) squares, to which the insulation was attached. An outer layer of road mesh was placed over the insulation and the entire assembly was wired securely together. The insulation consisted of a 2 in (50.8 mm) thick layer of 8 lb/ft^3 (128.1 kg/m^3) density mineral wool covered by a 1 in (25.4 mm) thick layer of 6 lb/ft^3 (96.1 kg/m^3) density refractory ceramic fiber.

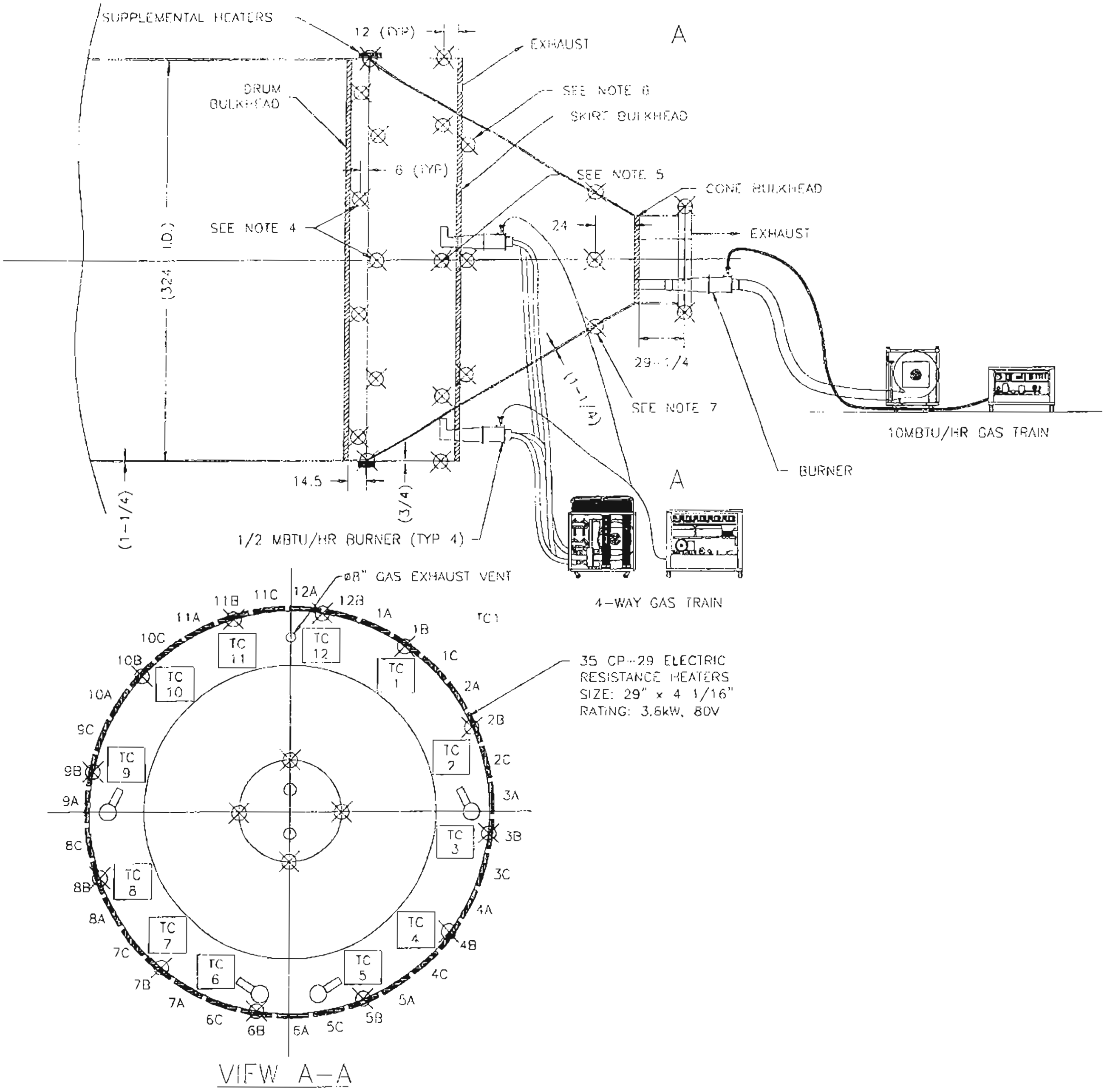


Fig. 26—Burner, heater and thermocouple layout for case history described in section 17.4 in which bulkhead internal gas firing with supplemental electric heating was used for the PWHT of skirt and cone welds on a coke drum.

A circular bulkhead was installed in the coke drum at a distance of 14-1/2 in (368.3 mm) above the shell-to-skirt weld, to enclose a chamber consisting of the complete cone and 14-1/2 in (368.3 mm) of drum shell.

An annular, or donut, bulkhead was installed at the base of the skirt and attached to the concentric cone. It thereby formed an annular ring of triangular cross section between the skirt and the cone. Holes were present in the bulkhead to accommodate insertion of burners. In addition, an 8 in (203.2 mm) diameter hole was placed near its top to serve as an exhaust port. No damper plate was used.

The annular chamber beneath the skirt was heated with a 2 MBtu/hr (0.59 MW) four-way gas train, employing four independently controlled burners, each with a maximum heating capacity of 1/2 MBtu/hr (0.15 MW). Two burners were installed into the bottom of the annular bulkhead, each equipped with a right-angle discharge tube to direct the heated air parallel to the plane of the bulkhead rather than toward the converging space between skirt and cone. In addition, the angular orientation of each tube was adjusted to establish opposing air flows directed toward the top of the annulus. Similarly, each of two additional burners was mounted at opposing sides of the annulus, with a 90° discharge tube directed toward the top of the annulus, to reinforce the opposing air flows.

The cone and girth weld chamber formed by the drum bulkhead was heated with a 10 MBtu/hr (2.9 MW) gas train whose burner was mounted near the bottom of a special blanking plate which was mounted to the cone's discharge flange, and directed into the chamber. This same blanking plate contained a 10 in (254 mm) diameter hole near its top to serve as an exhaust vent. No damper plate was used.

ASME Section VIII, Division 1 requires that a girth weld PWHT soak band extend beyond the weld in each direction a minimum distance equal to twice the maximum vessel wall thickness at the weld. It was for this reason that the drum bulkhead was located a distance of 14-1/2 in (368.3 mm) from the weld centerline, to ensure that code temperature was achieved at the weld, after accounting for a temperature drop across the bulkhead that typically begins approximately 6 in (152.4 mm) in front of the bulkhead.

To assist the two heated chambers in achieving soak band temperature across the girth weld, a circumferential band of heat was placed with its centerline coincident with that of the weld (i.e. straddling the weld). The band was composed of 35 CP29 (29 x 4 in [736.6 x 101.6 mm]) heaters arranged into eleven 3-heater zones and one 2-heater zone.

All thermocouples were attached by means of capacitor discharge welding, and each thermocouple had a spare attached within a distance of 1 in (25.4 mm). One control thermocouple was used for each of the 12 zones of supplemental electric heating on the girth weld. In addition, monitor/control thermocouples were placed around the drum, skirt, and cone outer surfaces along the heated chambers, to enable the monitoring and control of temperature gradients in any 15 ft (4.6 m) length. Specifically, 8 thermocouples were equally spaced around the skirt at a distance of 1 ft (0.3 m) from its bottom end. A circumferential ring of 8 equally-spaced thermocouples was located around the drum and the skirt on either side of the girth weld at a distance of 6 in (152.4 mm) from the girth weld centerline, for a total of 16 thermocouples. Six thermocouples were equally spaced around the cone at the base of the skirt's annular bulkhead. In addition, 4 thermocouples were equally spaced around the cone at a distance of 2 ft (0.6 m) above the transition between cone and discharge flange neck.

In addition to the bulkhead insulation, the drum, skirt, and cone outer surfaces were covered with a 2 in (50.8 mm) thick layer of 8 lb/ft^3 (128.1 kg/m^3) density refractory ceramic fiber for a distance of 2 ft (0.6 m) past the drum bulkhead.

18. Conclusions and Recommendations

This document has attempted to comprehensively address the full spectrum of issues associated with local heating of welds in pressure vessels. Purposes for local heating which include bake-out, preheat/interpass heating, postheating and PWHT have been discussed. Use of special terminology (soak band, heated band, gradient control band, and control zone) has been recommended to improve the ability to address issues relating to these heating purposes and to specify local heating procedures. Where appropriate, important issues related to heating in general (both local and furnace) have also been examined. Recommendations have been made with regard to issues related both to local and furnace heating. In certain cases, additional research is justified to provide a stronger basis for recommended practices. With regard to local heating, issues which warrant additional research include:

1. Detailed assessments of the thermally-induced stresses resulting from local heating (both circumferential and spot) on cylindrical and spherical shells.
2. Development of unambiguous criteria for controlling temperature gradients for both through-thickness and axial directions and their relationships with heated band size, heating rate, hold time, etc.
3. Development of acceptance criteria for performing local heating to avoid excessive thermal stresses and to achieve adequate weld residual stress reduction.
4. Development of recommended simple analysis procedures for vessel configurations outside of the specifications in codes and practices.

The PVRC joint industry project [45] is intended to address the above major issues.

There is concern with regard to the effect of PWHT on material properties such as tensile strength, notch toughness and creep behavior. This concern will likely manifest itself in code adoption of more rigorous requirements to assess the effects of PWHT on properties. It would seem apparent that by resolving two current issues, means to address deterioration of these properties could be readily available and at the same time offer cost savings. These two issues are accounting for the effect of the heating portion of the PWHT cycle and the need for PWHT hold time to be a function of thickness. By resolving these issues, it may be possible to significantly reduce the hold time and thereby restrict the level of property deterioration while at the same time reducing the cost of the PWHT cycle. A better understanding of the effect of PWHT on creep behavior of Cr-Mo steels is also needed.

Adequate measurement of temperature during local heating represents the most cost effective means for assessing whether the desired outcome was achieved. Use of thermocouples directly attached to the surface by capacitor discharge welding provides a desirable method to measure temperature. Recommendations were provided for location of thermocouples at the weld centerline, edge of the soak band, edge of the heated band and on the side opposite to that of the heat source (where possible).

One of the objectives of this document was to provide an international perspective with regard to the issues associated with local heating. As such, comparisons of local heating requirements in both domestic and international codes have been provided. It is apparent that considerable differences exist among these codes. There is a great likelihood that such differences will remain in the foreseeable future. It would therefore seem highly desirable to develop a document which represents a consensus of international views regarding these issues. Such an international consensus document would serve to bridge code differences and promote common approaches to addressing the issues.

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Appendix A

Revisions to ASME Section VIII, Division 1, Paragraph UW-40

1998 Edition—Issued 07/01/98

(Appendix A) Figure 51.

PREVIOUS WORDING UW-40

(Words in underlined italics indicate deletions)

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

(a) The operation of postweld heat treatment shall be performed in accordance with the requirements given in the applicable Part in Subsection C using one of the following procedures:

(a)(1)—No changes

(a)(2) heating the vessel in more than one heat in a furnace, provided the overlap of the heated sections of the vessel is at least 5 ft. When this procedure is used, the portion outside of the furnace shall be shielded so that the temperature gradient is not harmful.

(a)(3) heating of shell sections and/or portions of vessels to postweld heat treat longitudinal joints or complicated welded details before joining to make the completed vessel. When the vessel is required to be postweld heat treated, and it is not practicable to postweld heat treat the completed vessel as a whole or in two or more heats as provided in (2) above, any circumferential joints not previously postweld heat treated may be thereafter locally postweld heat treated by heating such joints by any appropriate means that will assure the required uniformity. *The width of the heated band on each side of the greatest width of finished weld shall be not less than two times the shell thickness.* The portion outside the *heating device* shall be protected so that the temperature gradient is not harmful. This procedure may also be used to postweld heat treat portions of new vessels after repairs.

REVISED WORDING UW-40

(Bold italics indicate additions)

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

(a) The operation of postweld heat treatment shall be performed in accordance with the requirements given in the applicable Part in Subsection C using one of the following procedures. ***In the procedures that follow, the soak band is defined as the volume of metal required to meet or exceed the minimum PWHT temperatures listed in Table UCS-56. As a minimum, the soak band shall contain the weld, heat affected zone, and a portion of base metal adjacent to the weld being heat treated. The minimum width of this volume is the widest width of weld plus 1t or 2 in., whichever is less, on each side or end of the weld. The term t is the nominal thickness as defined in (f) below.***

(a)(1)—No Changes

(a)(2) heating the vessel in more than one heat in a furnace, provided the overlap of the heated sections of the vessel is at least 5 ft. (1.5 m) When this procedure is used, the portion outside of the furnace shall be shielded so that the temperature gradient is not harmful. ***The cross section where the vessel projects from the furnace shall not intersect a nozzle or other structural discontinuity.***

(a)(3) heating of shell sections and/or portions of vessels to postweld heat treat longitudinal joints or complicated welded details before joining to make the completed vessel. When the vessel is required to be postweld heat treated, and it is not practicable to postweld heat treat the completed vessel as a whole or in two or more heats as provided in (2) above, any circumferential joints not previously postweld heat treated may be thereafter locally postweld heat treated by heating such joints by any appropriate means that will assure the required uniformity. ***For such local heating, the soak band shall extend around the full circumference.*** The portion outside the ***soak band*** shall be protected so that the temperature gradient is not harmful. This procedure may also be used to postweld heat treat portions of new vessels after repairs.

PREVIOUS WORDING UW-40

(Words in underlined italics indicate deletions)

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

(a)(4)—No Changes

(a)(5) heating a circumferential band containing nozzles or other welded attachments that require postweld heat treatment in such a manner that the entire band shall be brought up uniformly to the required temperature and held for the specified time. The *circumferential band* shall extend around the entire vessel, shall include the nozzle or welded attachment, *and shall extend at least six times the plate thickness beyond the welding which connects the nozzle or other attachment to the vessel.* The portion of the vessel outside of the circumferential band shall be protected so that the temperature gradient is not harmful.

(a)(6) heating the circumferential joints of pipe or tubing by any appropriate means over a band *having a width on each side of the center line of not less than three times the greatest width of the finished weld.* The portion outside the *heated* band shall be protected so that the temperature gradient is not harmful.

REVISED WORDING UW-40

(Bold italics indicate additions)

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

(a)(4)—No Changes

(a)(5) heating a circumferential band containing nozzles or other welded attachments that require postweld heat treatment in such a manner that the entire band shall be brought up uniformly to the required temperature and held for the specified time. ***Except as modified in this paragraph below,*** **the** ***soak band*** shall extend around the entire vessel, ***and*** shall include the nozzle or welded attachment. ***The circumferentical soak band width may be varied away from the nozzle or attachment weld requiring PWHT, provided the required soak band around the nozzle or attachment weld is heated to the required temperature and held for the required time. As an alternative to varying the soak band width, the temperature within the circumferentical band away from the nozzle or attachment may be varied and need not reach the required temperature, provided the required soak band around the nozzle or attachment weld is heated to the required temperature, held for the required time, and the temperature gradient is not harmful throughout the heating and cooling cycle.*** The portion of the vessel outside of the circumferential ***soak*** band shall be protected so that the temperature gradient is not harmful. ***This procedure may also be used to postweld heat treat portions of vessels after repairs.***

(a)(6) heating the circumferential joints of pipe or tubing by any appropriate means ***using a soak band that extends around the entire circumference.*** The portion outside the ***soak*** band shall be protected so that the temperature gradient is not harmful. ***The proximity to the shell increases thermal restraint, and the designer should provide adequate length to permit heat treatment without harmful gradients at the nozzle attachment or heat a full circumferential band around the shell, including the nozzle.***

PREVIOUS WORDING UW-40

(Words in underlined italics indicate deletions)

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

REVISED WORDING UW-40 *(Bold italics indicate additions)*

UW-40 PROCEDURES FOR POSTWELD HEAT TREATMENT

(a)(7) heating a local area around nozzles or welded attachments in the larger radius sections of a double curvature head or a spherical shell or head in such a manner that the area is brought up uniformly to the required temperature and held for the specified time. The soak band shall include the nozzle or welded attachment. The soak band shall include a circle that extends beyond the edges of the attachment weld in all directions by a minimum of t or 2 in., whichever is less. The portion of the vessel outside of the soak band shall be protected so that the temperature gradient is not harmful.

(a)(8) heating of other configurations. Local area heating of other configurations not addressed in (a)(1) through (a)(7) above is permitted, provided that other measures (based upon sufficently similar, documented experience or evaluation) are taken that consider the effect of thermal gradients, all significant structural discontinuities (such as nozzles, attachments, head to shell junctures), and any mechanical loads which may be present during PWHT. The portion of the vessel or component outside the soak band shall be protected so that the temperature gradient is not harmful.

Appendix B

Revisions to ASME Section VIII, Division 2, Paragraphs AF-41- & 415(c)
1998 Edition—Issued 07/01/98

(Appendix B)

PREVIOUS WORDING AF-410

(Words in underlined italics indicate deletions)

AF-410 Heating Portions Before Joining and Local Heating of Circumferential Joints After Joining

The postweld heat treatment shall be performed in accordance with one of the procedures of this paragraph.

AF-410.1 & AF-410.2—No Changes

AF-410.3 Heating Shell Sections, Heads, and Other Portions Before Joining. Heating of shell sections, heads and/or portions of vessels for postweld heat treatment of longitudinal joints or complicated welded details before joining to make the completed vessel. When it is not practicable to postweld heat treat the complete vessel as a whole or in two or more heats as provided in AF-410.2, any circumferential joints not previously postweld heat treated may be locally postweld heat treated *by heating a circumferential band which includes such joints* by any appropriate means that will assure the required uniformity. *The width of the heated band on each side of the greatest width of finished weld shall be not less than two times the shell thickness.* The portion outside the *heating device* shall be protected so that the temperature gradient is not harmful.

AF-410.4—No Changes

REVISED WORDING AF-410

(Bold italics indicate additions)

AF-410 Heating Portions Before Joining and Local Heating of Circumferential Joints After Joining

The postweld heat treatment shall be performed in accordance with one of the procedures of this paragraph. ***In the procedures that follow, the soak band is defined as the volume of metal required to meet or exceed the minimum PWHT temperatures listed in Table AF-402.1. As a minimum, the soak band shall contain the weld, heat affected zone, and a portion of base metal adjacent to the weld being heat treated. The minimum width of this volume is the widest width of weld plus t or 2 in. (51 mm), whichever is less, on each side or end of the weld. The term t is the nominal thickness as defined in AF-402.3.***

AF-410.1 & AF-410.2—No Changes

AF-410.3 Heating Shell Sections, Heads, and Other Portions Before Joining. Heating of shell sections, heads and/or portions of vessels for postweld heat treatment of longitudinal joints or complicated welded details before joining to make the completed vessel. When it is not practicable to postweld heat treat the complete vessel as a whole or in two or more heats as provided in AF-410.2, any circumferential joints not previously postweld heat treated may be locally postweld heat treated by any appropriate means that will assure the required uniformity. ***For such local heating, the soak band shall extend around the full circumference.*** The portion outside the ***soak band*** shall be protected so that the temperature gradient is not harmful. ***This procedure may also be used to postweld heat treat portions of new vessels after repairs.***

AF-410.4—No changes

PREVIOUS WORDING AF-410
(Words in underlined italics indicate deletions)

AF-410.5 Local Heating of Nozzles to Vessels and External Attachments

(a) Heating a circumferential band containing nozzles or other welded attachments that require postweld heat treatment in such a manner that the entire band shall be brought up uniformly to the required temperature and held for the specified time. The *circumferential* band shall extend around the entire vessel, shall include the nozzle or welded attachment, *and shall extend at least six times the plate thickness beyond the welding which connects the nozzle or other attachment to the vessel.* The portion of the vessel outside of the circumferential band shall be protected so that the temperature gradient is not harmful; this procedure may also be used for local heat treatment of circumferential joints in pipe, tubing, or nozzle necks. In the latter case, proximity to the shell increases thermal restraint, and the designer should provide adequate length to permit heat treatment without harmful gradients at the nozzle attachment.

(b)—No Changes

REVISED WORDING AF-410
(Bold italics indicate additions)

AF-410.5 Local Heating of Nozzles to Vessels and External Attachments

(a) Heating a circumferential band containing nozzles or other welded attachments that require postweld heat treatment in such a manner that the entire band shall be brought up uniformly to the required temperature and held for the specified time. ***Except as modified in this paragraph below,*** the ***soak band*** shall extend around the entire vessel, ***and*** shall include the nozzle or welded attachment. The portion of the vessel outside of the circumferential ***soak*** band shall be protected so that the temperature gradient is not harmful; this procedure may also be used for local heat treatment of circumferential joints in pipe, tubing, or nozzle necks. In the latter case, proximity to the shell increases thermal restraint, and the designer should provide adequate length to permit heat treatment without harmful gradients at the nozzle attachment, ***or heat a full circumferential band around the shell, including the nozzle.***

The circumferential soak band width may be varied away from the nozzle or attachment weld requiring PWHT, provided the required soak band around the nozzle or attachment weld is heated to the required temperature and held for the required time. As an alternative to varying the soak band width, the temperature within the circumferential band away from the nozzle or attachment may be varied and need not reach the required temperature, provided the required soak band around the nozzle or attachment weld is heated to the required temperature, held for the required time, and the temperature gradient is not harmful throughout the heating and cooling cycle. The portion of the vessel outside of the circumferential ***soak*** band shall be protected so that the temperature gradient is not harmful.

(b)—No Changes

PREVIOUS WORDING AF-410
(Words in underlined italics indicate deletions)

REVISED WORDING AF-410
(Bold italics indicate additions)

AF-410.6 Local Area Heating of Double Curvature Heads or Shells. ***Heating a local area around nozzles or welded attachments in the larger radius sections of a double curvature head or a spherical shell or head in such a manner that the area is brought up uniformly to the required temperature and held for the specified time. The soak band shall include the nozzle or welded attachment. The minimum soak band size shall be a circle whose radius is the widest width of the weld attaching the nozzle, reinforcing plate, or structural attachment to the shell, plus t or 2 in. (51 mm), whichever is less. The portion of the vessel outside of the soak band shall be protected so that the temperature gradient is not harmful.***

AF-410.7 Heating of Other Configurations. ***Local area heating of other configurations not addressed in AF-410.1 through AF-410.6 above is permitted provided that other measures (based upon sufficiently similar documented experience or evaluation) are taken that consider the effect of thermal gradients, all significant structural discontinuities (such as nozzles, attachments, head to shell junctures), and any mechanical loads which may be present during PWHT. The portion of the vessel outside of the soak band shall be protected so that the temperature gradient is not harmful. The soak band shall include a circle that extends beyond the edges of the attachment weld in all directions by a minimum of t or 2 in., whichever is less.***

PREVIOUS WORDING AF-415(c)
(Words in underlined italics indicate deletions)

AF-415(c)—Operation of Postweld Heat Treatment

During the holding period, there shall not be a difference greater than *100°F* between the highest and lowest temperatures throughout the portion of the vessel being heated, except where the range is further limited in Table AF-402.1.

REVISED WORDING AF-415(c)
(Bold italics indicate additions)

AF-415(c)—Operation of Postweld Heat Treatment

During the holding period, there shall not be a difference greater than ***150°F (83°C)*** between the highest and lowest temperatures throughout the portion of the vessel being heated, except where the range is further limited in Table AF-402.1.

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