AWS D10.10/D10.10M:2021
An American National Standard

Recommended Practices for Local Heating of Welds in Piping and Tubing

Approved American National Standard
ANSI

AWS American Welding Society®

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An American National Standard

Approved by the
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Recommended Practices for Local Heating of Welds in Piping and Tubing

4th Edition

Revises AWS D10.10/D10.10M:1999

Prepared by the
American Welding Society (AWS) D10 Committee on Piping and Tubing

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This standard provides information on recommended practices, equipment, temperature control, insulation, and advantages and disadvantages for the methods presently available for local heating of welded joints in pipe and tubing.

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Foreword

This foreword is not part of this standard but is included for informational purposes only.

This recommended practice is intended to supply useful information to those with a need to apply heat to welds in piping and tubing under circumstances that do not permit placing the entire component in a furnace or oven.

The first edition of the recommended practice prepared by the AWS Committee on Piping and Tubing was approved and published as AWS D10.10-75, *Local Heat Treatment of Welds in Piping and Tubing*.

The second edition, ANSI/AWS D10.10-90, was revised to bring the document abreast of the present "state-of-the-art," and to reemphasize certain important topics; particularly, thermocouple selection and placement, proper provision for insulation, and use of the radiant heating methods.

The third edition of D10.10 was extensively revised to: identify/consider related domestic and international codes, standards, and practices; more fully recognize the range of purposes for local heating; introduce terminology for local heating; consider the issues affecting important parameters and provide recommendations for specifying these parameters; consider both local 360° band and spot heating; expand the information regarding thermocouple location, attachment, and accuracy; expand/update the information relating to insulation; expand the information regarding the thermal cycle; identify common process deviations and responses; introduce considerations regarding service environment; introduce quality assurance system considerations; and update and emphasize the heating methods most commonly used. This fourth edition applies to both new construction and repairs.

During preparation of this document, it was attempted to include recommendations based upon the best available, most current data regarding local heating. In most cases, the recommendations given are based upon published research, with extensive references provided. It is acknowledged that in some cases, the resulting recommendations may exceed the prevailing practice within industry, especially domestically. However, it is felt that the objective of this document is to present recommended practices based on an ordered assessment of available research and information, rather than a summary of current practice.

A vertical line in the margin or underlined text in clauses, tables, or figures indicates an editorial or technical change from the 1999 edition.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS D10 Committee on Piping and Tubing, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166. A formal reply will be issued after it has been reviewed by the appropriate personnel following established procedures.

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Table of Contents

Page No.

Page No.

List of Tables

List of Figures

Figure **Page No.**

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Recommended Practices for Local Heating of Welds in Piping and Tubing

1. General Requirements

1.1 Scope. These recommended practices describe several methods of applying controlled heat to weld joints and a limited volume of base metal adjacent to the joints, as opposed to heating the complete weldment in a furnace or oven. Additional criteria (e.g., thermocouple requirements, temperature requirements, heat placement) may be required for Creep Strength-Enhanced Ferritic (CSEF) Steels. The applicable code or standard shall take precedence in the event of conflict with this standard.

The primary purpose for the requirements in this document is to ensure that the root of the weld at the inside diameter (ID) of the pipe or tube achieves minimum postweld heat treatment (PWHT) temperature.

1.2 Units of Measurement. This standard makes use of both U.S. Customary Units and the International System of Units (SI). The latter are shown within brackets ([ ]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system must be used independently.

Units used for dimensions shall be consistent within any given formula.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard; some safety and health information is provided, but such issues are not fully addressed herein.

Safety and health information is available from the following sources:

American Welding Society:

(1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

(2) AWS Safety and Health Fact Sheets

(3) Other safety and health information on the AWS website.

Material or Equipment Manufacturers:

(1) Safety Data Sheets supplied by materials manufacturers

(2) Operating Manuals supplied by equipment manufacturers.

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments or revisions of the publications may not apply since the relevant requirements may have changed.

American Welding Society (AWS) documents:

AWS A1.1, *Metric Practice Guide for the Welding Industry*;

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*; and

AWS Safety and Health Fact Sheet No. 15, *Style Guidelines for Safety and Health Documents*

American Society for Mechanical Engineers (ASME) documents:

ASME B31.1, *Power Piping*;

ASME B31.3, *Process Piping*; and

ASME BVPC-III, *Boiler and Pressure Vessel Code, Rules for Construction of Nuclear Power Plant Components,* Division 1—Subsection NB, Class 1 Components. (Note: Although direct reference is made to Subsection NB and its related paragraphs, Subsections NC and ND for Class 2 and 3 components have essentially the same requirements.)

British Standards Institution (BSI) document:

BS 2633, *Specification for Class I Arc Welding of Ferritic Steel Pipework for Carrying Fluids*

National Board of Boiler and Pressure Vessel Inspectors (NBBI) document:

NBIC National Board Inspection Code (ANSI/NB-23)

American Petroleum Institute (API) documents:

API 570, *Piping Inspection Code*; and

API 945, *Avoiding Environmental Cracking in Amine Units*

NACE International (NACE) document:

NACE SP0472, *Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

control zone. A control zone consists of a grouping of one or more heat sources that are controlled based upon input from a single temperature measuring device (typically a thermocouple). One or more control zones may be present in either the circumferential direction, axial direction, or both.

gradient control band (GCB). The gradient control band consists of the surface area over which insulation is placed. It should encompass the soak band, heated band, and sufficient adjacent base metal such that the maximum permissible axial temperature gradient within the heated band is not exceeded.

If supplementary heat sources are used to maintain the gradient temperature, they will be considered part of the gradient control band.

heated band (HB). The heated band consists of 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 weld. It should consist of the soak band plus any adjacent base metal necessary to both control the temperature and to limit induced stress within the soak band.

hydrogen bakeout. Heating a base metal at elevated temperature (below 800°F [427°C]) for the purpose of hydrogen diffusion. This is done before welding, on a partially completed weld, or a completed weld. It can also be done on hydrogen-charged base metal of service-exposed equipment prior to repair.

postheating. The application of heat to an assembly after brazing, soldering, thermal spraying, thermal cutting, or welding. Also see **hydrogen bakeout** and **postweld heat treatment (PWHT)**.

postweld heat treatment (PWHT). The controlled heating, holding at temperature and cooling of a metal or metal alloy in its solid state, to produce certain desirable changes in its properties. The three primary reasons are tempering, relaxation of residual stresses, and hydrogen removal. See 5.4 for further information.

preheat. The heat applied to the workpiece(s) to attain and maintain the preheat temperature immediately prior to and during the welding process, thermal cutting, or thermal spraying.

soak band (SB). The soak band consists of the through-thickness volume of metal, which is heated to the minimum but does not exceed the maximum allowable temperature. As a minimum, it should consist of the weld metals, HAZ, and a portion of the base metal adjacent to the weld being heated.

4. Introduction

These recommended practices consider the various issues associated with local heating of welds in piping and tubing. They specifically address 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 entire component (piping or tubing system) in a furnace or oven. The recommended practices generally address issues associated with circumferential butt welds. As such, primary emphasis is given to considering local 360° band heating. However, limited consideration of local spot heating is also provided. Although aimed at local heating, various issues common to both local and furnace heating are also discussed.

In the manufacture, field fabrication, repair of piping and tubing, or both, it may be necessary to heat components before welding (hydrogen bakeout or preheat) between passes (interpass heating) or after welding (postheating or postweld heat treatment [PWHT]). This document addresses all of these purposes for heating, with the main emphasis on PWHT.

Although heating of piping and tubing may be performed in a furnace, factors such as component size, type (e.g., valve to pipe joints), convenience, or the need to apply preheat 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 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.

The need for PWHT is driven by fabrication, construction, or other applicable code requirements or concerns regarding the service environment. So-called “code required” PWHT is generally aimed at improving resistance to brittle fracture. To accomplish this, PWHT attempts to improve notch toughness, relax residual stresses, and reduce weld zone hardness. When service requirements dictate the need for PWHT, additional objectives such as hardness reduction or stress relaxation aimed to be below a specific threshold level become important, depending upon the environment. The PWHT considerations and recommendations discussed in Clause 6 are aimed at “code required” PWHT. Clause 13 considers some of the issues and objectives associated with service environments and makes additional recommendations. The strategy followed in providing recommendations for local, “code required” PWHT was to attempt to duplicate the outcome of furnace heating (e.g., heating the entire component) within a localized region (soak band) surrounding the weld. While a similar strategy is applied to meet the additional objectives associated with service environments, the ability of furnace or local PWHT to meet these objectives must be carefully assessed based upon the specific environment.

5. Purposes for Local Heating

Brief discussions of the purposes for hydrogen bakeout, preheat, and PWHT as applied for steel and alloyed-steel pipe and tubing are provided in this clause.

5.1 Preweld Hydrogen Bakeout. This heating is performed to remove hydrogen from material prior to manufacture, fabrication or repair activity. At the temperatures commonly used for such heating, removal of atomic hydrogen (H), as opposed to molecular hydrogen (H_2), is generally the objective. Molecular hydrogen which is trapped at voids such as inclusions, weld defects, blisters, etc. will not be removed unless the temperature is raised sufficiently to dissociate it to atomic hydrogen. The temperature required to accomplish such dissociation is typically near that used for PWHT. When molecular hydrogen is present, care must be exercised such that temperature and hydrogen partial pressure do not result in conditions under which high temperature hydrogen attack can occur. As a result, temperature limitations may be imposed.

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 for removing the hydrogen is to prevent hydrogen-induced (delayed) cracking in the weld metal and HAZ. 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 the following:

(1) Initial hydrogen content (dependent upon welding process, service environment, or both)

(2) Desired final hydrogen content (based upon knowledge of the critical level for the material)

(3) Hydrogen diffusion coefficient as a function of temperature for the material

(4) Diffusion path or distance to free surface (typically one-half of the material thickness)

(5) Model to describe the diffusion process

(6) Selection of temperature based upon knowledge of hydrogen trapping

(7) Temperature restrictions to avoid adverse effects upon the material

A detailed methodology for selecting hydrogen removal parameters is available (Reference A1). In most cases, a quantitative approach (e.g., one accounting for all of the above considerations) for the selection of parameters is not applied. Instead, experience-based parameters are used. The cited fabrication codes contain no guidance with regard to hydrogen bakeout parameters. However, API 945, *Avoiding Environmental Cracking in Amine Units*, does provide recommendations: 450°F to 600°F [230°C to 316°C] for 2 to 4 hours. 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°F to 600°F [260°C to 316°C] for two hours per inch [25 mm] of thickness, with two hours minimum, is reported (Reference A1) to be a reasonable approach for carbon and low alloy steels. However, based upon concerns with regard to hydrogen trapping, it appears prudent to use temperatures of 600°F [316°C] and higher. Temperature restrictions may need to be imposed to avoid high temperature hydrogen attack and adverse metallurgical reactions such as temper embrittlement.

5.2 Preheat. This process is aimed at achieving the minimum preheat temperature prior to and during the welding process.

One reason for preheat is to prevent hydrogen cracking in the weld metal and HAZ. This objective is accomplished by the interaction of several effects including: driving off moisture prior to the start of welding, reducing the cooling rate, and increasing the rate of hydrogen diffusion. A second reason for preheat is the redistribution of solidification stresses that results from the greater time for this to occur afforded by the slower cooling rate. A third reason for preheat is to reduce the cooling rate in materials that 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 composition (carbon equivalent) and thickness. These fabrication codes may also utilize preheat temperature requirements to provide exemptions from PWHT.

More restrictive preheat requirements should be imposed for repairs involving highly restrained weldments and for specialized welding such as controlled deposition. In addition, for materials with higher hardenability and for welding processes or consumables with increased hydrogen potential, maintenance of preheat may be required until the application of hydrogen bakeout or PWHT.

5.2.1 Interpass Temperature. Welding procedures specify a minimum preheat and maximum interpass temperature. Many welding procedures specify maximum interpass temperatures, which should not be exceeded prior to depositing the next pass in the same area for metallurgical reasons such as maintaining the notch toughness of ferritic steels or the corrosion resistance of austenitic stainless steels and some nonferrous alloys.

5.3 Postweld Hydrogen Bakeout (also referred to as Postheating). By definition, postweld hydrogen bakeout encompasses heating performed after welding has been completed or interrupted. However, hydrogen bakeout is performed at a lower temperature, generally under 800°F [427°C].

The primary objective for postweld hydrogen bakeout is the removal of hydrogen and the prevention of hydrogen-induced cracking. The latter is also known as delayed cracking since it can occur 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 potential for introducing hydrogen from the welding consumables or hydrogen-charged or contaminated base metal is not adequately controlled, or when preheat is not sufficient. As such, much of the hydrogen bakeout discussion in 5.1 is also applicable to this subclause. Depending upon the actual temperatures used, some degree of tempering may also occur.

If postweld hydrogen bakeout is deemed necessary due to concerns regarding hydrogen cracking, the minimum preheat temperature should be maintained until the application of such postweld hydrogen bakeout.

Frequently, postweld hydrogen bakeout 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 temperature until PWHT, postweld hydrogen bakeout may be used. Similarly, a delay may be necessary before completion of welding. Again, when not practical to maintain the preheat temperature until welding is resumed, so-called "intermediate" hydrogen bakeout may be used. If postweld hydrogen bakeout will be a requirement after completion of the weld, it is recommended to plan for the postweld hydrogen bakeout during the design of the preheat setup. Minimum recommended soak bands for postweld hydrogen bakeout are larger than minimum recommended soak bands for preheat. Refer to 6.1.3 for minimum recommended soak band widths. Another example is the use of postweld hydrogen bakeout with controlled deposition welding as described below.

Fabrication or repair code requirements for postweld hydrogen bakeout are generally associated with temper bead or controlled deposition welding when used as an alternative to PWHT. For example, ASME Section III and the National Board Inspection Code (NBIC) provide such requirements. The Section III (paragraph NB-4622.9) requirement (for P-No. 1 materials) is 450°F to 550°F [232°C to 288°C] for a minimum of 2 hours, while the NBIC (Part 3, 2.5.3) requirement is 450°F [232°C] minimum for a minimum of two hours. Consult the current NBIC for updated information regarding times and temperatures. It is again recommended to specify time as a function of thickness to account for the variable diffusion path, with a minimum time requirement. Temperatures in the range of 500°F to 600°F [260°C to 316°C] for two hours per inch [25 mm] of thickness, with two hours minimum, is consistent with requirements for carbon and low alloy steels found in various codes. However, based upon concerns with regard to hydrogen trapping, it appears prudent to use temperatures of 600°F [316°C] and higher (hydrogen bakeout). Temperature restrictions may also be necessary, as discussed in 5.1, due to adverse metallurgical reactions.

5.4 Postweld Heat Treatment (PWHT). As discussed previously, 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 the temperature to drop below the minimum for preheat.

Local PWHT of carbon and low-alloy steels is typically performed below the lower transformation temperature. The lower transformation temperature is where the crystal structure of steel begins to transform from body centered cubic to face centered cubic upon heating, and the upper transformation temperature is the temperature at which that transformation is completed. When cooling, the reverse happens.

There are several reasons why 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 bands of partially-transformed microstructures that would result in large variation in properties across the weldment. Depending upon the prior heat treatment of the material, this could result in a detrimental effect upon properties (tensile/yield strength, impact toughness, and local inhomogeneity). Additionally, when components are heated above the upper transformation temperature, the material becomes soft and there is 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 in the rest of this document refers to PWHT performed below the lower transformation temperature unless otherwise noted.

PWHT can have both beneficial and detrimental effects. Three primary benefits of PWHT are recognized. These are tempering, relaxation of residual stresses, and hydrogen removal. Consequential benefits such as avoidance of hydrogen induced cracking, dimensional stability, and improved ductility, toughness, and corrosion resistance result from the primary benefits. 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 later. When the objective of tempering is to achieve specific hardness requirements, it is important to recognize that fabrication code minimum temperatures may not be adequate; this will be discussed later.

Excessive or inappropriate PWHT temperatures, long holding times, or both, can adversely affect properties. These adverse effects can include reduced tensile strength, creep strength, and notch toughness (generally caused by embrittlement due to precipitate formation). 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 (Reference A3) and Shiga, et al., (Reference A4) provide good summaries of the effect of PWHT on properties.

The need for PWHT is usually driven by either a direct requirement within a particular fabrication or repair code, or by service environment concerns. Within the fabrication codes cited in Clause 2, requirements to apply PWHT are generally triggered by material type and thickness. These fabrication codes provide detailed requirements regarding local PWHT. Such “code required” PWHT is generally aimed at reducing susceptibility to brittle fracture, and as such is targeted to improve notch toughness and relax residual stress. The local PWHT recommendations provided in Clause 6 are given with these objectives in mind.

The need for PWHT based upon service environment is not treated by the fabrication codes cited in Clause 2. Instead, guidance may be found in recommended practices regarding service environment, such as those cited in Clause 2. Applying PWHT for “service” can have a variety of objectives. Reduction of hardness and stress relaxation are two of the more common objectives related to service environments. It is important to note that the threshold residual stress levels in such cases are often less than those required for brittle fracture related concerns, and more detailed requirements may therefore apply. The PWHT recommendations provided in Clause 13 address additional considerations related to the service environment.

Several comprehensive reviews regarding PWHT of welded structures are available (References A3, A5, A6). In addition, The Japan Welding Engineering Society has published a document, which specifically addresses local PWHT considerations related to piping (Reference A7). Recent assessments of issues related to ASME Code and Japan High Pressure Institute Standard (HPIS) PWHT practices are also available (References A8, A9).

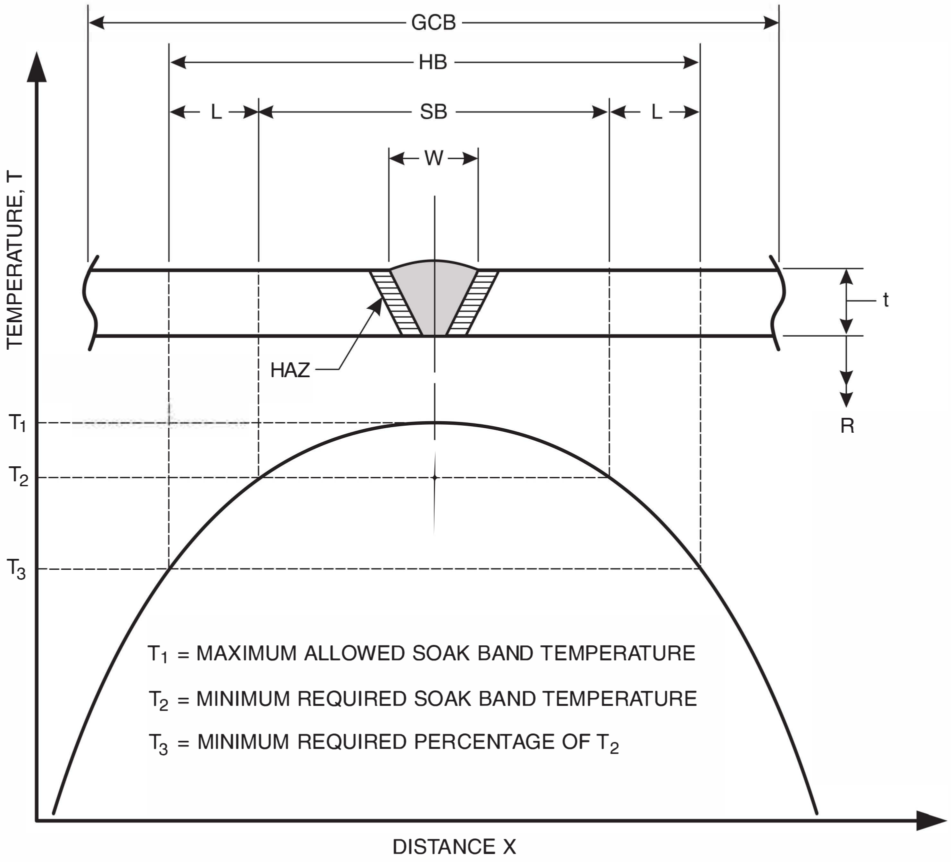
For PWHT to be successful, it should be based upon engineering assessment and optimization of parameters to meet the desired objectives. For example, as discussed previously, PWHT may degrade notch toughness for certain materials. Consideration of issues such as those stated above should be included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

6. Local 360-Degree Band Heating

The cited fabrication codes are based upon the use of 360-degree bands for local heating (see Figure 6.1). For preheat, the cited fabrication codes typically specify only soak band width. For PWHT, the cited fabrication codes may specify soak band width, heated band width, and axial temperature gradients. Since local heating of piping is typically from the outside, radial (through-thickness) temperature gradients should be considered, but are not addressed. The cited fabrication codes do not address any of these issues with respect to hydrogen bakeout or postheating. Repair codes such as NBIC and paragraphs relating to repair in fabrication codes typically specify only the soak band width for preheat.

The following subclauses consider the various issues affecting the soak band, heated band, gradient control band, and axial temperature gradient, then provide recommendations. The presentation of issues and recommendations addresses hydrogen bakeout, preheat, and PWHT. A more in-depth examination of the issues and recommendations is available in Annexes B and C. Also included in this clause are recommended PWHT practices for common piping welds. **Since requirements may differ between different codes and specifications, the applicable version of these documents should govern for each specific application.**

6.1 Soak Band. The soak band width identifies the required volume of metal that needs to achieve the required temperature to produce the desired effect. Tables 6.1 and 6.2 compare the minimum preheat and PWHT soak band widths specified by several of the codes cited in Clause 2.



Nomenclature:
W = Widest width of weld.
HAZ = Heat-affected zone.
SB = Soak band (width of the volume of the material where the holding temperature is expected to be controlled to within the minimum and maximum temperature limits. The minimum width is typically specified as W plus a multiple of t 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 gradient heat source, if required).
t = Nominal thickness of piping, branch connection, nozzle neck, or attachment.
R = Inside radius of piping, branch connection, or nozzle neck.

Note: Drawing is not to scale.

Figure 6.1—Schematic Diagram for Description of Local PWHT 360-Degree Band Heating

6.1.1 Soak Band Width for Preheat. The requirement for preheat of an area 3 in [75 mm], or 1.5t (where t = pipe wall thickness), whichever is greater, in all directions from the point of welding appears to work well and is also used by pressure vessel and structural welding codes. Use of the greater of the minimum soak band width shown below or that provided in the governing document for preheat is recommended.

Minimum Recommended Soak Band Width for Preheat
For new construction, 3 in [75 mm] or 1.5t, whichever is greater, in all directions from the point of welding, where t = pipe wall thickness.

Table 6.1
Comparison of Minimum Preheat Soak Band Widths

Code	Minimum Soak Band Widths
ASME B31.1 and B31.3	3 in [75 mm] or 1.5 times the base metal thickness, whichever is greater, in all directions from the point of welding
ASME Section III, Subsection NB	None specified for initial weld
	The weld area plus a band around the repair area of at least 1.5 times the component thickness or 5 in [125 mm], whichever is less for temper bead weld repair without PWHT
BS 2633	3 in [75 mm] from the joint
NBIC	4 in [102 mm] or 4 times the material thickness, whichever is greater on each side of the weld groove for repairs which penetrate the full thickness
	4 in [102 mm] or 4 times the depth of the repair weld, whichever is greater on each side of the joint for repairs which do not penetrate the full thickness

Table 6.2
Comparison of Minimum PWHT Soak Band Widths

Code	Minimum Soak Band Width
ASME B31.1 and B31.3	Piping Girth Welds
	3 times the wall thickness at the weld of the thickest part being joined, with the weld in the middle of the band
	Nozzle and Attachment Welds
	Shall extend beyond the nozzle weld or attachment weld on each side at least 2 times the header thickness and shall extend completely around the header
ASME Section III, Subsection NB	Thickness of the weld or 2 in [50 mm], whichever is less, on each side of the weld face at its greatest width
BS 2633	1.5 times the pipe thickness on each side of the weld centerline

6.1.2 Soak Band Width for PWHT. Note the desirability of the ASME Section III PWHT sizing approaches shown in Table 6.2 which prevent the soak band from becoming unnecessarily large as thickness increases. Use of the greater of the minimum soak band width shown below or that provided in the governing document for PWHT is recommended.

Minimum Recommended Soak Band Width for PWHT
t or 2 in [50 mm], whichever is less, on either side of the weld at its greatest width, where t = pipe wall thickness.

6.1.3 Soak Band Width for Hydrogen Bakeout. The cited fabrication codes do not provide guidance regarding the width of the soak band for hydrogen bakeout or postheating. The soak band width for hydrogen bakeout should be larger than that for either preheat or PWHT. This is to ensure that hydrogen does not diffuse back into the weld area during welding. Use of the greater of the minimum soak band width shown below or that provided in the governing document for hydrogen bakeout is recommended.

The objective is to remove hydrogen from weld metal, HAZ, and surrounding base metal. Use the greater of the minimum soak band width shown below or that provided in the governing document for postheating.

Minimum Recommended Soak Band Width for Hydrogen Bakeout and Postheating
6 in [150 mm] or 3t, whichever is greater, in all directions from the weld, where t = pipe wall thickness.

6.2 Heated Band. The size of the heated band is important with regard to two considerations. Because of the inherent radial temperature gradient, the band should be large enough to ensure that the minimum required temperature extends through the thickness in the soak band. In addition, local heating of a cylindrical shell will produce bending moments and shear stresses. These bending moments and shear stresses can cause distortion, induce residual stress, or both, in the weld region. The magnitude and location of these stresses are affected by the width of the heated band and axial temperature distribution. The through-thickness temperature gradient issue is relevant for all heating purposes while induced stresses are principally of concern for PWHT.

ASME Section III, B31.1, and B31.3 do not provide specific guidance regarding the width of the PWHT heated band. BS 2633 provides a minimum recommended PWHT heated band width of five times pipe wall thickness (5t). However, in one figure it implies use of a heated area of $2.5\sqrt{Rt}$ on each side of a branch connection, where R = inside radius and t = pipe wall thickness. Although not explicitly stated, many users interpret BS 2633 to require a heated band width extending $2.5\sqrt{Rt}$ on each side of a weld. None of the codes cited in Clause 2 provide guidance with regard to the heated band width for hydrogen bakeout, preheat, or postheating.

When attempting to establish the minimum required heated band width, the user should first ensure that it is adequate to achieve the minimum temperatures required in the soak band. Further consideration should 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.

6.2.1 Heated Band Width for PWHT. The following recommendations are aimed at meeting the typical PWHT objectives found in fabrication codes (so-called "code required" PWHT). Further discussion and recommendations when the service environment should also be considered are provided in Clause 13. In addition, 6.6.1 and 6.6.2 address PWHT practices related to piping in the horizontal and vertical positions. The position of the piping has an effect on one criterion used to establish the width of the heated band.

Recommendations regarding the heated band width are presented based upon both induced stress and through-thickness temperature gradient criteria as discussed in Annex B. Additionally, it is recommended that the minimum heated band width be at least the minimum soak band width plus 2 in [50 mm]. This recommendation is made to prevent the edge of the soak band getting too close to the edge of the heater and the associated temperature drop. The SB plus 2 in [50 mm] criterion will determine the width only when the diameter is very small. Minimum heated band widths determined by the induced stress criterion are referred to as HB1 and were calculated using Equation (1). Those determined using the through-thickness temperature criterion are referred to as HB2 and were calculated using Equation (2).

Minimum Heated Band Width Based upon Induced Stress Criterion

$$HB1 = SB + 4\sqrt{Rt} \qquad (1)$$

where:
SB = soak band width
R = pipe inside radius
t = pipe wall thickness

Minimum Heated Band Width Based upon Through-Thickness Temperature Criterion

$$HB2 = \frac{H_i\left[\frac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD} \qquad (2)$$

where:
H_i = ratio of heat source area to heat loss area
OD = outside diameter of pipe
ID = inside diameter of pipe
SB = soak band width

As discussed in Annex B, the empirical nature of the through-thickness temperature criterion used to calculate HB2 results in the need to vary the H_i ratio for different conditions. Therefore, different H_i ratios are recommended depending upon piping position, number of control zones, and temperature. In addition, the user is cautioned that H_i ratios larger than recommended below may be required as thickness increases significantly beyond 1 in [25 mm], the thickness at which the empirically derived data was obtained.

Use the greater of the minimum heated band width shown below or that provided in the governing document for PWHT. The user should note that the resultant minimum recommended heated band widths are considerably larger than current domestic practices and greater than international practices for those cases where HB2 is larger.

Minimum Recommended Heated Band Width for PWHT[1]
Use larger of minimum soak band width plus 2 in [50 mm], HB1, or HB2. Use $H_i = 5$ for piping in the horizontal position with pipe sizes up to NPS 6 [DN 150] and one circumferential control zone. If two circumferential control zones are used for piping in the horizontal position with pipe sizes of NPS 6 [DN 150] and below, $H_i = 3$ could be used. Use $H_i = 3$ for piping in the horizontal position with pipe sizes over NPS 6 [DN 150] with a minimum of two circumferential control zones and for all vertical piping.

H_i	NPS	Control Zone [CZ(s)]	Position
5	<6	1	H
5 or 3	≤6	2	H
3	>6	≥2	H, V

Table 6.3 provides recommended minimum PWHT heated band widths for common piping dimensions based upon the above recommendations of ASME B31.1 and B31.3 minimum PWHT soak band requirements respectively. It should be noted that the recommendations in Table 6.3 are for piping in the horizontal position. However, the heated band widths for pipe sizes greater than NPS 6 [DN 150] in these table can also be used for vertical piping since an H_i ratio of 3 is used for piping in both the horizontal (with a minimum of two control zones) and vertical positions.

It is recommended that the larger of HB1 or HB2 in Table 6.3 be used. It should be noted that the SB plus 2 in [50 mm] criterion is already included in the calculations of HB1 and HB2 shown in this table. As can be seen in the table, the piping dimensions, soak band size (e.g., code), and appropriate H_i ratio based upon the number of control zones determine which will be larger. The larger of the two sizes for HB1 and HB2 in Table 6.3 are shown in **bold.**

6.2.2 Heated Band Width for Hydrogen Bakeout and Preheat. As a result of the lower temperatures, which are generally assumed to be well less than 800°F [427°C], the heated band width for hydrogen bakeout, preheat, and post-heating can be based solely upon through-thickness temperature gradient criteria. The ratio approach, with $H_i = 2$ (based upon less heat loss at the lower temperature), could be used as discussed in Annex B. Minimum heated band widths could therefore be calculated using Equation (2) with $H_i = 2$.

Use the greater of the minimum heated band width shown below or that provided in the governing document for hydrogen bakeout and preheat.

Minimum Recommended Heated Band Width for Hydrogen Bakeout and Preheat
Use HB2 calculated from Equation (2), with $H_i = 2$.

[1] NPS = Nominal Pipe Size
DN = Diameter Number

Table 6.3
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
2	50	std	2.375	60	2.067	52	0.154	3	0.5	11	2.1	52	**3.5**	**87**	5.0	128	1
2	50	80	2.375	60	1.939	49	0.218	5	0.7	16	2.5	63	**4.6**	**118**	6.5	164	1
4	100	std	4.500	114	4.026	102	0.237	6	0.7	18	3.5	88	**5.4**	**137**	8.2	208	1
4	100	80	4.500	114	3.826	97	0.337	8	1.0	25	4.2	107	**7.4**	**188**	10.6	269	1
4	100	120	4.500	114	3.624	92	0.438	11	1.3	33	4.9	123	**9.2**	**234**	12.8	325	1
4	100	160	4.500	114	3.438	87	0.531	13	1.6	40	5.4	137	**10.8**	**273**	14.6	370	1
6	150	std	6.625	168	6.065	154	0.280	7	0.8	21	4.5	115	**6.5**	**165**	10.2	259	1
6	150	80	6.625	168	5.761	146	0.432	10	1.3	32	5.8	146	**9.7**	**245**	14.1	359	1
6	150	120	6.625	168	5.501	139	0.562	14	1.7	42	6.7	169	**12.1**	**308**	17.1	434	1
6	150	160	6.625	168	5.187	131	0.719	18	2.2	54	7.6	193	**14.9**	**377**	20.3	516	1
													↑$H_i = 5$↑, ↓$H_i = 3$↓				
8	200	std	8.625	219	7.981	202	0.322	8	1.0	24	**5.5**	**139**	4.5	115	10.0	254	2
8	200	80	8.625	219	7.625	193	0.500	12	1.5	38	**7.0**	**178**	6.8	172	12.3	313	2
8	200	120	8.625	219	7.187	182	0.719	18	2.2	54	8.6	218	**9.3**	**237**	15.8	400	2
8	200	160	8.625	219	6.813	173	0.906	23	2.7	69	9.7	247	**11.3**	**287**	18.3	465	2
10	250	std	10.750	273	10.020	254	0.365	9	1.1	27	**6.5**	**165**	5.2	131	11.9	302	2
10	250	80	10.750	273	9.562	242	0.594	15	1.8	45	**8.5**	**216**	8.1	206	15.3	387	2
10	250	120	10.750	273	9.062	230	0.844	21	2.5	64	10.4	263	**11.1**	**281**	18.9	479	2

(Continued)

Table 6.3 (Continued)
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
10	250	160	10.750	273	8.500	215	1.125	28	3.4	85	12.1	307	**14.0**	**356**	22.8	579	2
12	300	std	12.750	323	12.000	304	0.375	9	1.1	28	**7.1**	**181**	5.4	136	13.1	333	2
12	300	80	12.750	323	11.374	288	0.688	17	2.1	52	**10.0**	**253**	9.4	239	17.9	454	2
12	300	120	12.750	323	10.750	273	1.000	25	3.0	76	12.3	311	**13.1**	**333**	22.4	568	2
12	300	160	12.750	323	10.126	257	1.312	33	3.9	100	14.2	361	**16.4**	**417**	26.7	679	2
14	350	std	14.000	355	13.250	336	0.375	9	1.1	28	**7.4**	**188**	5.4	136	13.7	348	3
14	350	80	14.000	355	12.500	317	0.750	19	2.3	57	**10.9**	**277**	10.3	261	19.6	497	3
14	350	120	14.000	355	11.812	300	1.094	27	3.3	83	13.4	341	**14.4**	**364**	24.5	623	3
14	350	160	14.000	355	11.188	284	1.406	35	4.2	107	15.4	392	**17.7**	**449**	28.9	734	3
16	400	std	16.000	406	15.250	387	0.375	9	1.1	28	**7.9**	**200**	5.4	137	14.7	372	3
16	400	80	16.000	406	14.312	363	0.844	21	2.5	64	**12.4**	**314**	11.6	294	22.2	563	3
16	400	120	16.000	406	13.562	344	1.219	30	3.7	92	15.2	385	**16.1**	**407**	27.6	699	3
16	400	160	16.000	406	12.812	325	1.594	40	4.8	121	17.6	446	**20.1**	**510**	32.9	835	3
18	450	std	18.000	457	17.250	438	0.375	9	1.1	28	**8.3**	**211**	5.4	138	15.5	394	3
18	450	80	18.000	457	16.124	409	0.938	23	2.8	71	**13.8**	**350**	12.9	327	24.8	630	3
18	450	120	18.000	457	15.250	387	1.375	34	4.1	104	17.1	433	**18.1**	**459**	31.1	788	3
18	450	160	18.000	457	14.438	366	1.781	45	5.3	135	19.7	500	**22.5**	**571**	36.8	935	3
20	500	std	20.000	508	19.250	488	0.375	9	1.1	28	**8.7**	**221**	9.1	231	16.3	414	4
20	500	80	20.000	508	17.938	455	1.031	26	3.1	78	**15.3**	**387**	14.2	360	27.4	696	4

(Continued)

Table 6.3 (Continued)
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
20	500	120	20.000	508	17.000	431	1.500	38	4.5	114	18.8	477	**19.8**	**502**	34.1	865	4
20	500	160	20.000	508	16.062	407	1.969	50	5.9	150	21.8	554	**24.9**	**632**	40.8	1036	4
22	550	std	22.000	558	21.250	539	0.375	9	1.1	28	**9.1**	**231**	5.5	139	17.1	434	4
22	550	80	22.000	558	19.750	501	1.125	28	3.4	85	**16.7**	**424**	15.5	393	30.0	763	4
22	550	120	22.000	558	18.750	476	1.625	41	4.9	123	20.5	520	**21.5**	**546**	37.1	942	4
22	550	160	22.000	558	17.750	450	2.125	53	6.4	161	23.7	603	**26.9**	**684**	44.3	1125	4
24	600	std	24.000	609	23.250	590	0.375	9	1.1	28	**9.5**	**240**	5.5	139	17.8	452	4
24	600	80	24.000	609	21.744	552	1.218	31	3.4	86	**17.4**	**441**	15.6	397	31.4	797	4
24	600	120	24.000	609	20.376	517	1.812	46	5.4	138	22.6	574	**23.9**	**607**	41.1	1043	4
24	600	160	24.000	609	19.314	490	2.343	59	7.0	178	26.1	661	**29.7**	**753**	48.7	1236	4
26	650	n/a	26	660	23	584	1.500	38	4.5	114	**21.1**	**536**	20.4	518	37.7	958	4
26	650	n/a	26	660	22	558	2.000	50	6.0	152	**24.8**	**628**	26.3	668	43.5	1105	4
26	650	n/a	26	660	21	533	2.500	630	7.5	190	28.0	711	**31.7**	**806**	52.2	1326	4
26	650	n/a	26	660	20	508	3.000	76	9.0	228	30.9	785	**36.7**	**932**	58.6	1488	4
26	650	n/a	26	660	19	482	3.500	88	10.5	266	33.6	852	**41.2**	**1046**	64.3	1632	4
26	650	n/a	26	660	18	457	4.000	101	12.0	304	36.0	914	**45.2**	**1148**	69.2	1758	4
28	700	n/a	28	711	25	635	1.500	38	4.5	114	**21.8**	**554**	20.6	522	39.1	994	4
28	700	n/a	28	711	24	609	2.000	50	6.0	152	**25.6**	**650**	26.6	674	45.2	1147	4
28	700	n/a	28	711	23	584	2.500	63	7.5	190	28.9	735	**32.1**	**816**	53.6	1361	4

(Continued)

Table 6.3 (Continued)
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
28	700	n/a	28	711	22	558	3.000	76	9.0	228	32.0	812	**37.3**	**947**	60.3	1530	4
28	700	n/a	28	711	21	533	3.500	88	10.5	266	34.7	882	**42.0**	**1066**	66.2	1682	4
28	700	n/a	28	711	20	508	4.000	101	12.0	304	37.3	947	**46.3**	**1175**	71.6	1818	4
28	700	n/a	28	711	19	482	4.500	114	13.5	342	39.7	1007	**50.1**	**1273**	76.3	1937	4
28	700	n/a	28	711	18	457	5.000	127	15.0	381	41.8	1062	**53.6**	**1360**	80.4	2042	4
28	700	n/a	28	711	17	431	5.500	139	16.5	419	43.8	1113	**56.6**	**1436**	83.9	2131	4
30	750	n/a	30	762	27	685	1.500	38	4.5	114	**22.5**	**571**	20.7	525	40.5	1028	4
30	750	n/a	30	762	26	660	2.000	50	6.0	152	26.4	670	**26.8**	**680**	47.2	1198	4
30	750	n/a	30	762	25	635	2.500	63	7.5	190	29.9	758	**32.5**	**825**	54.9	1393	4
30	750	n/a	30	762	24	609	3.000	76	9.0	228	33.0	838	**37.8**	**960**	61.8	1569	4
30	750	n/a	30	762	23	584	3.500	88	10.5	266	35.9	911	**42.7**	**1084**	68.1	1729	4
30	750	n/a	30	762	22	558	4.000	101	12.0	304	38.5	978	**47.2**	**1198**	73.7	1872	4
30	750	n/a	30	762	21	533	4.500	114	13.5	342	41.0	1041	**51.3**	**1303**	78.8	2001	4
30	750	n/a	30	762	20	508	5.000	127	15.0	381	43.3	1099	**55.0**	**1397**	83.3	2115	4
30	750	n/a	30	762	19	482	5.500	139	16.5	419	45.4	1153	**58.3**	**1480**	87.2	2215	4
32	800	n/a	32	812	29	736	1.500	38	4.5	114	**23.2**	**588**	20.8	528	41.8	1062	4
32	800	n/a	32	812	28	711	2.000	50	6.0	152	**27.2**	**690**	27.0	685	48.3	1227	4
32	800	n/a	32	812	27	685	2.500	63	7.5	190	30.7	780	**32.8**	**833**	56.1	1423	4
32	800	n/a	32	812	26	660	3.000	76	9.0	228	34.0	863	**38.3**	**971**	63.2	1606	4

(Continued)

Table 6.3 (Continued)
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
32	800	n/a	32	812	25	635	3.500	88	10.5	266	37.0	938	**43.3**	**1100**	69.8	1772	4
32	800	n/a	32	812	24	609	4.000	101	12.0	304	39.7	1008	**48.0**	**1219**	75.7	1923	4
32	800	n/a	32	812	23	584	4.500	114	13.5	342	42.3	1073	**52.3**	**1328**	81.1	2059	4
32	800	n/a	32	812	22	558	5.000	127	15.0	381	44.7	1134	**56.3**	**1428**	85.9	2182	4
32	800	n/a	32	812	21	533	5.500	139	16.5	419	46.9	1191	**59.8**	**1519**	90.2	2291	4
36	900	n/a	36	914	33	838	1.500	38	4.5	114	**24.4**	**619**	21.0	533	44.3	1125	5
36	900	n/a	36	914	32	812	2.000	50	6.0	152	**28.6**	**727**	27.3	694	51.3	1301	5
36	900	n/a	36	914	31	787	2.500	63	7.5	190	32.4	823	**33.3**	**846**	58.2	1479	5
36	900	n/a	36	914	30	762	3.000	76	9.0	228	35.8	910	**39.0**	**990**	65.8	1672	5
36	900	n/a	36	914	29	736	3.500	88	10.5	266	39.0	990	**44.3**	**1126**	72.8	1849	5
36	900	n/a	36	914	28	711	4.000	101	12.0	304	41.9	1065	**49.3**	**1253**	79.3	2013	5
36	900	n/a	36	914	27	685	4.500	114	13.5	342	44.7	1134	**54.0**	**1371**	85.2	2163	5
36	900	n/a	36	914	26	660	5.000	127	15.0	381	47.2	1200	**58.3**	**1481**	90.6	2300	5
36	900	n/a	36	914	25	635	5.500	139	16.5	419	49.7	1261	**62.3**	**1583**	95.5	2425	5
42	1050	n/a	42	1066	39	990	1.500	38	4.5	114	**26.1**	**663**	21.2	538	47.8	1213	6
42	1050	n/a	42	1066	38	965	2.000	50	6.0	152	**30.7**	**778**	27.7	703	55.3	1405	6
42	1050	n/a	42	1066	37	939	2.500	63	7.5	190	34.7	881	**33.9**	**861**	61.1	1552	6
42	1050	n/a	42	1066	36	914	3.000	76	9.0	228	38.4	975	**39.9**	**1012**	69.3	1759	6
42	1050	n/a	42	1066	35	889	3.500	88	10.5	266	41.8	1061	**45.5**	**1155**	76.8	1950	6

(Continued)

Table 6.3 (Continued)
Minimum Recommendations for Local 360-Degree Band PWHT[a] of Girth Welds on Piping in the Horizontal Position Based on ASME B31.1 and B31.3 Minimum PWHT Soak Band Requirements

Nominal Pipe Diameter Size			Outside Diameter (OD)		Inside Diameter (ID)		Wall Thickness		Minimum Soak Band Width		HB1		HB2		Minimum GCB Width centered over the HB		Minimum Number of Circ. Control Zones
NPS	[DN]	Sch No.	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	
42	1050	n/a	42	1066	34	863	4.000	101	12.0	304	45.0	1142	**50.9**	**1291**	83.8	2129	6
42	1050	n/a	42	1066	33	838	4.500	114	13.5	342	48.0	1218	**55.9**	**1420**	90.4	2296	6
42	1050	n/a	42	1066	32	812	5.000	127	15.0	381	50.8	1289	**60.7**	**1542**	96.5	2450	6
42	1050	n/a	42	1066	31	787	5.500	139	16.5	419	53.4	1357	**65.2**	**1656**	102.1	2594	6
48	1200	n/a	48	1219	45	1143	1.500	38	4.5	114	**27.7**	**704**	21.4	542	51.0	1294	6
48	1200	n/a	48	1219	44	1117	2.000	50	6.0	152	**32.5**	**826**	28.0	711	59.1	1500	6
48	1200	n/a	48	1219	43	1092	2.500	63	7.5	190	36.8	935	**34.4**	**873**	66.2	1681	6
48	1200	n/a	48	1219	42	1066	3.000	76	9.0	228	40.7	1035	**40.5**	**1028**	72.5	1841	6
48	1200	n/a	48	1219	41	1041	3.500	88	10.5	266	44.4	1127	**46.4**	**1177**	80.3	2038	6
48	1200	n/a	48	1219	40	1016	4.000	101	12.0	304	47.8	1213	**52.0**	**1320**	87.8	2229	6
48	1200	n/a	48	1219	39	990	4.500	114	13.5	342	51.0	1294	**57.4**	**1457**	94.8	2409	6
48	1200	n/a	48	1219	38	965	5.000	127	15.0	381	54.0	1371	**62.5**	**1587**	101.5	2577	6
48	1200	n/a	48	1219	37	939	5.500	139	16.5	419	56.8	1444	**67.4**	**1711**	107.7	2736	6

[a] This table is based on pipe wall thicknesses, not weld metal or attachment weld thickness.

Notes:
1. NPS = nominal pipe size, DN = diameter number, OD = outside diameter, t = wall thickness, R = inside radius, ID = inside diameter.
2. The minimum PWHT soak band (SB) width for girth welds is defined as 3t.
3. In all cases, the minimum heated band width shall be at least the minimum soak band width plus 2 in [50 mm].
4. Minimum heated band width HB1 = greater of SB + $[4 \times \sqrt{Rt}]$ or Note 3.
5. Minimum heated band width HB2 = greater of $5 \times [(OD^2 - ID^2)/2 + (ID \times SB)]/OD$ or Note 3 for piping size up to NPS 6, where one circumferential control zone is used. If two zones are used, the width in Note 6 could be used.
6. Minimum heated band width HB2 = greater of $3 \times [(OD^2 - ID^2)/2 + (ID \times SB)]/OD$ for piping size up to NPS 6 and with a minimum of two circumferential control zones.
7. The larger heated band is shown in **bold**.
8. Minimum gradient control band (GCB) width beyond heated band width = $[4 \times \sqrt{Rt}]$.

An example of determining the minimum heated band width for preheat is shown below. This example assumes no insulation on the inner surface, that the full cross sectional area is present on both sides (e.g., near completion of the weld), and that the heater is at least 1 in [25 mm] away from the edge of the weld preparation to provide access for the welder.

Example Using Equation (2), with $H_i = 2$, to Determine Minimum Heated Band Width
Pipe dimensions: 12.75 in [324 mm] outside diameter by 1 in [25 mm] wall thickness
B31.3 preheat SB width: 3 in [75 mm] beyond the edge of the weld
Minimum recommended preheat heated band width: 15.5 in [394 mm]

6.3 Gradient Control Band. As the name implies, the primary function of this band is to control the axial temperature gradient. It also serves to minimize heat losses in the heated band (heat source). 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 Clause 9. The width of the insulated area directly affects the axial temperature gradient. The cited fabrication codes do not provide any guidance with regard to the width.

6.3.1 Gradient Control Band Width for PWHT. International pressure vessel codes generally recommend a $10\sqrt{Rt}$ PWHT gradient control band width centered on the weld. Accompanying this recommendation is the notation that such a width will generally ensure achieving the maximum permissible axial temperature gradient (i.e., one-half temperature drop to the edge of the heated band). Annex C provides a detailed discussion regarding considerations for establishing the gradient control band width based upon induced stress criteria. It concludes that a minimum width of $2\sqrt{Rt}$ on each side of the heated band, as shown in Equation (3), will reasonably limit the thermally induced stress during PWHT.

$$\text{Gradient control band width} = HB + 4\sqrt{Rt} \quad (3)$$

where:
HB = heated band width
R = inside radius
t = pipe wall thickness

The total gradient control band width depends upon whether HB1 or HB2 is larger. For cases where HB1 is larger, the total gradient control band width equals the width of the soak band plus $8\sqrt{Rt}$. This width is similar to that used by international codes and practices, except it is ~$1\sqrt{Rt}$ smaller depending upon the width of the soak band. Any gradient control band width recommendation also depends upon the characteristics of the insulation. It is therefore further recommended that the minimum thermal resistance, R-value, of the insulation be 2°F to 4°F-ft^2-hr/BTU [0.35°C to 0.70°C-m^2/W]. R-value is simply the inverse of the conductance of an insulating layer (i.e., R-value = insulation thickness/k-value). Various combinations of insulation types and thicknesses can be used as required to achieve R-values within this recommended range.

Use the greater of the minimum gradient control band width shown below or that provided in the governing document for PWHT.

Minimum Recommended Gradient Control Band Width and Insulation Characteristics for PWHT
Use Equation (3) to calculate the minimum width, with a minimum R-value for the insulation of 2°F to 4°F-ft^2-hr/BTU [0.35°C to 0.70°C-m^2/W].

Minimum recommended PWHT gradient control band widths (beyond the heated band width) based upon the above recommendations have been calculated using Equation (3) for ASME B31.1 and B31.3 piping applications and are shown in Table 6.3.

It is also important to note that if pipe wall thickness changes, attachments are present within the gradient control band, or the pipe is being welded to flanges, valves, etc., the use of supplemental heat source(s) within the gradient control band may be required.

6.3.2 Gradient Control Band Width for Hydrogen Bakeout and Preheat. With the lower temperatures associated with hydrogen bakeout and preheat, the width of the gradient control band is not critical. The main purpose of the insulation during preheating is to protect the welder.

Use the greater of the minimum gradient control band width shown below or that provided in the governing document for hydrogen bakeout and preheat.

Minimum Recommended Gradient Control Band Width and Insulation Characteristics for Hydrogen Bakeout, Preheat, and PWHT
3t or 3 in [75 mm], whichever is greater, on either side of the HB, where t = pipe wall thickness, with a minimum R-value for the insulation of 2°F to 4°F-ft^2-hr/BTU [0.35°C to 0.70°C-m^2/W].

6.4 Axial Temperature Gradient. The axial temperature distribution plays an important role in limiting induced stresses during PWHT. Although it is the second derivative of the axial temperature distribution (the rate of change in the axial temperature gradient) which affects induced stress, the axial temperature gradient is the parameter which is generally specified. The axial temperature gradient is not generally specified for hydrogen bakeout, preheat, or postheating because of the lower temperatures associated with these processes.

6.4.1 Axial Temperature Gradient for PWHT. Table 6.4 provides a comparison of the requirements for controlling axial temperature gradients during PWHT in the cited fabrication codes. Note that USA codes either have no requirement or use the undefined terms "gradually diminishing" or "gradually diminished." BS 2633 provides the most specific requirement. It requires that material at a distance of $2.5\sqrt{Rt}$ on each side of the weld centerline be at a temperature greater than one-half of the heat treatment temperature (i.e., soak band temperature). Such an approach is common in various international piping and pressure vessel codes. 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 1100°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 1100°F [593°C], the minimum temperature allowed at the edge of the heated band would be 567°F [297°C]. Based upon the magnitude of the difference, this is not expected to be significant.

Table 6.4
Comparison of PWHT Axial Temperature Gradient Control Requirements

Code	Axial Temperature Gradient Control Requirement
ASME B31.1	None specified
ASME B31.3	Gradually diminishing beyond a band which includes the weldment
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 2633	The temperature gradient shall be such that the length of the material on each side of the weld at a temperature exceeding half the heat treatment temperature is at least $2.5\sqrt{Rt}$, where R is the bore radius and t is the pipe thickness

The Dutch pressure vessel code (Reference A10) limits the temperature drop at two locations: one-half the distance to the edge of the heated band and at the edge of the heated band. The minimum temperature required at one-half the distance to the edge of the heated band is 80%, while that at the edge of the heated band is 50%. Such a requirement provides greater assurance of a uniform axial temperature gradient.

Annex C provides a detailed discussion regarding the effect of controlling the axial temperature gradient in the heated band by limiting the maximum temperature drop at its edge. This discussion demonstrates that by limiting the maximum temperature drop to one-half of the temperature at the edge of the soak band, stresses are adequately controlled within the soak band for some common piping materials. The one-half temperature drop approach appears to be the most appropriate based upon its:

(1) Ability to control induced stresses (as discussed in Annex C),

(2) Widespread use in international practice,

(3) Ease of use, and

(4) Ability to account for varying pipe flexibility (since the distance over which the drop may occur is based upon a function of $\sqrt{Rt}$).

In contrast, an approach based upon a fixed maximum axial temperature gradient for all pipe diameter/thickness combinations can be overly conservative in some cases and nonconservative in others. The one-half temperature drop approach also avoids a concern that may arise when using a fixed maximum axial temperature gradient. In such situations, the maximum gradient may be applied to inappropriately short intervals of length and result in unnecessary rejections.

Use the lesser of the maximum axial temperature gradient shown below or that provided in the governing document for PWHT.

Maximum Recommended Axial Temperature Gradient for PWHT
The temperature at the edge of the heated band should be no less than one half the temperature at the edge of the soak band during heating, hold, and cooling.

6.4.2 Axial Temperature Gradient for Hydrogen Bakeout, Preheat, and Postheating. Based upon the lower temperatures normally associated with hydrogen bakeout, preheat, and postheating, control of the axial temperature gradient is not required. This is due to the fact that at temperatures below 800°F [427°C] the material retains a significant fraction of its tensile properties and modulus of elasticity and that the magnitude of thermal growth at these temperatures is proportionally smaller. If temperatures are to be above 800°F [427°C], the maximum permissible axial temperature gradient recommended for PWHT should be used.

Use the lesser of the maximum axial temperature gradient shown below or that provided in the governing document for hydrogen bakeout, preheat, or postheating.

Maximum Recommended Axial Temperature Gradient for Hydrogen Bakeout, Preheat, and Postheating
Not required unless soak band temperature is above 800°F [427°C], in which case use the recommendation for PWHT.

6.5 Summary of Recommendations for SB, HB, GCB, and Axial Temperature Gradient. In all cases, the user should follow the requirements provided in the governing document (applicable code or specification). In most cases, especially for USA codes, specific requirements are limited to the soak band width for PWHT. Additional considerations and recommendations when concerns exist regarding the service environment are discussed in Clause 13. Tables 6.5 and 6.6 provide summaries of the recommendations for each of the purposes for heating (hydrogen bakeout, preheat, and PWHT). These tables can be used to either supplement existing requirements in the governing document or provide guidance where requirements are not present. Table 6.5 addresses the soak band, while Table 6.6 covers the heated band, gradient control band and axial temperature gradient. **It should be noted that Tables 6.5 and 6.6 have been designed to provide the user with all of the information required to determine the minimum band widths and maximum axial temperature gradient.**

Table 6.5
Summary of Recommendations for the Soak Band

Use the greater of the requirements below or that provided in the governing document

Purpose for Heating	Minimum Soak Band (SB) Width[a]
Hydrogen Bakeout or Postheating	6 in [150 mm] or 3t, whichever is greater, in all directions from the point of welding
Preheat	For new construction, 3 in [75 mm] or 1.5t, whichever is greater, in all directions from the point of welding, where t = pipe wall thickness. For repair welding, the recommended preheat soak band width is 4 in [100 mm] or 4 times the material thickness in all directions from the point of welding. (Note: An alternate requirement may be specified by the applicable code)
PWHT	t or 2 in [50 mm], whichever is less, on each side of the weld at its greatest width (Note: This or an alternate requirement is generally specified by the applicable code)

[a] t = pipe wall thickness

Table 6.6
Summary of Recommendations for HB, GCB, and Axial Temperature Gradient

Use the greater of the requirements below or that provided in the governing document

Purpose for Heating	Minimum Heated Band (HB) Width[a]	Minimum Gradient Control Band (GCB) Width[a,b]	Maximum Axial Temperature Gradient
Hydrogen Bakeout	$\frac{2\left[\frac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD}$	3t or 3 in [75 mm], whichever is greater, on each side of the HB	Not required unless temperature is above 800°F [427°C]; then use PWHT criteria
Preheat	$\frac{2\left[\frac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD}$	3t or 3 in [75 mm], whichever is greater, on each side of the HB	Not required unless temperature is above 800°F [427°C]; then use PWHT criteria
Postheating	$\frac{2\left[\frac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD}$	3t or 3 in [75 mm], whichever is greater, on each side of the HB	Not required unless temperature is above 800°F [427°C]; then use PWHT criteria
PWHT[c, d]	Larger of: $SB + 2$ in [50 mm] or $\frac{H_i\left[\frac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD}$ or $SB + 4\sqrt{Rt}$	$HB + 4\sqrt{Rt}$	The maximum allowed temperature drop from the edge of the SB to the edge of the HB is one-half the temperature at the edge of the SB

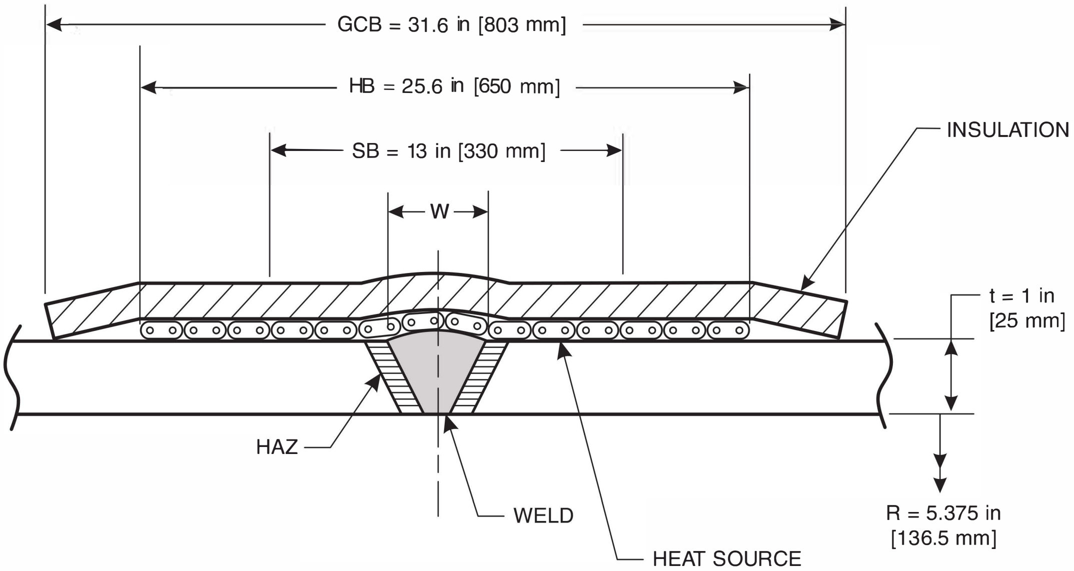
[a] NPS = nominal pipe size, DN = diameter number, OD = outside diameter, ID = inside diameter, SB = soak band width, t = pipe wall thickness, R = inside radius.
[b] Thermal resistance (R-value) of insulation to be 2°F to 4°F-ft^2-hr/Btu [0.35°C to 0.70°C-m^2/W].
[c] These recommendations are for "code required" PWHT. Additional requirements may be required when concerns exist regarding the service environment.
[d] Use H_i = 5 for piping in the horizontal position with pipe sizes up to NPS 6 [DN 150] and one circumferential control zone. If two circumferential control zones are used with pipe sizes of NPS 6 [DN 150] and below, H_i = 3 could be used for piping in the horizontal position. Use H_i = 3 for piping in the horizontal position with pipe sizes over NPS 6 [DN 150] with a minimum of two circumferential control zones and for all piping in the vertical position.

As a further aid to the user, Table 6.3 provides minimum recommended PWHT soak band, heated band, and gradient control band widths for common piping dimensions based upon ASME B31.1, B31.3, and ASME Section III requirements respectively. Note that it is recommended to use the larger of the two heated band widths (larger of HB1 or HB2, indicated in **bold**) in Table 6.3.

In addition, specific examples of the minimum band widths for local 360-degree band hydrogen bakeout, preheat, and PWHT based upon the recommendations in Tables 6.5 and 6.6 are provided in Figures 6.2 through 6.4, respectively. The examples shown in these figures are based upon heating a butt weld in a NPS 12 [DN 300], 1 in [25 mm] wall thickness pipe. In all cases, the soak band width is based upon the assumption that the weld is 1t wide.

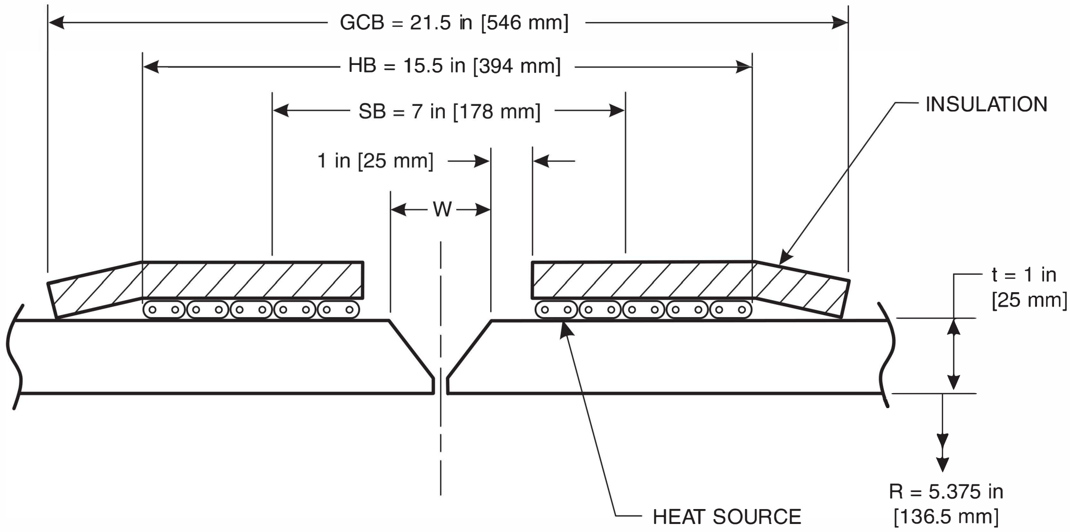
6.6 Recommended PWHT Practices. The following subclause discusses recommended PWHT practices for butt welds for piping in the horizontal and vertical positions; pipe butt welds to heavier wall thickness components; branch connections and other attachment welds to pipe; intersections with branch connections, nozzles and attachments not requiring PWHT; and proximity of pipe-to-nozzle welds to shell or head.

6.6.1 Groove Welds Joining Piping in the Horizontal Position. Due to natural convection heat flow, the 12:00 position on a groove weld for horizontally oriented piping can be considerably hotter than the 6:00 position. This issue is discussed in Reference A11 and addressed in Annex B. For example, electric resistance heating with a single zone of control on the outside surface at the 12:00 position can result in the 6:00 position being considerably cooler, especially on the inside surface. As a result, inadequate tempering, stress relaxation, or both, could occur on the surface exposed to the service environment.



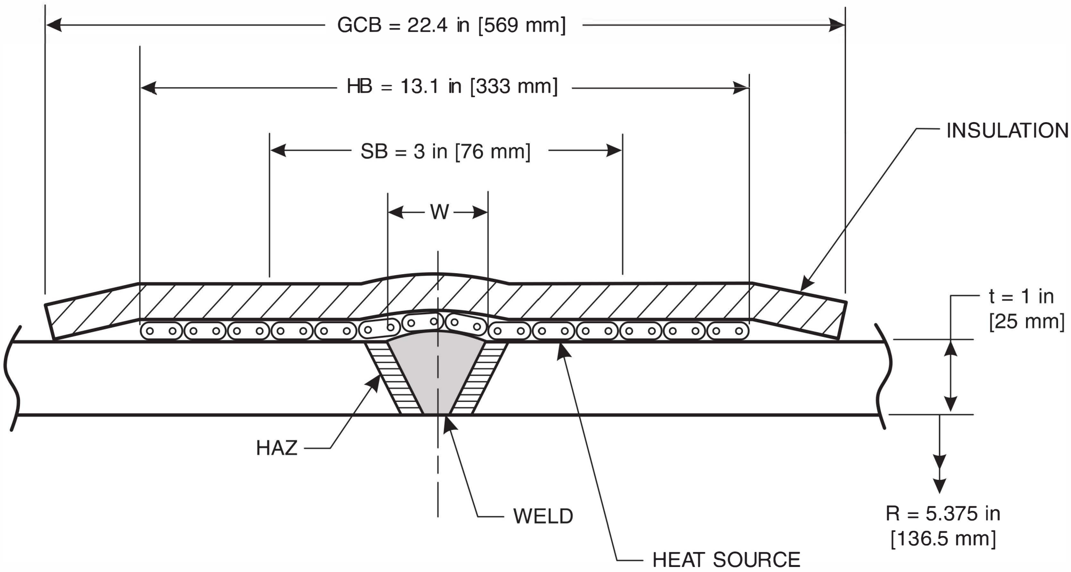
Notes:
1. SB, HB, and GCB widths shown are minimum recommended based upon Tables 6.5 and 6.6.
2. Width of SB based upon assumption that W = 1 in [25 mm].
3. Assumes that hydrogen is to be removed from the weld and surrounding region at 600°F [316°C], therefore no axial temperature gradient control is required.

Figure 6.2—Example of Parameters for Local 360-Degree Band Hydrogen Bakeout of a Butt Weld in an NPS 12 [DN 300], 1 in [25 mm] Wall Thickness Pipe



Notes:
1. SB, HB, and GCB widths shown are minimum recommended based upon Tables 6.5 and 6.6.
2. Width of SB based upon assumption that W = 1 in [25 mm].
3. Assumes preheat at 175°F [79°C], therefore no axial temperature gradient control is required.

Figure 6.3—Example of Parameters for Local 360-Degree Band Preheat a Butt Weld in an NPS 12 [DN 300], 1 in [25 mm] Wall Thickness Pipe



Notes:
1. SB, HB, and GCB widths shown are minimum recommended based upon Tables 6.5 and 6.6.
2. Width of SB based upon assumption that W = 1 in [25 mm].
3. Assuming temperature at the edge of the SB = 1100°F [593°C], minimum temperature at the edge of the HB must be 550°F [288°C].
4. H_i = 3 was used based upon the assumption that the pipe was either in the horizontal position with a minimum of two zones of control or in the vertical position.

Figure 6.4—Example of Parameters for Local 360-Degree Band PWHT of a Butt Weld in an NPS 12 [DN 300], 1 in [25 mm] Wall Thickness Pipe

Various approaches, including a combination of several, can be used to address this issue. Approaches include:

(1) Increase the number of circumferential control zones as the piping diameter increases,

(2) Use a method for determining the minimum required heated band width which attempts to account for the convection and other heat losses (e.g., HB2),

(3) Control the 12:00 position to the high side for the allowable temperature range,

(4) Use additional outside insulation layers at the 6:00 position,

(5) Utilize an eccentric heater layout (wider heater at the 6:00 versus 12:00 position), and

(6) Insulate the inner surface.

For all of these approaches, the temperature should be controlled or monitored at both the 12:00 and 6:00 positions. This is especially important where techniques such as the eccentric heater layout are used which could cause over-compensation (i.e., overheating). When using the eccentric heater layout approach, the effect upon induced stress should also be evaluated.

A commonly used approach is to increase the number of control zones as piping diameter increases and when possible insulate the inside surface. The recommendations shown in Table 6.7 regarding the number of control zones are based upon published (Reference A11) and experience data (Reference A12) (relating to the number of control zones). As stated above, it should be clearly recognized that several different approaches or a combination of approaches could be used to address this issue. As a result, when employing a combination of several approaches, it may be possible to use a lower number of control zones than shown in Table 6.7.

The recommendations regarding the heated band width for PWHT in 6.2.1 account for the position of the piping in the through-thickness temperature criterion, HB2. For piping in the horizontal position, the recommendation is to use $H_i = 5$ with pipe sizes up to NPS 6 [DN 150] and one circumferential control zone. If two circumferential control zones are used with pipe sizes of NPS 6 [DN 150] and below, $H_i = 3$ could be used. Use $H_i = 3$ for pipe sizes over NPS 6 [DN 150] with a minimum of two circumferential control zones.

6.6.2 Groove Welds Joining Piping in the Vertical Position. Due to natural convection heat flow, the top side of the heated band in vertical piping can be hotter than the bottom side. Several approaches can be used to address this issue. The recommendations regarding the heated band width for PWHT in 6.2.1 account for the position of the piping in the through-thickness temperature criterion, HB2. For piping in the vertical position, the recommendation is to use $H_i = 3$.

Table 6.7
Recommended Number of Control Zones and Thermocouple Locations for PWHT of Piping in the Horizontal Position

Piping Size (NPS)	Recommended Number of Control Zones and Thermocouple Locations
Up to 6	One zone, with control thermocouple at 12:00
8 and up to 12	Two zones, with control thermocouples at 12:00 and 6:00
14 and up to 18	Three zones, with control thermocouples at 11:00, 1:00, and 6:00
20 and up to 30	Four zones, with control thermocouples at 12:00, 3:00, 6:00, and 9:00
Over 30	Number of control zones and associated thermocouples as required by circumferential spacing of heaters

Note: Control thermocouples should be placed at the location of highest expected temperature to help avoid exceeding the maximum allowed temperature.

Other approaches include use of separate control zones above and below the weld. For electric resistance heating, the heated band (heaters) could be biased below the weld to balance heat flow. One approach is to bias the heated band such that approximately 60% of the heated band area is below the weld. It has also been suggested that a supplemental or so-called "blocking" heat source could be used on the bottom side of the weld. Such an approach is in effect a form of biasing the heated band. Alternately, the insulation could be biased towards the bottom side of the weld. The use of monitoring thermocouples, as discussed in 8.7, while not addressing the control aspects of the issue can help verify that the required temperatures are achieved. For this situation, it would certainly be desirable to use additional monitoring thermocouples above and below the weld.

6.6.3 Groove Welds Joining Piping to Valves and Flanges. During PWHT of groove welds between piping and components such as valve bodies or heavy flanges, uneven conductive heat loss (or so-called "heat sink effect") can occur. As a result, it is desirable that separate control zones are used on the thicker and thinner components. Where it is not practical to adopt this method (typically with smaller pipe sizes) an optional method is to bias the heating elements towards the heavier component. Pipe-to-flange and pipe-to-valve welds may not allow the heaters to be biased sufficiently towards the heavier component, thereby creating a hot spot on the thinner component. In instances where neither the heaters can be biased, nor separate control zones used, nor additional heat applied to the flange or valve, monitoring thermocouples should be used to ensure that the thinner section is not overheated and that the heavier section achieves the required temperature. This may require reducing the volume of insulation used on the thinner section heated band in order to achieve the desired temperature profile across the soak band.

The ratio approach for determining the minimum heated band width discussed in Annex B provides a tool to calculate the degree of bias required toward the heavier component. The cross sectional area heat loss contribution in the denominator can be adjusted to account for thickness differences on each side of the weld. Using this approach, heated band widths could be determined for each side of the weld centerline using Equation (4).

$$HB2(1/2) = \frac{H_i \left[\frac{OD^2 - ID^2}{4} + (ID)\left(\frac{SB}{2}\right) \right]}{OD} \tag{4}$$

where:

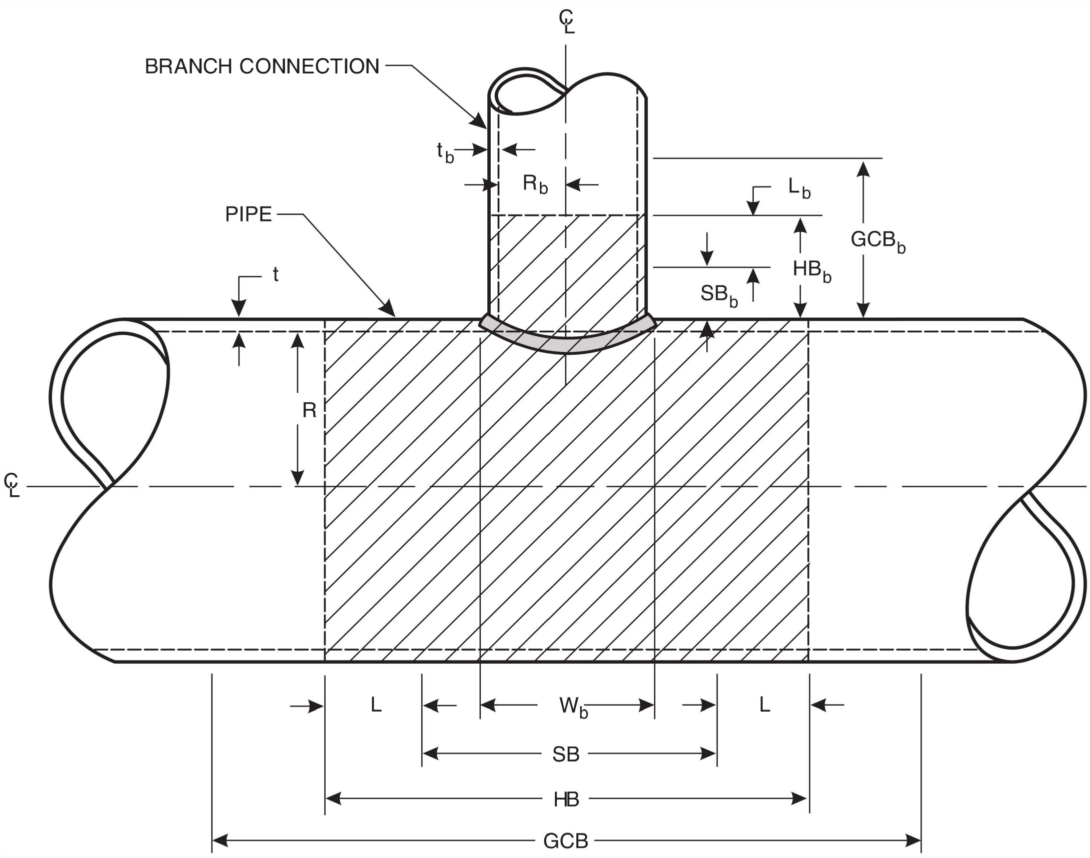
H_i = ratio of heat source area to heat loss area
OD = outside diameter (pipe or heavier wall component)
ID = inside diameter (pipe or heavier wall component)
SB = soak band width

The resultant HB2(1/2) heated band widths on each side would have to be compared to one-half of the calculated HB1 heated band width using Equation (1). The larger of each HB2(1/2) or one-half HB1 should be used to ensure complying with the induced stress criteria.

The use of monitoring thermocouples was discussed above with regard to a specific situation, i.e., the case where heat flow compensation could not be used. However, it is generally very desirable to use additional monitoring thermocouples to ensure that the required temperatures are achieved on both the thinner and heavier wall thickness components.

6.6.4 Butt Welds Joining Branch Connections or Attachments to Piping. For welds joining branch connections or attachments to pipe, 360-degree band PWHT practices, as illustrated in Figures 6.5 through 6.7, are recommended. Figure 6.5 has been adapted from the requirements in BS 2633 (Figure 6.4). Note that in Figures 6.6 and 6.7, depending upon the size of the nozzle or attachment, the more desirable approach may be to include the entire nozzle or attachment in the soak band.

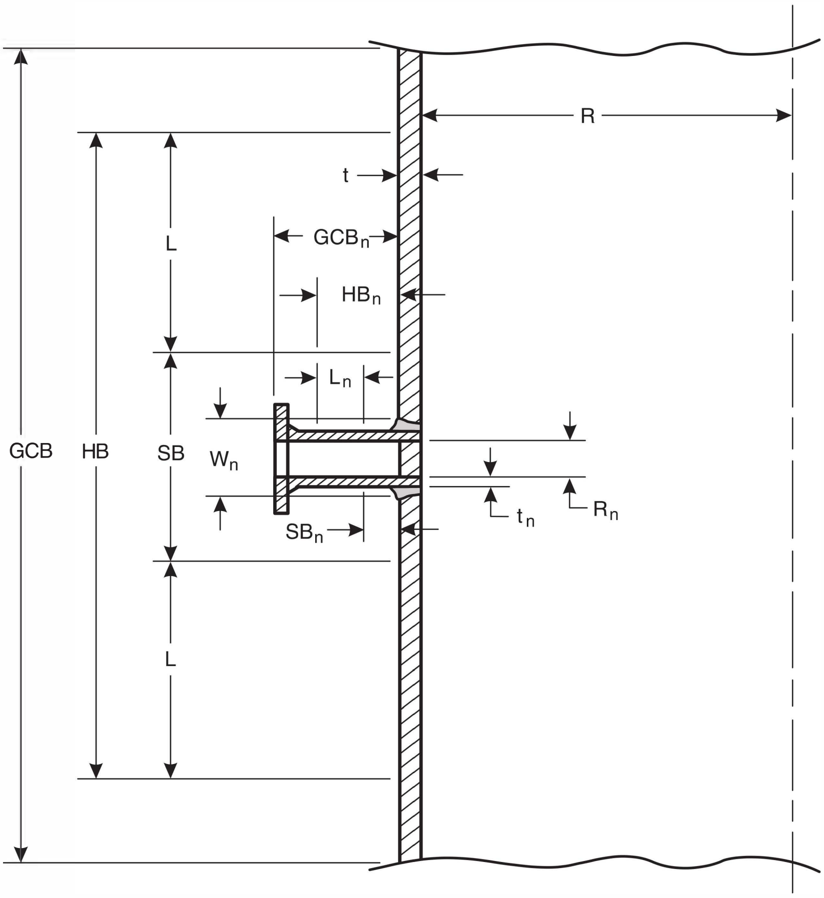
For branch connections, it is likely that the heaters fitted to the weld will not contour to the shape without leaving larger than normal gaps between the heaters. In such instances, it is good practice to attach additional monitoring thermocouples in the expected cold spots created by these gaps and heat the control thermocouples to the higher end of the soak range such that the cold spots achieve the desired temperature. It is good practice to use separate control zones on both the pipe and branch connections.



Nomenclature:

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

Figure 6.5—Local 360-Degree Band PWHT Practice for Branch Connection to Pipe Attachment Weld

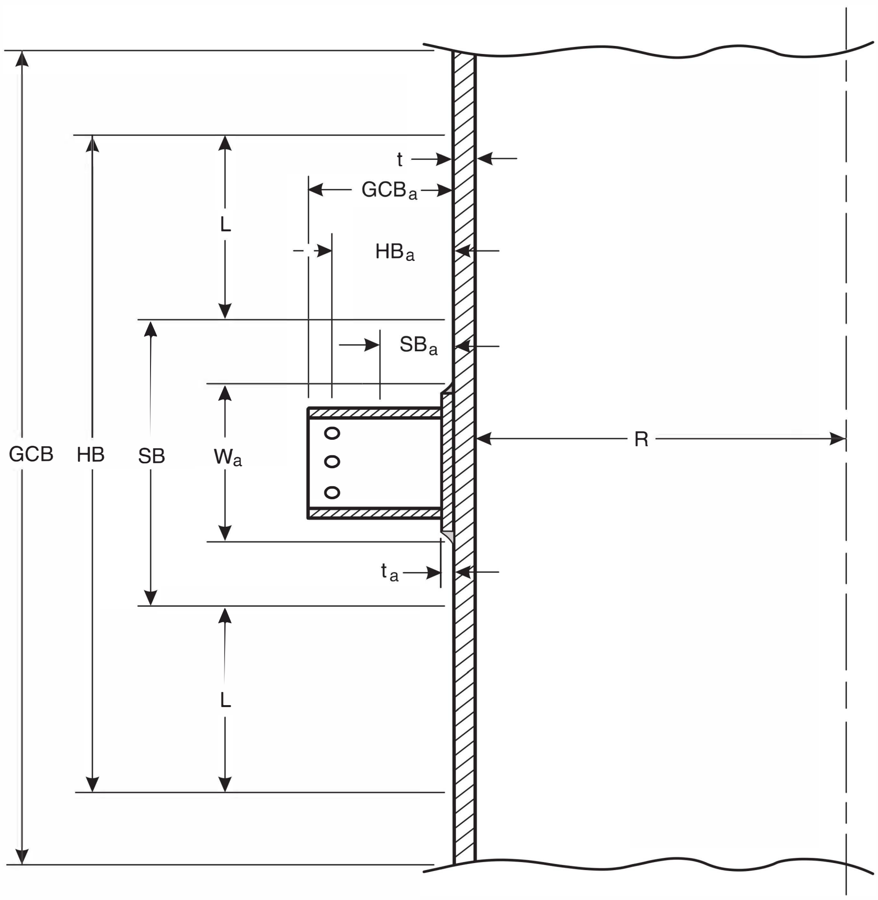


Note: It is recommended that the entire nozzle be included in the soak band unless there are technical reasons to justify otherwise.

Nomenclature:

- W_n = Widest width of nozzle attachment weld.
- SB = Soak band on pipe (width of the volume of the material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as W_n plus a multiple of t on each side of the weld attaching the nozzle to the pipe).
- SB_n = Soak band on nozzle. The minimum width is typically specified as a multiple of t_n beyond the widest width of the weld attaching the nozzle to the pipe.
- L, L_n = 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, or both).
- t, t_n = Nominal thickness of piping or nozzle neck.
- R, R_n = Inside radius of piping or nozzle neck.

Figure 6.6—Local 360-Degree Band PWHT Practice for Nozzle to Pipe Attachment Weld



Note: It is recommended that the entire attachment be included in the soak band unless there are technical reasons to justify otherwise.

Nomenclature:

W_a = Widest width of attachment weld.

SB = Soak band on pipe (width of the volume of the material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as W_a plus a multiple of t on each side of the attachment weld).

SB_a = Soak band on structural pad/clip attachment. The minimum width is typically specified as a multiple of t_a.

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

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

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

t, t_a = Nominal thickness of piping or attachment.

R = Inside radius of piping.

Figure 6.7—Local 360-Degree Band PWHT Practice for Structural Pad/Clip Attachment Weld

Where small branch connections, 1/2 in to 1-1/2 in [12.7 mm to 38.1 mm] diameter, are welded to larger pipe sections, it may be desirable to heat the entire region as shown in Figure 6.5 using heaters with control thermocouples on the larger pipe and monitoring thermocouples on the smaller branch connection. The reasoning for this is that the amount of energy required to heat the branch is small in comparison with that required to heat the pipe.

6.6.5 Intersection With Branch Connections and Attachments not Requiring PWHT. The soak band, heated band, or gradient control band of welds which require PWHT may intersect branch connections or attachments which do not require PWHT. As a result, there may be concerns with regard to distortion, induced residual stress, or both, in the intersected nozzles, branch connections, or attachments. This is generally not a concern at the lower temperatures normally associated with hydrogen bakeout, preheat, and postheating.

In order to avoid distortion, induced residual stresses, or both, during PWHT, a good practice is to minimize the temperature gradient across the components that are intersected. This may require the application of a supplementary heat source(s) to the 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 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 extended to beyond the region of intersection. Figure 6.8 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 should be noted that although the nonspecific term "approximately uniform" is used to describe the temperature drop across the intersected component, over-zealous inspection of this temperature drop is not intended. **The aim is to maintain an "approximately uniform" temperature across the intersected component.** However, in order to provide a measurable limit, a maximum temperature drop is recommended as stated below.

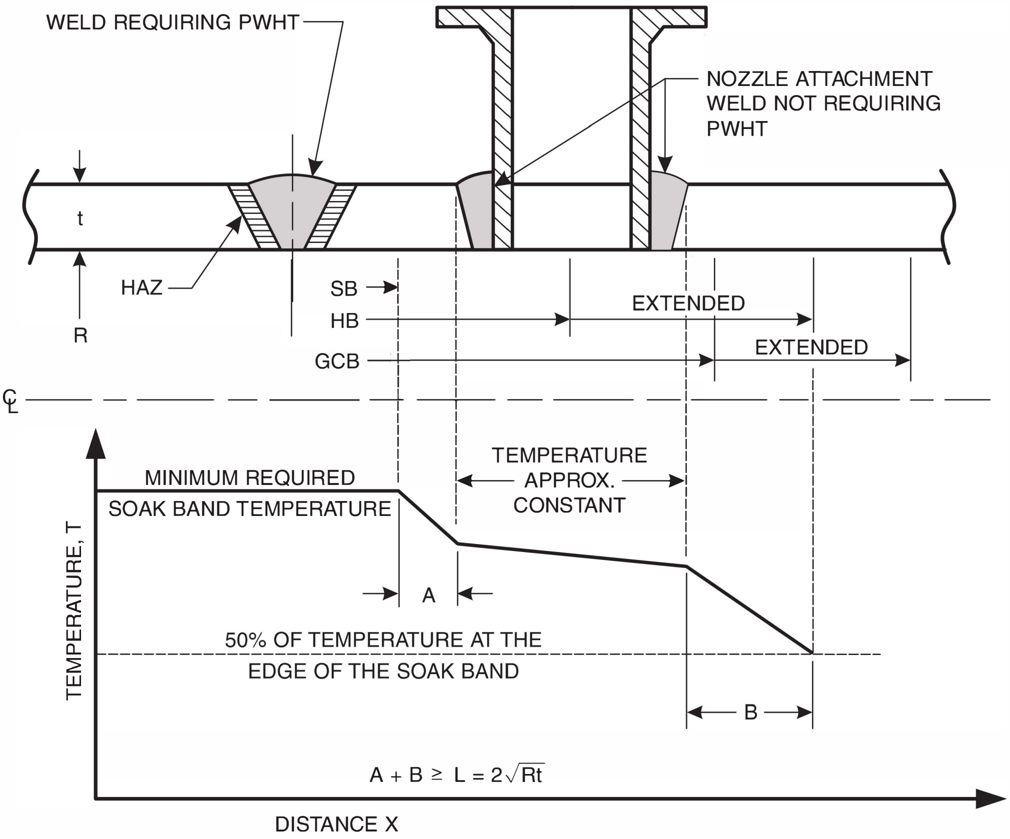
Maximum Recommended Temperature Gradient Across Intersected Component
100°F [56°C] **or** that resulting from application of the maximum permissible axial temperature gradient, $\frac{(50\% \text{ temperature at the edge of soak band})}{2\sqrt{Rt}}$, whichever is less

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

6.6.6 Proximity of Pipe-to-Nozzle Welds to Shell or Head. Local 360-degree band PWHT of pipe-to-nozzle welds may result in heating the nozzle and surrounding shell or head section to temperatures such that concerns arise with regard to distortion and induced stresses. There is generally less concern regarding the proximity of pipe-to-nozzle welds when the nozzles are attached to piping. This is due to the thinner wall thickness and smaller diameters, which result in greater flexibility. In addition, there is generally not a concern at the lower temperatures normally associated with hydrogen bakeout, preheat, and postheating.

7. Local Spot PWHT

Applications may arise where it is more practical to apply local PWHT that does not consist of a 360° band. Such situations are more commonly associated with pressure vessels. A typical situation involves attaching a small diameter nozzle to a large diameter pressure vessel. Because this generally involves heating a circular or elliptical area, it is often referred to as local spot PWHT.



Notes:

1. The nozzle attachment weld shown as "not requiring PWHT" does not imply that such a weld would not require PWHT. It simply means that it does not require PWHT now. For example, it may have previously received PWHT.
2. The intent is to maintain an "approximately constant" temperature across the intersected component. However, a maximum temperature drop of 100°F [56°C] **or** that resulting from application of the maximum recommended axial temperature gradient, whichever is less, is permitted.

Nomenclature:

SB = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as 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, or both).
t = Nominal thickness of pipe.
R = Inside radius of pipe.

Figure 6.8—Example of One Approach When the Heated Band from a Weld Requiring PWHT Intersects a Weld Not Requiring PWHT

The following subclause provides a brief discussion regarding the applicability of such PWHT practices. Because of the smaller diameters associated with piping, local 360° band heating practices make the most sense since they can more easily be designed to control induced stress and do not impose significant economic or implementation penalties. In addition, the costs associated with analysis/assessment to justify local spot PWHT should be weighed against the cost of performing 360° band heating.

7.1 Requirements in Fabrication and Repair Codes. The cited fabrication codes do not provide an allowance for local spot PWHT, nor do many pressure vessel codes. One international pressure vessel code provides specific requirements for PWHT of a local area around nozzles or attachments on spheres or dished ends. ASME Section VIII (for pressure vessels) allows local spot PWHT.

API 570, *Piping Inspection Code*, (subclause 7.2.2.2) explicitly allows local spot PWHT on piping provided that certain precautions and requirements are applied. In general, these precautions and requirements include:

(1) Review and development of a procedure by a piping engineer;

(2) Consideration of various factors such as expected strains/distortion, material properties, thermal gradients, etc.;

(3) Using a minimum preheat temperature of 300°F [149°C];

(4) Soak band should extend at least 2t beyond the weld;

(5) Monitoring by a suitable number of thermocouples;

(6) Supplementary heating of intersected branch connections or attachments; and

(7) Not allowed if the objective is environmental cracking resistance.

Although not explicitly stated in NBIC, alternative methods of PWHT per section RC-1103 (which are assumed to include local spot PWHT) may be used if acceptable to the Authorized Inspector.

7.2 Basis for Current Practices. Published work regarding local spot PWHT appears to be limited to spherical vessels or heads (Reference A13). Published and unpublished work has generally utilized a circular or elliptical heated band with radial sizing and temperature gradient control based upon a function of $\sqrt{Rt}$. Furthermore, various unpublished work has concluded that the application of such local spot PWHT on nonspherical surfaces generally has a greater likelihood to produce undesirable distortion, residual stress, or both. Therefore, the application of generalized rules for local spot PWHT of nonspherical surfaces has not been recommended. Instead, each application involving local spot PWHT of a nonspherical surface should be evaluated on its own merit.

7.3 Experience or Analysis to Justify Use. The acceptability of local spot PWHT to nonspherical components should be determined on a case-by-case basis. Generally, such PWHT is **not** considered appropriate when thermally induced stresses are a concern.

Documented experience of previously successful local spot PWHT can be used for justification. Such documented experience should involve sufficiently similar components (configuration, geometry and dimensions) and service conditions in order to judge the applicability. Citing previous successful local spot PWHT experience in which the dimensions and configuration of the components were identical, but had different service conditions (such as the new application involving stress corrosion cracking, while the previous did not), is generally **not** recommended.

The approach outlined in API 570 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 570. The evaluation should include the effect of all significant or major structural discontinuities (such as nozzles, attachments, and branch connections) and any mechanical loads, which may be present during PWHT within the gradient control band.

8. Measurement of Temperature

It is necessary to measure temperature during heating operations and frequently required to produce a continuous permanent record of the temperature during the heating cycle. Temperature-indicating crayons and paints, thermocouples, resistance temperature detectors (RTDs), infrared instruments, bi-metallic switches, expansion bulbs, or other temperature sensitive devices may be selected to measure the temperature, depending upon the application and required accuracy. Although temperature can be measured using these various methods, temperature-indicating crayons/paints and thermocouples are most common for local heating.

8.1 Temperature-Indicating Crayons and Paints. Temperature-indicating crayons and paints are of compositions that 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 crayons or paints with appropriate melting temperatures, one can determine that the temperature is above the one that melts and lower than the one that does not melt. The surface of the work should be accessible for the use of these materials. As a result, this generally limits the applicability to preheat.

While it is possible to use such a manual approach if proper attention is exercised, it should 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 should only be considered for preheat.

Temperature indicating crayons or paint offer the advantages of low cost and simplicity and are suitable for most preheat. The use of thermocouples is recommended for hydrogen bakeout, postheating and PWHT.

8.2 Selection of Thermocouples. A thermocouple consists of a dissimilar wire pair in electrical contact with each other on a hot surface (hot junction) while the other end of the pair is in contact with a cold surface (cold or reference junction). 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. The voltage difference is 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 configured for that combination.

A more complete discussion of thermocouples and their use is given in ASTM manual MNL 12 (Reference A14) and ANSI standard MC96.1 (Reference A15). Of the seven combinations of thermocouple wire classified and discussed in these documents, two are commonly selected for local heating operations. Their classification, nominal composition, upper temperature limits, and color coding are shown in Table 8.1. 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. When selecting a thermocouple type, it is important to ensure both its appropriateness for the intended service (e.g., temperature) and that the temperature control and recording instruments are configured to accommodate it.

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 should 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 (Reference A16). The size of wire commonly used in local heating (with attachment by capacitor discharge welding) is #20 American Wire Gage (AWG), which has a diameter of 0.032 in [0.81 mm].

Table 8.1
Thermocouple Data

Type	Nominal Composition	Normal Upper Temperature Limit	Positive Color	Negative Color
J	Iron–Constantan	1400°F [760°C]	White	Red
K	Chromel–Alumel	2300°F [1260°C]	Yellow	Red

Note: To facilitate correct polarity termination in the USA, the color red is used for the covering on the negative side of both thermocouples and extension leads, regardless of the thermocouple type. It should be noted that other countries may use a different color convention. However, the negative lead is always magnetic.

The wires should be electrically insulated from each other and from any other conductor, such as the metal being heated, except at the hot junction. Wire pairs with high temperature insulation, sheathed thermocouple assemblies, ceramic beads, or similar systems accomplish such separation. It is important that the thermocouple, insulation material, and construction withstand the temperatures and environments to which they will be exposed.

8.3 Installation of Thermocouples. Any controlling or recording instrument reads the temperature at the junction (short or point of electrical contact) between the thermocouple wires closest to the instrument. Therefore, the wires should "touch each other" or be in electrical contact only where the temperature is to be measured. At all other locations, electrically insulate wires from each other and from the pipe being heated. If these wires are not insulated, electrical shock or short circuit can result. Therefore, if bare thermocouple wire is twisted together, the temperature being measured will be that at the closest twist to the instrument instead of the surface where the thermocouple wires were attached.

In order to make the hot junction have the same temperature as the surface whose temperature is being measured, this requires that:

(1) The hot junction is thermally insulated from external radiant heat (this may require application of insulating material),

(2) The thermocouple wire be kept under insulation for approximately 6 in [150 mm] to prevent heat conduction along the wire (the effect is expected to be minor for thin gauge wire),

(3) The hot junction be in intimate contact with the surface whose temperature is being measured, and

(4) Thermocouple and thermocouple lead mechanical connections which could create a high-resistance junction and thus an error in readings be minimized and securely connected.

Note that significant errors can be caused if the junction is not in contact with the surface or the wires are in electrical contact outside the hot junction (such as results from twisting bare wire together away from the 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 thermocouples attached by capacitor discharge welding. 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 (Reference A11) that capacitor discharge 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 needed to reduce the effect of radiant heating and thereby improve the accuracy of the temperature readings.

Several methods may be used to attach the thermocouple to the surface and form the junction; each having advantages and disadvantages. The nature of local heating is such that the thermocouple is generally between the workpiece and the heat source. The recommended thermocouple attachment method for use with such heating is to attach each wire separately to the surface of the workpiece by capacitor discharge welding, with the wires in close proximity (~1/4 in [6 mm]) to each other. Figure 8.1 provides a schematic depiction of the equipment used to directly attach thermocouples by capacitor discharge welding. A recommended procedure for attachment by capacitor discharge welding is provided in Annex D.

ASTM Manual MNL 12 specifically recognizes the directly attached, separated junction method (see 9.2.2). Figure 8.2 is an adaptation of a figure from the ASTM manual, which depicts this attachment method. The directly attached, separated junction method is characterized in the ASTM manual (Reference A14) as follows:

(1) A series of two junctions,

(2) Has the advantage that the junctions form a part of the surface,

(3) Measures a weighted mean of the two individual junction temperatures, and

(4) Attach the two wires as close together as possible to minimize error from temperature differences.

The ASTM manual (Reference A14) further states that "This type of junction has been shown to be more accurate than a bead junction." A bead junction typically involves joining (by welding) the two ends of the wire to form a bead.

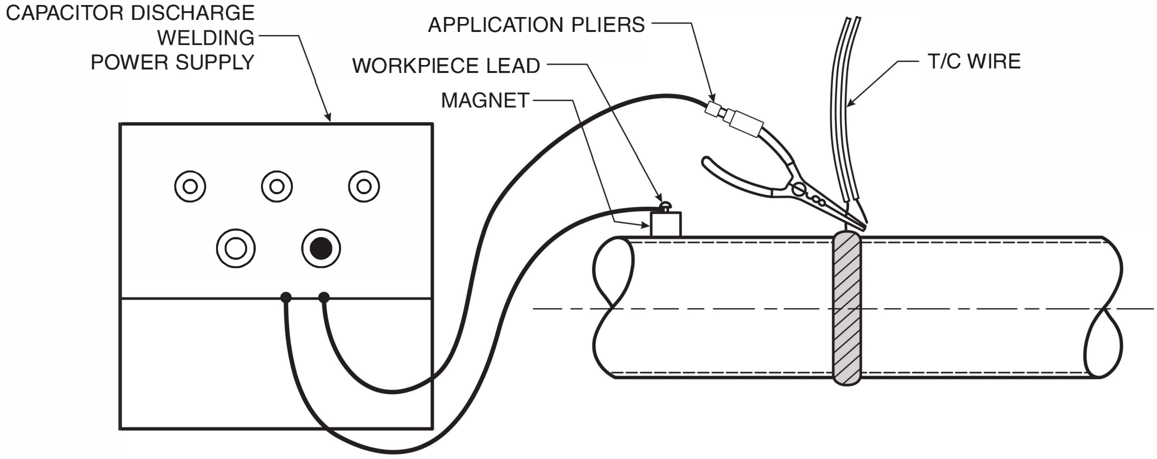
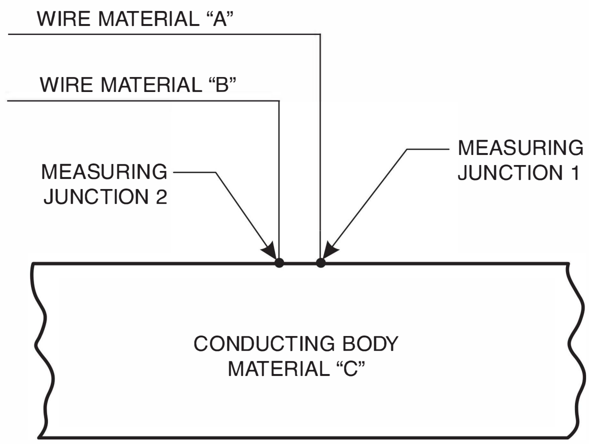


Figure 8.1—Schematic Representation of Equipment Used to Directly Attach Thermocouples by Capacitor Discharge Welding



Source: Adapted from ASTM MNL 12-4th, *Manual on the Use of Thermocouples in Temperature Measurement*, Figure 9.3, ASTM International.

Note: The maximum recommended spacing between measuring junctions 1 and 2 is 1/4 in [6 mm].

Figure 8.2—Schematic Representation of the Direct Attachment, Separated Junction Method for Thermocouple Attachment

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. For such mechanically attached thermocouples, the temperature at the junction may not represent the temperature of the metal surface due to the configuration of the attachment and the proximity of the heat source. 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 have been reported (Reference A19) to be ~130°F [72°C] greater than those of capacitor discharge welded thermocouples reading 1292°F [700°C]. Another source reports (Reference A11) that "stainless steel sheathed thermocouples secured to the pipe wall with a welded clip consistently reported temperature values 30°F to 40°F [16°C to 22°C] above the temperature reported by thermocouple junctions welded to the pipe wall by capacitance discharge." The data reported (Reference A11) for these stainless steel sheathed thermocouples were taken during PWHT in the temperature range of 1100°F to 1200°F [593°C to 649°C].

Fabrication codes such as ASME B31.1 (subclause 127.4.9), B31.3 (subclause 330.1.3), and ASME Section III (subclause 4311.2) provide a special allowance for attachment of thermocouples by low energy (usually limited to 125 W-sec [joule]) 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 covering with insulation or application of heat. Slight pulling on the attached thermocouple wires is an effective way to ensure 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. **Therefore, installation of a spare thermocouple is strongly recommended.** This is especially important for PWHT where the higher temperatures preclude access during heating. Duplex thermocouple/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.

8.4 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.

8.4.1 Control Thermocouples. The location of control thermocouples should be based upon the nature of the heat source, location(s) of heat source(s), and the component being heated. In general, control thermocouples should be located at the point of highest expected temperature for the zone. Specific recommendations are provided in 6.6 with regard to the need for additional control thermocouples (control zones) to effectively deal with issues such as thickness differences. The objective of control thermocouples is to ensure that appropriate heat is supplied to regions (control zones) to achieve the temperatures required in these regions. 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, in the middle of the center heater of the control zone.

8.4.2 Monitoring Thermocouples. Monitoring thermocouples should be placed to ensure that all of the parameters specified to control the local heating operation are being achieved. In addition, they should be placed to measure the maximum and minimum anticipated metal temperatures. 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 heated band (heat source). Additionally and if accessibility permits, it is always good practice to locate thermocouples on the surface opposite to that of the heat source (i.e., inside surface of the pipe) for one sided heating, to ensure that the required temperatures are achieved throughout the thickness. Additional thermocouples should be used whenever differences in thickness or component geometry occur. The use of monitoring thermocouples represents a cost-effective means to ensure 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 dissimilar heat sinks are present.

ASME B31.1, B31.3, and ASME Section III do not provide any specific guidance with regard to the placement of thermocouples or other measuring devices. For PWHT, BS 2633 requires that thermocouples be placed so as to ensure that a band at least 1.5t wide on each side of the weld is at the soak temperature.

Table 8.2
Recommended Locations of Monitoring Thermocouples for Local 360-Degree Band PWHT

Location	Purpose
Centerline of weld	Ensure that the maximum temperature is not exceeded since this represents a likely location for such an occurrence
Edge of the soak band	Determine if the minimum temperatures have been achieved throughout the soak band
Edge of the heated band	Determine if the maximum allowed temperature drop (maximum axial temperature gradient) has been exceeded

Note: Thermocouples should be placed around planes at these locations. The number of thermocouples in each plane would depend upon the specific component size, configuration, and geometry.

It is recommended that monitoring thermocouples be placed around planes located as described in Table 8.2. 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.

8.4.3 Examples of Thermocouple Locations. Figures have been used to provide examples of the recommended thermocouple locations for common local 360-degree band PWHT applications. In some instances, both monitoring and control thermocouples have been shown. Figures 8.2 through 8.6 provide recommended monitoring and control thermocouple locations for PWHT of butt welds in horizontally oriented piping with 1, 2, 3, and 4 zones of control. Figure 8.7 provides recommended monitoring thermocouple locations for PWHT of a weld attaching a branch connection to pipe (as shown in Figure 6.5), but can also be used for nozzle and attachment welds as shown in Figures 6.6 and 6.7.

The location of monitoring thermocouples for 360-degree band hydrogen bakeout, preheat, and postheating would be the same as for PWHT (Table 8.2), with one exception. Thermocouples would generally not be required at the edge of the heated band since the axial temperature gradient is not monitored at the lower temperatures normally associated with these processes. As discussed above, the number and location of control thermocouples would be dependent upon the number of control zones and heating method.

Control and monitoring thermocouple locations for local spot PWHT would have to be based upon the specific temperature gradient and other requirements identified in the written procedure, as justified by analysis or experience.

8.5 Thermocouple Extension Wires. Usually, the temperature controlling or recording 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°F to 390°F [0°C to 199°C] (Reference A23). In the ANSI designation system, thermocouple extension wires have the letter "X" included in their designation. For example, thermocouple Type K (chromel–alumel) uses thermocouple extension Type KX. The plug and socket connectors used for thermocouple wire to extension wire, extension wire to extension wire, and extension wire to measuring instrument connections is typically constructed using extension grade material.

In designing the extension cable system, the engineer should select an extension cable wire gauge that will minimize the loop resistance for a given length of wire. A typical rule of thumb is not to exceed 600 ft [182.9 m] of 20 gauge type K extension wire. For further discussion of this issue, refer to Annex D or manufacturer's literature (Reference A17). Because of the low voltage generated by the thermocouple, typically millivolts, the extension cable should not be run with power cables such as 480 volt alternating current (mains) that could induce noise.

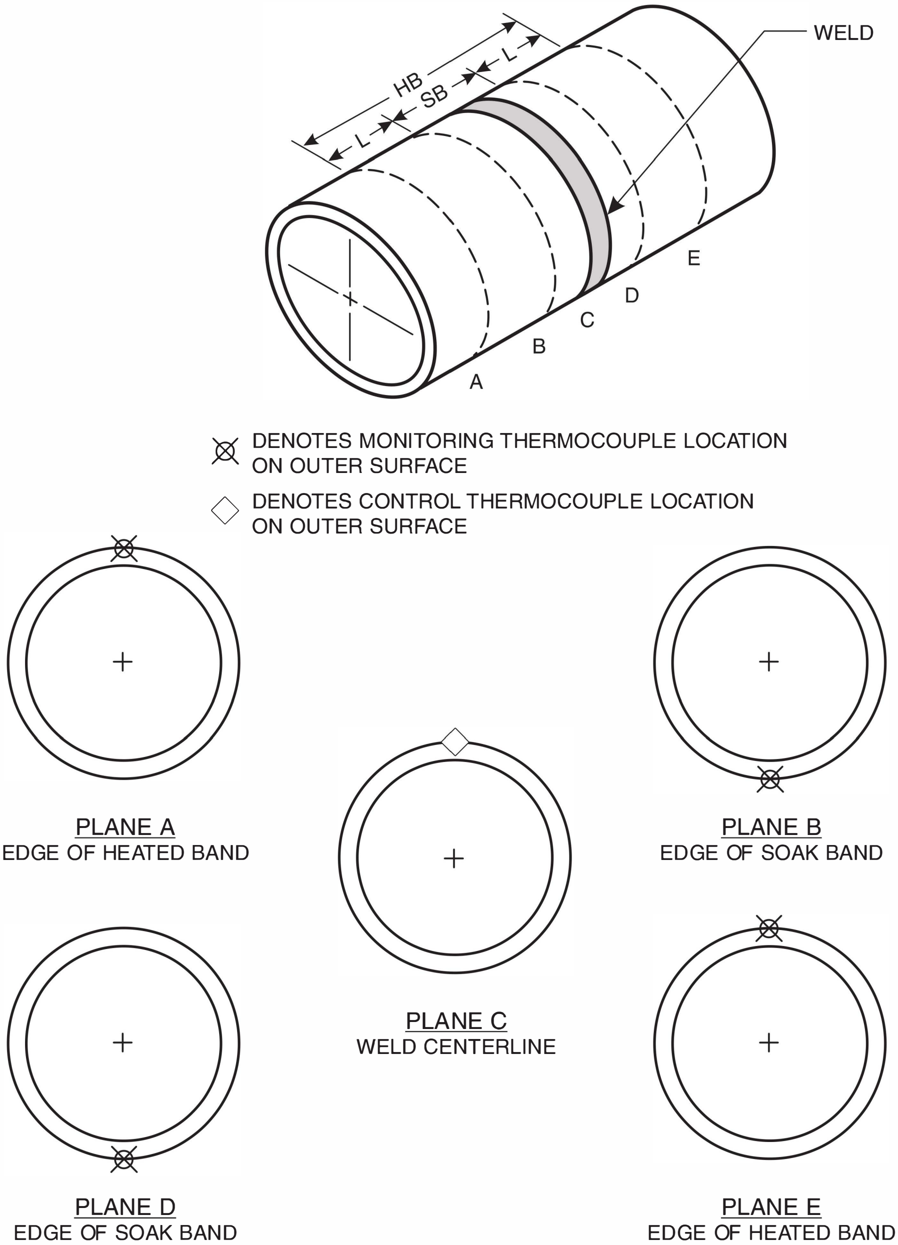


Figure 8.3—Minimum Number of Thermocouples (Monitoring and Control) Recommended for Local 360-Degree Band PWHT of a Butt Weld for Piping in the Horizontal Position with Pipe Size up to NPS 6 [DN 150] and One Control Zone

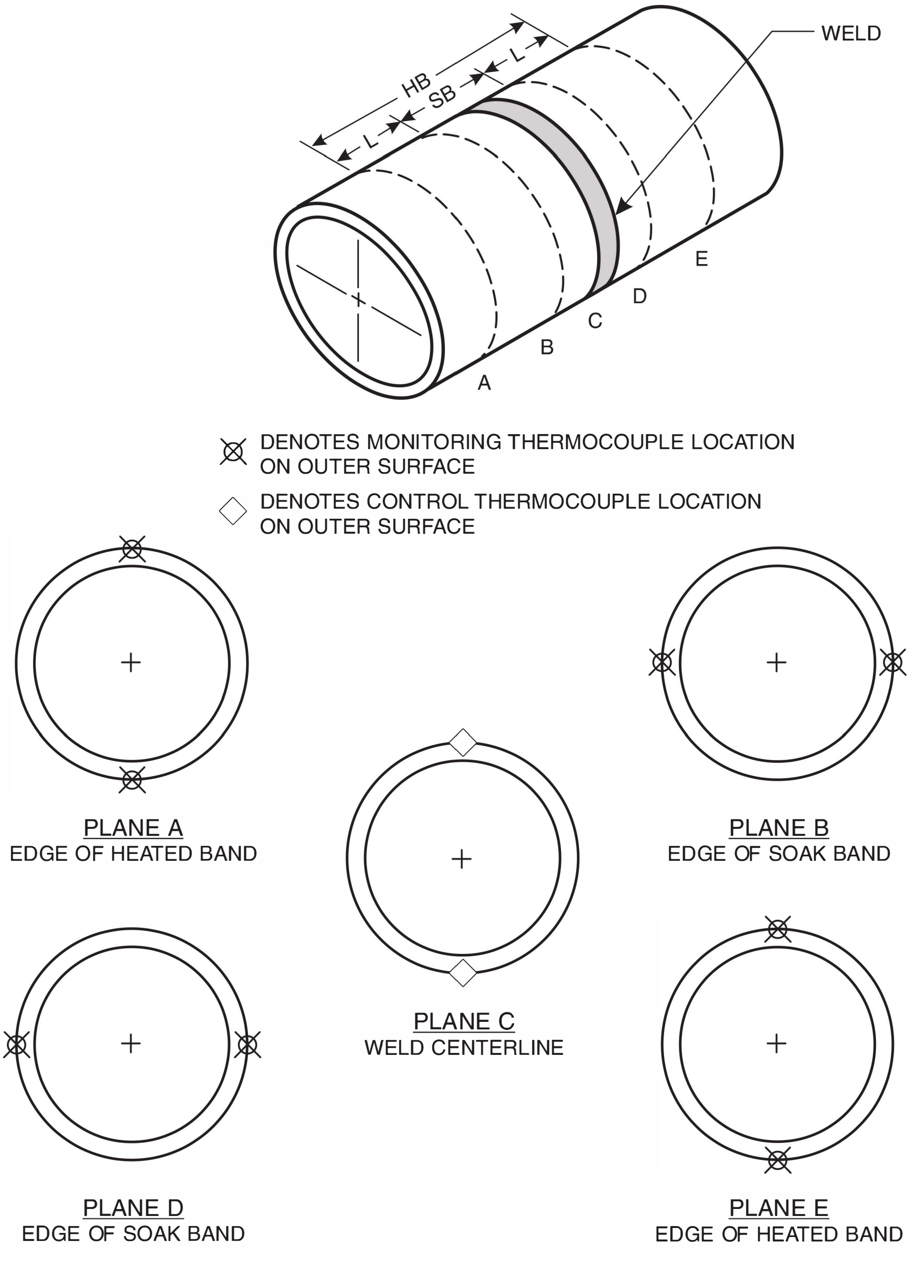


Figure 8.4—Minimum Number of Thermocouples (Monitoring and Control) Recommended for Local 360-Degree Band PWHT of a Butt Weld for Piping in the Horizontal Position with Pipe Sizes of NPS 8 and up to NPS 12 [DN 200 to DN 300] and Two Control Zones

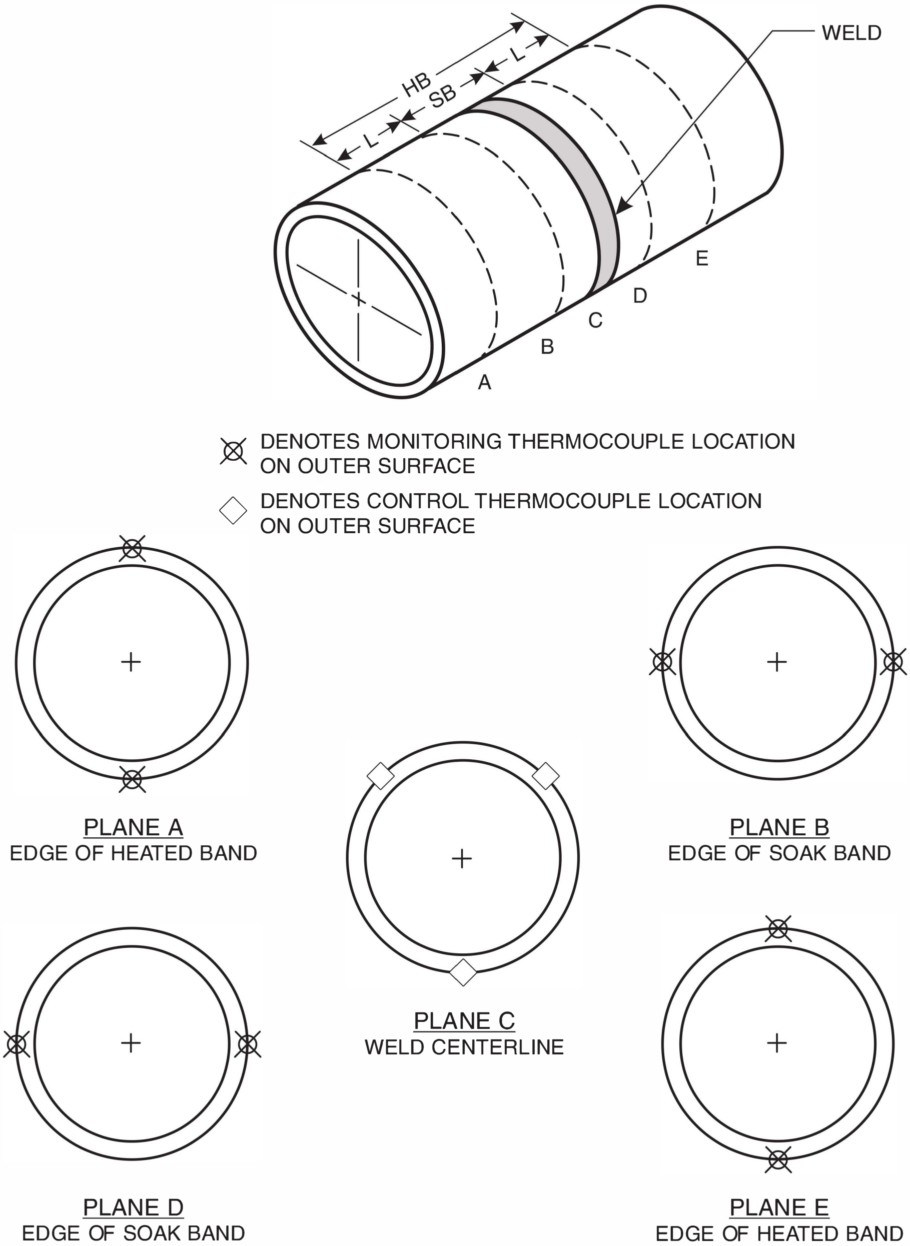


Figure 8.5—Minimum Number of Thermocouples (Monitoring and Control) Recommended for Local 360-Degree Band PWHT of a Butt Weld for Piping in the Horizontal Position with Pipe Sizes from NPS 14 and up through NPS 18 [DN 350 to DN 450] and Three Control Zones

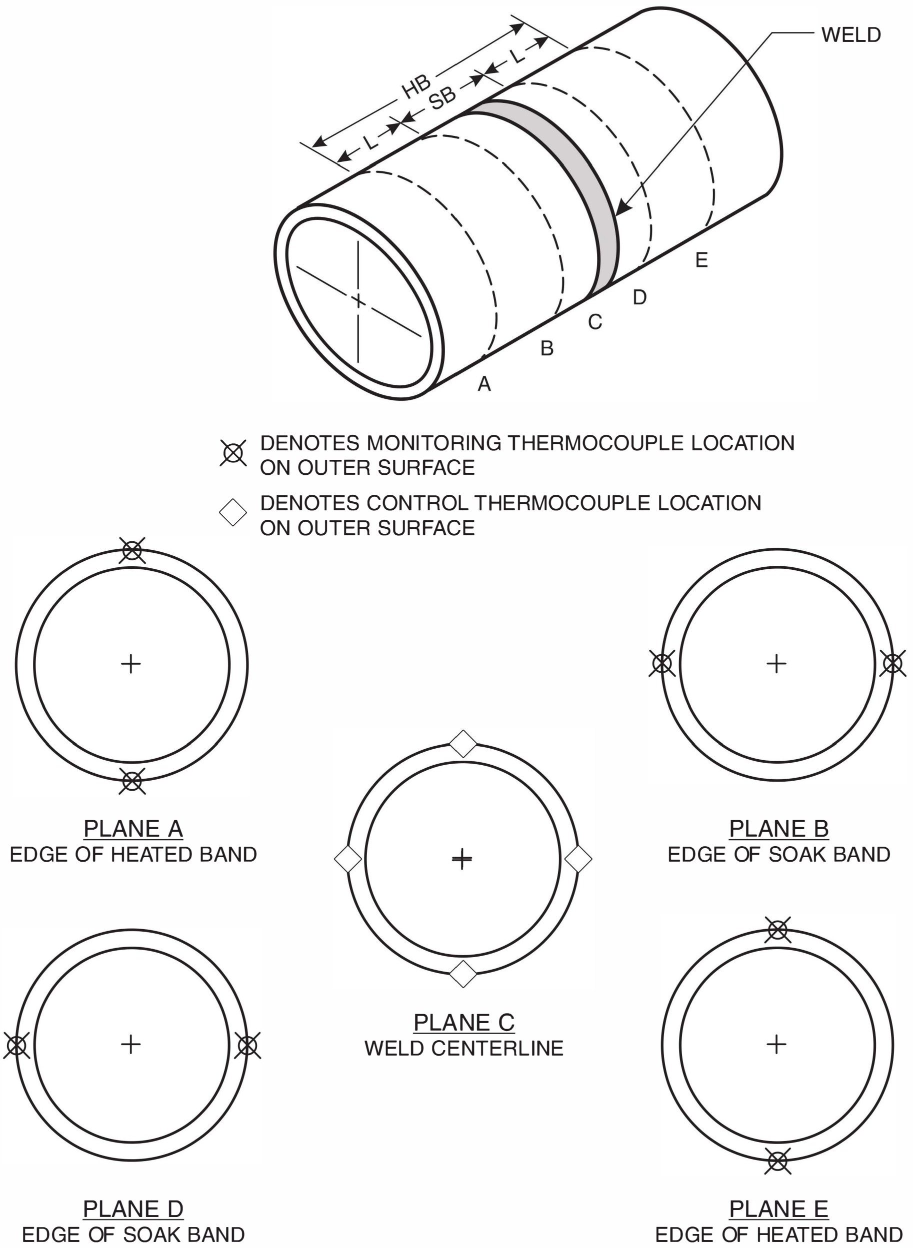


Figure 8.6—Minimum Number of Thermocouples (Monitoring and Control) Recommended for Local 360-Degree Band PWHT of a Butt Weld for Piping in the Horizontal Position with Pipe Sizes of NPS 20 and up to 30 NPS [DN 500 to DN 750] and Four Control Zones

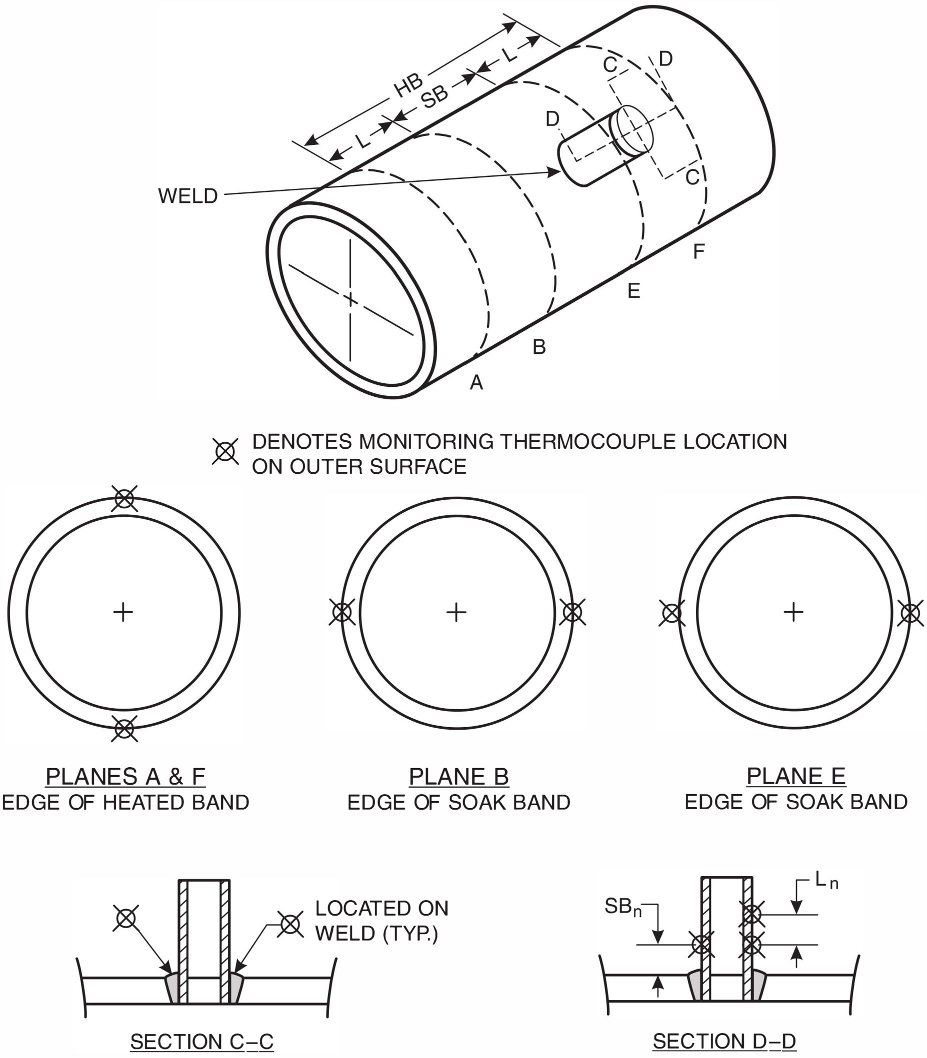


Figure 8.7—Minimum Number of Monitoring Thermocouples Recommended for a Branch, Nozzle, or Attachment When Heating in Accordance with Figures 6.5, 6.6, or 6.7

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 should 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 [305 m]. A shield system with an integral drain wire is also recommended. The drain system should only be grounded at one location to prevent ground loops (Reference A18).

8.5.1 Polarity Reversal. Care should be exercised to prevent a polarity reversal. The most likely situation for a polarity reversal occurs when thermocouple or extension wire is being terminated to a connector. Care should be taken to terminate the positive side of the thermocouple wire to the positive side of the connector and the negative to the negative (and likewise for extension wire termination). To facilitate correct polarity termination in the USA, the color red is used for the covering on the negative side of both thermocouples and extension leads, regardless of the thermocouple type. It should be noted that other countries may use a different color convention. However, the negative lead is always magnetic. To minimize the likelihood of polarity reversals, different diameter plugs and sockets are used on the negative and positive of the connector, with the negative having the larger diameter. **Convention is for the red lead to be terminated to the larger diameter plug or socket.** When checking for polarity reversal, use the mnemonic device **BIG-RED-NEGATIVE** as a guide. It should be noted that the plugs and sockets on the connector are not color coded. Generally, a thermocouple plug and socket connection can only be made with the incorrect polarity if excessive force is used, thereby providing an indication of a polarity reversal. It is also important to check for polarity reversal during setup prior to the start of the heating cycle. In the **Standard Procedure for Local Heating** provided in Annex G, step G8 specifically requires a check for polarity reversal. Such a check would typically involve energizing the circuit (e.g., powering the heaters and control/monitoring instruments) and observing whether a downscale reading (negative) occurs when the temperature should be increasing. It should also be noted that a downscale response from a control instrument will cause the heaters to be energized. Therefore, failure to find and correct a polarity reversal prior to the start of the heating cycle could result in excessive heating rates and over-temperature conditions during the heating cycle.

8.5.2 Double Polarity Reversal. A double polarity reversal is more difficult to identify. A double reversal consists of polarity reversals at two separate locations such that one reversal counteracts or restores the incorrect polarity caused by the other. While the measuring instrument sees the correct polarity (and does not provide a downscale response), the section of the extension wire between the reversals does not have the same resistance as the adjacent wire. The effect of a double reversal on the measured temperature depends upon the length of wire present between the locations of the individual polarity reversals. This is because as the length increases, the contribution from the section of wire with different resistance has a greater effect. Therefore, it may be difficult to detect a double polarity reversal by observing the temperature controlling or recording instruments.

It is important to check for double polarity reversal during setup, prior to the start of the heating cycle. In the **Standard Procedure for Local Heating** provided in Annex G, step G8 specifically requires a check for double polarity reversal. Such a check would typically involve visual inspection of terminations and plug to socket mechanical connections. **While it may be possible to detect a double reversal by visual inspection, prevention by careful attention during terminations and mechanical connection of plugs and sockets is more desirable.**

8.6 Temperature Control and Recording Instruments. The voltages produced by the thermocouples are sent to two types of instruments:

(1) Temperature controllers, which have been programmed to turn on and shut off the heat source at a specific temperature or follow a specific heating rate, holding temperature and time, and cooling rate, and

(2) Recorders, which document the thermocouple temperature at specific times during the heating cycle.

It is recommended that temperature control and recording instruments be operated in an upscale burnout mode such that they read maximum scale in the event of a break (at the junction, in the thermocouple or extension wire, or at the plug/socket connections). Such an upscale response to a break prevents the heater from being energized.

Instrumentation incorporating an isolated input design should be used to avoid erroneous readings when utilizing multiple grounded thermocouples. An instrument without isolated inputs will cause an "averaging" effect among the thermocouple inputs as well as a slower response time to reach a full burn-out condition due to an open circuit junction.

In addition to strip chart type recorders, data acquisition systems enable capture of data on electronic media.

8.6.1 Potentiometers. Temperature control and recording instruments generally contain a potentiometer. 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 15.6 regarding control of inspection, measuring, and test equipment.

Stray alternating current, especially high frequency currents, can cause errors. AC rejection filters in the input circuit of the instrument can reduce these errors.

Galvanometer instruments are also still in use. These instruments need to be connected to an external fixed resistance loop. Therefore, extension leads should be of sufficient length to compensate for the resistance loop.

8.7 Accuracy of Thermocouple Temperature Measurements. A number of factors determine the overall accuracy of a thermocouple temperature measuring system. They include sensor, system connections, and instrumentation error contributions. A detailed discussion of these factors is provided in Annex E. When using a type K thermocouple attached by capacitor discharge welding, the overall accuracy of the system (including sensor, system connections, and instrument error contributions) is estimated to be ±5°F [±2.78°C] if proper calibration and installation techniques are used. This correlates well with recently reported work in which the accuracy was reported to be ±4.5°F [±2.5°C] (see Reference A11).

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 Clause 14.

9. 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:

(1) Conduction through the heated structure itself,

(2) Radiation from the inner surface,

(3) Natural convection from the inner surface,

(4) Convection from the inner surface via moving air within the piping (chimney effect), and

(5) Conduction, radiation, and convection from the outer surface of the pipe 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 from radiation and natural convection from the inner surface are addressed by controlling the size of both the heated band and gradient control band and, if possible, use of internal insulation. Heat losses due to the chimney effect are best addressed by closing off the ends of the piping as discussed in 9.3. Insulation is 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 pipe to reduce the through-thickness temperature gradient which results from radiation and convection heat losses from the inner surface.

9.1 Classification of Insulation. Fibrous insulation, such as commonly used for local heating, is generally classified by attributes which include fiber type, construction, and 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 should include fiber type, construction, density, and thickness. As previously discussed in 6.3, specifying insulation based upon the thermal resistance (R-value) is a convenient method to indicate thermal performance independent of thickness and conductivity. Recall that recommendations for the gradient control band width were based upon R-values of 2°F to 4°F-ft^2-hr/BTU [0.35°C to 0.70°C-m^2/W]. Therefore, when using these gradient control band width recommendations, insulation with R-values within the suggested range should be used.

The North American Insulation Manufacturers Association (NAIMA), formerly the Thermal Insulation Manufacturers Association (TIMA), has issued a publication (Reference A20) which provides standard nomenclature for describing/classifying man-made vitreous fibers.

9.1.1 Man-Made Vitreous Fibers. The first level in NAIMA's classification system differentiates between man-made and natural fibers. For example, asbestos is classified as a natural, inorganic, crystalline fiber. Man-made, inorganic, non-metallic, 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, noncrystalline 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 are usually silicate MMVF produced by continuous or discontinuous manufacturing processes.

9.2 Health and Safety Issues Regarding Fiber Respirability. Health and safety issues regarding insulation have become very significant in recent years. Specifically, the type of fiber, its size characteristics, concentration of fibers, and phase changes to crystalline form are important with regard to these health and safety issues. 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 lower lungs) has become very significant. Usage of insulation that contains respirable fibers can result in the need to use special personnel 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 among 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 continuous filament 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 continuous filament fibers can remain nonrespirable 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.

9.3 Types of Insulation. Insulation materials commonly used in local heating include: glass wool, mineral wool, refractory ceramic fiber (RCF), and recently continuous filament fiber. Asbestos is no longer used or recommended. Table 9.1 provides a summary of the important characteristics of these materials. A detailed discussion regarding the four types of insulation is presented in Annex F.

RCF insulation with a density of 6 lbs/ft^3 to 8 lbs/ft^3 [96.1 kg/m^3 to 128.1 kg/m^3] is commonly used. A 1 in [25 mm] layer is generally used for temperatures up to 1200°F [649°C], while a 2 in [50 mm] (two each 1 in [25 mm]) layers are used for temperatures above 1200°F [649°C]. The R-values for these two thicknesses are within the range of 2°F to 4°F-ft^2-hr/BTU [0.35°C to 0.70°C-m^2/W]. Therefore, when using these thicknesses with the recommended gradient control band widths, axial temperature gradients are expected to be within the maximum permissible.

9.4 Attachment of Insulation. Ideally, insulation pieces should be cut so that the ends butt against themselves when the piece(s) are wrapped around the pipe. 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 banding or tie wire. Other attachment techniques such as insulation pins, which are capacitor discharge welded to the pipe, and magnetic clamping may be used depending upon the circumstances. Galvanized material shall never be used for insulation attachment. For magnetic clamping, the temperature at the location of the magnet should be well below the Curie temperature, which is approximately 1418°F [770°C]. This is the temperature at which ferromagnetism is lost and the magnets cease to hold. Generally, magnetic clamping is only used for preheat. When multiple layers of insulation are used, seams should be staggered to minimize the possibility of gaps.

The insulation should normally extend well beyond the edge of the heated band to diminish heat losses and ensure that the permissible maximum axial temperature gradient from heated to unheated sections is not exceeded.

Table 9.1
Comparison of the Characteristics[a] of Commonly Used Insulation Materials

Insulation Type	Potential for Respirable Fibers	Maximum Usage Temperature	Crystalline Transformation Temperature	Thermal Conductivity	Relative Cost
Glass Wool	Present due to manufacturing process and if transformation to crystalline state with subsequent fracture into smaller size. Loss of binder facilitates fibers becoming airborne.	840°F [450°C]	Above maximum usage temperature	>Mineral wool and RCF	Low cost outer layer
Rock and Slag (Mineral) Wool	Present due to manufacturing process and if transformation to crystalline state with subsequent fracture into smaller size. Loss of binder facilitates fibers becoming airborne.	1200°F [649°C]	1337°F–1517°F [725°C–825°C]	<Glass wool; >RCF	Lowest
Refractory Ceramic Fiber (RCF)	Present due to manufacturing process and if transformation to crystalline state with subsequent fracture into smaller size.	2000°F [1093°C]	1832°F [1000°C]	<Glass wool; <mineral wool	>Glass or mineral wool
Continuous Filament Fiber	Manufacturing process allows production of nonrespirable fibers. Respirable fibers can be present if transformation to crystalline state with subsequent fracture into smaller size.	2012°F[b] [1100°C]	1832°F[b] [1000°C]	Depends upon composition	Expensive; multiple use important

[a] As reported in Reference A20.
[b] Assumes high purity silica.

10. Other Considerations

Additional issues to consider when performing local heating of pipe include structural integrity, the presence of internal liquids, internal convection, and thermal expansion.

10.1 Structural Integrity. Structural integrity is generally a concern only at the higher temperatures associated with PWHT. There are two issues that should be considered when performing a structural integrity evaluation to determine the acceptability of a proposed PWHT for piping. Both are a direct result of the reduction in yield strength that occurs during PWHT. These include:

(1) Does the piping have sufficient strength at temperature to be self-supporting?

(2) Will the piping experience an unacceptable permanent distortion?

The stresses caused by the loads acting on the piping during PWHT should be compared to its strength at PWHT temperature. The source of the loads to be considered can be classified as resulting from either dead weight or external forces. The primary concern during the performance of PWHT is whether or not the piping will be self-supporting while at elevated temperature. Dead weight is normally the source of the load that should be considered. Unacceptable permanent wrinkles or sag and, in rare cases, collapse can occur as a result of dead weight loads. Piping components that are not self-supporting will require temporary external supports during PWHT. On large diameter piping, internal spiders may also be required.

External forces are generally addressed by unbolting flanged connections to prevent moment or piping system loading, insuring that supports are free to slide and move with the piping, and accommodating thermal growth as discussed in 10.4. When it is not possible to address such external forces by eliminating them, their contribution to the stresses acting on the piping must also be considered and compared to the strength of the pipe at PWHT temperature.

10.2 Internal Liquids. The presence of liquids, even in small amounts, can prevent the soak band from reaching the desired temperature. One tell tale indicator of water being present in piping is the thermocouples near the bottom of the pipe will only be able to be heated a few hundred degrees. Sometimes the thermocouples will rise and fall as the water is boiled out, condenses, and drains back into the area being treated. If combustible liquids or residues are present, fire, explosion, or both, may result. It is therefore necessary to remove internal liquids and prevent the flow of liquids inside the pipe while it is being heated. However, adequate venting should be used to ensure that there is no pressure buildup within the pipe. All venting should be dampened to prevent air from flowing through the pipe, causing undesirable heat losses.

10.3 Internal Convection. Natural convection can cause circulating air flow within otherwise sealed off sections of piping. It must therefore be recognized that closing valves, blinding flanges, and other techniques to seal off a section of piping will not prevent this form of natural convection. The resulting circulating air flow can cause undesirable heat transfer on the inside surface of the pipe. For pipe in the horizontal position, this can result in significant temperature differences between the 12:00 outside surface and 6:00 inside surface positions as discussed in Annex B. Such losses are best addressed by internal insulation (if possible) and adequate heated band and gradient control band widths.

Natural drafts can occur when the flow of air is possible through parts of a piping system that are not sealed off. This is often referred to as the chimney effect. Such flow can result in considerable convection losses on the inside surface of the pipe. It is therefore desirable to close valves and manways, blind flanges, erect bulkheads, and use other means to prevent such air circulation.

10.4 Thermal Expansion. Large thermal stresses can be developed during PWHT if adequate provisions to permit thermal growth are not made. Typically this requires that connecting piping be unbolted at their flanges and that the piping supports be permitted to slide and move with the piping as it grows.

Depending upon the service temperature, piping is normally designed to accommodate some degree of thermal expansion. However, it is desirable to verify whether the pipe will be able to accommodate the expansion associated with the local heating cycle. To the extent possible, the pipe should be free to expand in all directions (axially, radially, and circumferentially). Piping supports should be free to expand. It may be necessary to release or modify such existing supports to accommodate expansion. An example of the amount of growth due to thermal expansion is provided below.

Example of Growth When Heating from 70°F to 1100°F [21°C to 593°C]
Carbon or low alloy steel pipe Diameter = 24 in [610 mm] Heated band width = 24 in [610 mm] Growth in diameter = approximately 0.2 in [5 mm] Growth in length = approximately 0.2 in [5 mm] plus contribution from gradient region

11. Thermal Cycle

It is important to control four aspects of the thermal cycle associated with heating operations (both furnace and local). These include temperature uniformity, the heating rate above a specified temperature, the specified hold temperature and time, and the cooling rate above a specified temperature.

Temperature uniformity is the aspect of the thermal cycle that has received the least amount of treatment by the cited fabrication codes. Concern with regard to temperature uniformity is generally aimed at only PWHT because of the lower temperatures associated with hydrogen bakeout, preheat, and postheating. ASME Section III is the only cited code that provides specific requirements regarding temperature uniformity during PWHT.

Control of heating and cooling rates is typically associated only with PWHT, since the temperatures for hydrogen bakeout, preheat, and postheating are frequently below the specified temperature which triggers control requirements. ASME B31.1 and B31.3 require heating and cooling rate control above 600°F [316°C], ASME Section III requires control above 800°F [427°C], and BS 2633 requires control above 752°F [400°C].

The cited 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 pipe is a source of stress. As thickness increases, the gradient will increase for a given heat input. Therefore, limits upon rates of heating and cooling are frequently specified as a function of thickness.

The effects and benefits produced during hydrogen bakeout, postheating, and PWHT are time-temperature dependent. However, 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 targeted effects are produced in reasonably short time periods (as opposed to selection of longer times at lower temperatures). This helps to limit the variability of the outcome. Further discussion of the issues associated with the use of longer PWHT times at lower temperatures can be found in 11.3. The effects and benefits from preheat while deriving some benefit from time, are primarily dependent upon temperature.

11.1 Temperature Uniformity. Requirements regarding temperature uniformity are generally specified separately for the heating/cooling and hold portions of the PWHT cycle. ASME Section III limits temperature variation during heating and cooling to not more than 250°F [139°C] within any 15 ft [4.6 m] interval of weld length. This limit generally acts as a circumferential temperature gradient due to the fact that it is most often applied to heating of circumferential butt welds. The requirement in B31.3 that states "The heating method shall provide the required metal temperature, metal temperature uniformity,…" does not provide useful guidance. 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.

Concerns about temperature uniformity during PWHT are related to the resulting stresses and possible distortion or cracking which could occur as discussed in 11.2 and 11.4. Use the lesser of the maximum temperature differences shown below or that provided in the governing document for PWHT.

Maximum Recommended Temperature Differences for PWHT
During heating and cooling, the maximum temperature difference within the heated band should be 250°F [139°C] **or** as limited by the maximum axial temperature gradient.
During hold, the maximum temperature difference within the soak band should be 100°F [56°C] **or** the allowed temperature range, whichever is less.
During hold, the maximum temperature difference around any circumferential plane within that portion of the heated band outside of the soak band should be 100°F [56°C].

11.2 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 through-thickness temperature 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 no cracking results, high rates of heating may be tolerable since associated residual stresses are relaxed during the hold period.

Table 11.1 compares the maximum allowed rates of heating during PWHT for ASME B31.1, B31.3, ASME Sections III and BS 2633. Maximum heating rates of 400°F to 600°F/hr [222°C to 333°C/hr] are allowed by these codes. Recently reported (Reference A11) work has concluded that heating rates of 800°F/hr [444°C/hr] divided by the thickness in inches can be safely applied as long as the heated band width is large enough (i.e., based upon $H_i \geq 2.5$). For the lesser of temperatures above 800°F [427°C] or that specified in the governing document, use of the lesser of the maximum heating rate shown below or that provided in the governing document for PWHT is recommended.

Maximum Recommended Heating Rate for PWHT
600°F/hr [333°C/hr] divided by the thickness in inches, **provided** that the recommended heated band width in Clause 5 is used **and** experience or analysis demonstrate that the resulting distortion or levels of residual stress are acceptable for the service environment.

11.3 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, the heating portion of the PWHT cycle can also make a contribution to the hold period, especially at slow rates of heating.

Table 11.1
Comparison of Maximum Rates of Heating and Cooling During PWHT

Fabrication Code	Maximum Rate of Heating	Maximum Rate of Cooling
ASME B31.1	Above 600°F [315°C], the rate of heating shall not exceed 600°F/hr [333°C/hr] divided by 1/2 the maximum thickness of material in inches at the weld, but in no case shall the rate exceed 600°F [333°C]; 600°F/hr [333°C/hr].	600°F/hr [333°C/hr] divided by 1/2 the maximum thickness in inches at the weld above 600°F [315°C]; 600°F/hr [333°C/hr] maximum; further restrictions for specific materials. (See Table 132 in B31.1 for cooling rate requirements for P-Nos. 7 and 10I materials.)
ASME B31.3	Above 600°F [315°C], the rate of heating shall not exceed 600°F/hr [333°C/hr] divided by 1/2 the maximum thickness of material in inches at the weld, but in no case shall the rate exceed 600°F/hr [333°C/hr].	600°F/hr [333°C/hr] divided by 1/2 the maximum thickness in inches at the weld above 600°F [315°C]; 600°F/hr [333°C/hr] maximum; further restrictions for specific materials. (See Table 331.1.1 in B31.3 for cooling rate requirements for P-Nos 7, 10I, 11A, and 62 materials).
ASME Section III, Subsection NB	400°F/hr [222°C/hr] divided by the maximum thickness in inches above 800°F [427°C]; 100°F/hr [56°C/hr] minimum; 400°F/hr [222°C/hr] maximum.	400°F/hr [222°C/hr] divided by the maximum thickness in inches above 800°F [427°C]; 100°F/hr [56°C/hr] minimum; 400°F/hr [222°C/hr] maximum; further restrictions for specific materials.
BS 2633	Depending upon the material, diameter and thickness, rates can vary from 11,250°F/hr [6250°C/hr] divided by the thickness in mm to 396°F/hr [220°C/hr] above 752°F [400°C].	Depending upon the material, diameter and thickness, rates can vary from 90°F/hr [50°C/hr] to 495°F/hr [275°C/hr] above 752°F [400°C].

The cited fabrication codes do not provide any guidance with regard to hydrogen bakeout and minimal guidance with regard to postheating. Minimum preheat 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 2633 provides 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 hydrogen bakeout and postheating. This is due to the fact that thickness determines the diffusion path. 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 ensure that the full thickness achieves the minimum required temperature. While it is recognized (Reference A21) 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 ensure achievement of the minimum temperature through the wall thickness.

It is recognized that for certain materials, prolonged time at PWHT temperature can reduce tensile and yield strength and increase the fracture transition temperature. ASME Section III requires 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 cycles. When determining the total expected time, manufacturers attempt to account for that normally associated with manufacturing, repairs during manufacturing, and an allowance for repairs or modifications after the piping is in service.

In addition to total time at a single temperature, it may also be necessary to account for multiple PWHT cycles at different temperatures. It also may be desirable to account for the effects of the heating and cooling portions of the PWHT cycle, especially for slow heating rates. An approach, based upon the Larson-Miller parameter, for determining a single test specimen PWHT cycle equivalent to several at different temperatures is reported (Reference A22).

As a result of concerns about deterioration of properties, various situations may arise when it would be desirable to shorten the PWHT hold time. For example, unexpected repairs during manufacturing or service may cause the total time at PWHT temperature to encroach upon the time which has been demonstrated (through test coupons) to provide acceptable properties. Justification for using shorter hold times may be desirable in such situations. Accounting for the effect of slow rates of heating and recognizing that the desired benefits are achieved in a short time once the minimum temperature is achieved throughout the thickness could be used for justification.

ASME B31.1, B31.3, and ASME Section III allow longer times at lower temperatures for PWHT of certain materials, while BS 2633 does not. 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 for PWHT and the service environment.

Whenever hardness reduction is targeted, for example due to the service environment, care should 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. This is discussed further in 12.3.

11.4 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. Residual stresses are generated as a result of temperature differences (resulting from fast cooling) which are sufficient to induce thermal stresses in excess of the yield strength. As temperature decreases, the yield strength of the material increases and as a result, the material can accommodate faster rates of cooling. This is the basis for fabrication codes establishing temperatures below which cooling rate control is not required. Depending upon the code, temperatures in the range of 600°F to 800°F [316°C to 427°C] are generally considered sufficiently low enough to avoid inducing residual stress as a result of fast cooling rates. The technical basis for the specific code maximum cooling rates and temperatures below which controls are not required is not known. It is most likely that they were established based upon successful past experience.

The cooling rate may also affect mechanical properties such as impact toughness and corrosion resistance. For subcritical PWHT, cooling rate can affect the final hardness due to the contribution of equivalent hold time. However, cooling rate is the least effective parameter to adjust in order to accomplish this aim.

In some instances, procedures have specified slower cooling rates because of a desire to ensure greater hardness reduction. The **most effective method** to accomplish greater hardness reduction is to increase the hold temperature. Increasing the hold time has less of an effect and can be accomplished in three ways. The most desirable and controllable approach is to simply increase the hold time. Since it appears that more of a contribution to equivalent hold time is derived from the heating portion of the cycle, decreasing the rate of heating would have a greater effect than decreasing the rate of cooling. Therefore, the order of preference to accomplish greater hardness reduction would be:

(1) Increase hold temperature,

(2) Increase hold time,

(3) Decrease heating rate, and

(4) Decrease cooling rate.

Note that decreasing the rate of cooling is the **least effective method** for producing greater hardness reduction.

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. ASME B31.1 and ASME Section III provide additional cooling rate requirements for these materials.

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 11.1 compares the maximum allowed rates of cooling during PWHT for ASME B31.1, B31.3, ASME Section III, and BS 2633. Maximum cooling rates of 400°F to 600°F/hr [222°C to 333°C/hr] are allowed by these codes. For the lesser of temperatures above 800°F [427°C] or that specified in the governing document, use of the lesser of the maximum cooling rate shown below or that provided in the governing document for PWHT is recommended.

Maximum Recommended Cooling Rate for PWHT
500°F/hr [278°C/hr] divided by the thickness in inches, **provided** that the recommended heated band width in Clause 5 is used **and** experience or analysis demonstrate that the resulting distortion or levels of residual stress are acceptable for the service environment.

12. 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. It would be highly desirable to prepare corrective action procedures for these deviations and train all affected personnel in their use.

12.1 Thermocouple Failure. This deviation is a concern during all of the purposes for heating. 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), the PWHT operation should be aborted with an acceptable cooling rate to reattach the thermocouples. 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.

12.2 Heat Source Failure. This deviation is a concern during all of the purposes for heating. 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.

12.3 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. Exceeding the maximum heating rate is generally a concern for only PWHT, while a heat source failure is a concern during heating for all of the purposes.

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. There is generally no need to return to ambient temperature and restart the heating. The principal concern with regard to exceeding the maximum heating rate is distortion resulting from excessive temperature differences in the component. An assessment of the distortion would have to be made at the completion of the PWHT cycle, after returning to ambient temperature.

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.

12.4 Interruption During Hold Period. This deviation is of most concern for PWHT, but can also be a concern for the other purposes. 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 should be to correct the cause of the interruption. Heating is then restarted at a rate appropriate for the temperature of the pipe 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 should be equal to or greater than the minimum required.

When the temperature exceeds the maximum for the soak period, the first response should 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 temperatures based upon either data for material groups/specifications or knowledge of composition and use of an empirical formula. Table 129.3.1-1 in ASME B31.1-2020 provides a convenient source of data by material P-No, while work reported by Andrews (Reference A23) is a well known source for empirical formulae. However, such information is generally not available at the time of the temperature excursion.

The following is recommended if it is suspected that the lower critical temperature has been exceeded. The temperature should be reduced to the soak range at a cooling rate no greater than the maximum allowed and should be held for the full required period, regardless of any time previously accumulated at the hold temperature. This is done to ensure adequate tempering of any material that 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, or other tests to determine if properties such as tensile strength and notch toughness were adversely affected. If properties have been adversely affected, a structural integrity assessment would be required.

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. Even though the lower critical temperature is not exceeded, material properties may still have been adversely affected and require a structural integrity assessment. For example, such a situation would occur if the tempering temperature of the base metal were exceeded.

12.5 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. Concern with regard to exceeding the maximum cooling rate is associated with distortion or introduction of residual stress, or both. If distortion occurs, it would have to be assessed after returning to ambient temperature. Exceeding the maximum cooling rate or failing to exceed the minimum cooling rate are generally a concern for only PWHT.

The following response addresses concerns regarding the introduction of residual stress as a result of cooling rates that exceed the maximum allowed. The first response should be to correct the cause of the interruption. It is recognized that cooling rates faster than those allowed in the various cited fabrication codes may be used without causing distortion or excessive residual stress. However, it may require analytical or experimental assessment to justify the use of faster cooling rates. The need for such justification would more likely occur for critical components and when stress driven environmental cracking mechanisms were operative. As a result, the most expedient approach may be to simply repeat all or a portion of the hold period. However, as discussed in 12.6, this should only be done when concerns do not exist regarding excessive hold times.

To repeat all or a portion of the hold period, heating should be restarted with a heating rate appropriate to the temperature of the piping 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 a short period (one hour or less) 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 materials such as ferritic stainless steel, a fast cooling rate (specified as a minimum rate) may be required to avoid embrittlement or other undesirable metallurgical reactions. For such materials, the interruption or deviation would result if the cooling were less than the minimum required. 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 pipe 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 ensure 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.

12.6 Excessive Heating or Hold Times During PWHT. Certain materials may have their properties adversely affected by prolonged times during the heating or hold portions of the PWHT cycle. The adverse effects of slow cooling (resulting in prolonged time in an undesirable temperature range) on certain materials were discussed in 12.5. The typical causes for a deviation associated with excessive heating or hold times, inadequate or faulty equipment or setup, would generally not result in prolonged cooling times since the equipment could simply be switched off.

There is no definitive answer regarding what constitutes excessive or prolonged heating or hold times. A frequently asked question is "How many times can PWHT be applied without causing undesirable effects?" Unfortunately, there is no simple answer, such as three, to this question. It depends upon the specific thermal cycles (temperatures and times), material (composition of weld metal and base metal, heat treated condition of the base metal), governing properties (toughness, etc.), and the response of the weld metal, HAZ, and base metal. Evaluation of available data or testing of specimens, which simulate the PWHT time-temperature conditions, may be required to determine suitability.

It must also be recognized that the governing codes or specifications may not identify prolonged heating or hold times as a deviation. While some codes may require testing of specimens that have been exposed to 80% or more of the time at the hold temperature, the time spent heating is not considered. Frequently, as long as maximum heating rates are not exceeded and minimum time at the hold temperature is achieved, a deviation is not considered to have occurred.

A common cause for prolonged heating or hold times is the use of inadequate equipment or improper setup. There simply may not be enough heaters or power to achieve the minimum temperature in a reasonable time, if at all. As a result, it may take excessively long to heat to the minimum temperature. Likewise, one or more thermocouples in a multiple zone PWHT may not reach temperature while the remainder are already at temperature. Excessive hold times result from waiting for these thermocouples to reach temperature. A common cause for this is omission of supplemental heaters on heavier wall sections. Faulty control or power equipment could also result in an excessive number of interruptions during heating or hold, leading to prolonged time, as discussed in 12.3 and 12.4.

If recognized early, the best response to a deviation associated with excessive heating or hold times is to change the setup or equipment. This obviously requires aborting the PWHT cycle, returning to ambient temperature and would typically result in a schedule delay. As a result, it may be difficult for the heat treatment contractor to acknowledge what is actually occurring. The outcome of failure to acknowledge this problem is often a futile attempt to achieve temperature, which could result in excessive heating, hold time, or both. If prolonged heating or hold time is recognized after its occurrence, the only recourse is to assess the material condition. The best way to prevent such deviations is to follow adequately designed and approved procedures with equipment that has been properly maintained and calibrated.

13. Considerations Related to Service Environment

The cited fabrication codes generally do not address heat treatment relative to 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 that relate to the specific service environment. The practices cited in this document, NACE SP0472, *Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments*, and API 945, consider environments such as wet H_2S, caustic, and amine.

ASME B31.1 and ASME Section III do not provide guidance regarding service environment, other than with respect to brittle fracture considerations. As previously discussed, BS 2633 does recognize the need for different PWHT thermal cycles for creep service or to achieve greater softening when tempering. In addition, BS 2633 includes a note which cautions the purchaser that for certain service conditions, such as those conducive to stress corrosion cracking or where high temperature/ high pressure hydrogen exposure exists, heat treatment may need to be carried out regardless of the pipe thickness.

13.1 Appropriateness of Furnace and Local PWHT. 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 heated band width for local 360-degree band PWHT are found in various recommended practices and international codes when stress driven failure mechanisms are of concern. As discussed in Annexes B and C, increasing the heated band width and decreasing the axial temperature gradient can be used to reduce the magnitude and shift the peak induced stress axially away from the weld centerline for local 360-degree band PWHT. It is generally acknowledged that the magnitude of the peak stress induced by local PWHT can be adequately reduced in the vicinity of the weld centerline by increasing the heated band width. However, concern is expressed that a stress peak of some magnitude still may occur in the adjacent base metal. Such concerns are described by the sentiment that local PWHT merely moves weld related residual stresses to another location. It can be argued that benefit is derived even if the peak induced stress has only been shifted. The benefit is that the residual stress peak is moved out of the weld metal and HAZ where there is a greater likelihood of crack initiation sites being present.

Precise knowledge of the stress thresholds associated with stress driven failure mechanisms is generally not available. Since it is difficult to accurately estimate 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 or difficult to interpret regarding the success or failure of the outcome.

It must also be recognized that the degree of stress relaxation resulting from standard furnace PWHT practices may not be adequate due to low stress thresholds for environmental cracking, such as for chloride stress corrosion cracking of austenitic stainless steel. In such cases, it may be necessary to consider the use of increased hold temperatures, times, or both, or the use of other techniques such as induction heating stress improvement (IHSI) which is discussed in 13.5.

The following recommendations are therefore offered based upon the above considerations. They are listed in descending order of preference. In all cases it should be recognized that for certain service environments, the standard hold temperatures and times may not be adequate.

(1) Whenever possible, consider heating the entire section of piping in a furnace.

(2) If heating the entire piping section is not possible, consider heating a 360° band. As a minimum, use heated band and gradient control band widths and an axial temperature gradient as recommended in Clause 6. If possible, perform an analysis to estimate the induced stress resulting from the proposed parameters and compare to the estimated threshold values for cracking.

(3) If local spot heating of a cylindrical shell such as piping is being considered, an analysis or similar previous experience should be used to establish acceptable practices.

13.2 Exemption from PWHT. Fabrication codes typically provide exemptions from PWHT based upon thickness, preheat, 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 concerns exist regarding environmental cracking.

The greater restraint associated with heavier wall thickness can result in plane strain conditions such that it is desirable to ensure 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 or hardened microstructure, or both. 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 other 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 (Reference A24) 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 (Reference A24) 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 on preheat is generally used in conjunction with thickness, weld size, or type. While preheat does slow the cooling rate during welding and thereby helps 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 as the only justification for exemption from PWHT when environmental cracking is operative.

Exemption from PWHT based upon diameter, weld type, or weld size is not appropriate when environmental cracking is operative. This is because these exemption criteria do not mitigate weld hardness or residual stress.

13.3 Tempering and Stress Relaxation Objectives. It is important that the user understand the needs imposed by a service environment to ensure 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 13.2, careful attention should be paid to ensure that the appropriate degree of tempering, or stress relaxation, or both, 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 (Reference A24) discusses this issue.

With regard to stress relaxation, the soak band should be large enough to accommodate the regions where tensile residual stresses are present. NACE SP0472 cites concern that tensile residual stresses may be present up to 2 in [50 mm] from the weld. There is also concern that local PWHT may induce stress as previously discussed in 13.1. NACE SP0472 specifically recommends that heating bands larger than required by codes be used for welds in piping with diameters greater than 10 in [25 cm]. It is assumed that this recommendation refers to the use of a larger heated band.

In addition, longer times at lower temperatures are not recommended. For example, both API 945 and NACE SP0472 contain recommendations that PWHT at lower temperature and longer time not be used. NACE 8X194 (Reference A24) cites survey results, which indicate that almost no users have employed PWHT temperature lower than 1125°F [607°C] for pressure vessels in wet H_2S service.

Another important concept is that multiple failure mechanisms may be operative. For example, both hydrogen stress cracking and alkaline stress corrosion cracking 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 ensure that areas exposed to such thermal cycles receive adequate tempering, and stress relaxation, or both. Concern is greatest when such areas occur on the inner surface with direct exposure to the process environment. However, external attachments that 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.

13.4 Hardness Testing. Hardness testing of production welds is commonly used as a quality control tool to ensure that adequate local PWHT has occurred. Such testing may be specifically aimed at insuring that adequate tempering has occurred (as measured by weld metal macro-hardness) during PWHT to mitigate hydrogen stress cracking. NACE 8X194 (Reference A24) reports survey results and states that "This (hardness) testing has been shown to identify gross misuse of welding consumables 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 ensure reasonable accuracy, portable field hardness measurements should be performed in accordance with recognized industry standards. ASTM A833–84 (Reference A25) provides requirements for Brinell hardness testing by comparison methods. NACE SP0472 requires the use of this ASTM practice and provides (in its 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 (Reference A24) states "There does not presently exist 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; 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.

The Welding Institute (TWI) has conducted several group sponsored projects to evaluate 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, indentation spacing, and the need for a large number of measurements, with statistical assessment of data.

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 or qualification of a specialized welding procedure, is necessary. Qualification of the welding procedure may include the modification of preheat and welding heat input to produce the required hardness. Hardness testing of welding procedure qualification test specimens is discussed in NACE 8X194 (Reference A24). Such testing utilizes multiple micro-hardness 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 evaluate the appropriateness of hardness testing before PWHT on a case by case basis.

Hardness testing before PWHT can help in the selection of time-temperature parameters. For example, testing before PWHT may identify an unexpected weld metal, material condition, or both, 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.

13.5 Induction Heating Stress Improvement (IHSI). A specialized local heating technique was developed (Reference A26) to address intergranular stress corrosion cracking (IGSCC) of welds in austenitic stainless piping in boiling water nuclear reactors (BWRs). The objective of the technique is to induce compressive residual stress on the inside surface of the pipe in the weld area by simultaneously induction heating from the outside while water cooling the inside surface. While it appears that the primary application of this technique has been to mitigate IGSCC in BWR piping, it may provide a useful tool for addressing stress driven environmental cracking in other applications.

It has already been pointed out that concerns exist regarding the use of PWHT to mitigate chloride stress corrosion cracking in austenitic stainless steels. The concerns result from several issues. First, the threshold for the tensile stress, which causes the cracking, is considered to be below the level of stress relaxation achieved by either furnace or local PWHT. In addition, local PWHT results in axial temperature gradients which can expose regions adjacent to the soak band to temperatures which may produce undesirable metallurgical reactions such as chromium carbide precipitation and sigma phase formation. The IHSI technique avoids these concerns by inducing compressive residual stress and utilizing heating temperatures and times that do not lead to adverse metallurgical reactions.

Considerable work has been performed to develop the key parameters for the application of IHSI to austenitic stainless steel piping. Table 13.1 provides a summary of the reported (Reference A27) key parameters. It may be desirable to apply the IHSI technique to austenitic stainless steel piping to prevent chloride stress corrosion cracking or other forms of environmental cracking driven by residual stress.

Table 13.1
Summary of Key Parameters for Induction Heating Stress Improvement (IHSI)

Parameter	Controlling Range[a]	Remarks
Temperature Difference	$\Delta T \geq \frac{4\sigma_y(1-\upsilon)}{E\alpha}$	
Heating Duration	$\tau \geq 0.7\frac{t^2}{a}$	
Coil Width	$L = 3\sqrt{Rt}$	
Coil Location	x = 0.6 in [15 mm] or $t/2$	Use whichever is greater
Maximum Temperature	T_o	Must be restricted to prevent deterioration of piping material. For example, for type 304 stainless steel, the maximum recommended temperature is 1022°F [550°C]
Current Frequency		Control is not required
Pipe Size		Automatically accounted for by other parameters
Cooling Water Conditions		Sufficient to achieve required ΔT

[a] Variables:
- ΔT = Difference in temperature between outside and inside surface of pipe ($T_o - T_i$)
- T_o = Temperature on the outside surface of the pipe °F [°C]
- T_i = Temperature on the inside surface of the pipe °F [°C]
- σ_y = Material yield strength lb/in² [kg/mm²]
- ν = Poisson's ratio
- E = Young's modulus lb/in² [kg/mm²]
- α = Thermal expansion coefficient, in/in°F [m/m°C]
- τ = Heating duration (sec)
- t = Wall thickness of pipe in [mm]
- a = Thermal diffusivity in²/sec [m²/sec]
- L = Width of coil, centered on weld in [mm]
- R = Mean radius of pipe in [mm]
- x = Distance from weld centerline to edge of coil in [mm]

Source: Adapted from ANSI/ASQC Q9002, *Quality Systems—Model for Quality Assurance in Production, Installation and Servicing*, American Society for Quality Control, 1994, Table 5.1.

14. Quality Assurance System

In order to ensure that local heating operations are in compliance 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, *Quality Systems—Model for Quality Assurance in Production, Installation and Servicing*, American Society for Quality Control, provides an appropriate model for such a system.

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

14.1 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 recommended that the user audit the supplier of local heating services to determine compliance with the written quality assurance system.

14.2 Process Control. The use of written procedures and associated drawings is highly recommended since it provides greater assurance that requirements will be met. NACE 8X194 (Reference A24) cites survey results which indicate that many users have required such procedures to obtain better control of the PWHT process. It is recommended that the Standard Procedure for Local Heating shown in Annex G, or an equivalent, be used in conjunction with a drawing/sketch that specifies placement of thermocouples, heat sources (including control zones), and insulation.

14.3 Response to In-Process Deviations. Various deviations can occur during the course of local heating operations as discussed in Clause 12. The supplier of heating services should have corrective action procedures and personnel trained in their use to ensure that appropriate actions are taken in response to such deviations.

14.4 Testing. A common testing method associated with local heating is hardness testing. Such testing should be performed in accordance with an established procedure. Hardness testing is discussed in 13.4.

Hardness testing both before and after PWHT can provide a useful comparison regarding the condition of welds before and after PWHT. Since hardness testing may involve the application of an impact load, concerns regarding brittle fracture should be addressed if testing is to be performed before PWHT.

14.5 Documentation. The most important documentation associated with any heating is a record of the thermal cycle. Currently, a strip or disk chart from a recorder typically provides such a record. 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. The record of the thermal cycle should contain information such as the temperature and time scales and correspondence between thermocouple numbers on the chart and drawing/sketch.

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.

A Standard Documentation Checklist for Local Heating is available in Annex H. It is recommended that the documentation shown in this checklist be submitted at the completion of local heating.

14.6 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 that conforms to specific requirements and has been properly calibrated and maintained cannot be overemphasized. Clause 8 addresses various issues relating to temperature measurement. Detailed consideration regarding the accuracy of thermocouple temperature measurement is provided in Annex E. ANSI/NCSL Z540-1 (Reference A28) provides requirements for controlling the accuracy of measuring and test equipment.

All thermocouples/extension wire should be traceable to Certificates of Conformance. Calibration of temperature recorders should be traceable to national standards, such as those maintained by the National Institute for Standards and Technology (NIST). Hardness test bars should be traceable to Certificates of Conformance and be used such that the proper spacing is maintained between successive indentations.

14.7 Training. All personnel performing local heating should be trained in the proper use and application of the associated processes and equipment, including safety, calibration, maintenance, and inspection considerations. Documentation of such training should be maintained.

14.8 Servicing. All equipment should be serviced at appropriate intervals as recommended by the manufacturer to ensure proper performance. Documentation of such servicing should be maintained.

15. Induction Heating

15.1 General. Induction heating involves the application of alternating current (AC) to coils wrapped around the part to be heated. Because electric current has a magnetic field associated with it, a magnetic field is produced around the conductor. The magnetic field penetrates the part around which the conductor is wrapped or placed. Since the current is alternating, the magnetic field alternates in phase with the current, sweeping through the part, collapsing, and then building up in the opposite direction. A current is induced in the part because a current is produced whenever there is relative motion between a magnetic field and a conductor. Resistance to this induced current plus hysteresis loss heats the part.

As the frequency of the current in the conductor increases, the radius of the magnetic field decreases, and current is induced in the part to a lesser depth. If the frequency is high enough, only a thin skin is heated. Of course, heat will be conducted inward from this skin, so that in time the center will also be heated, but this may result in overheating the outside of the part. The potential variation of temperature with depth below the surface should be taken into account when selecting other important process parameters such as the current and number of turns of the coil.

Induction heating is fully applicable to hydrogen bakeout, preheat, postheating, and PWHT. An additional local induction heating application, IHSI, was discussed in 13.5. This technique is aimed at introducing compressive residual stress on the inside surface of pipe to mitigate failure mechanisms driven by tensile residual stress.

15.2 Effect of Composition and Temperature. Pipe capable of being magnetized (ferromagnetic) tends to contain all of the magnetic field within its wall thickness. If the pipe is not capable of being magnetized (nonferromagnetic), lines of magnetic force will not be concentrated within the wall thickness. Instead, the magnetic field will then be distributed uniformly within the space surrounding the coils (air and metal). When this is true, induction heating can still be used, but much more energy must be supplied to the coils to heat the metal because the portion of the magnetic field in air obviously does not heat the metal.

Carbon, low alloy, and other ferritic steels are ferromagnetic below their Curie point (the point at which metals are no longer ferromagnetic), which is approximately 1418°F [770°C]. They are nonferromagnetic above that temperature. Austenitic stainless steels and most nonferrous metals are predominantly nonferromagnetic at both ambient and elevated temperatures.

When the temperature of ferromagnetic material is increased above the Curie point and the lines of magnetic force are able to penetrate into the air (instead of being concentrated only within the pipe wall thickness), there is less resistance to current flow in the coils. As a result, the current in the induction coils rises suddenly. For PWHT of ferromagnetic materials above their Curie point and for all nonferromagnetic materials, it is advisable to make the coils out of hollow tubes and pass water or some other coolant through them. Another consequence of having the magnetic field no longer concentrated only in the pipe wall thickness is the need for increased energy input to raise the temperature further. To accomplish this, more turns must be applied and the equipment must be capable of providing more energy.

15.3 Coil. An induction coil setup is shown schematically in Figure 15.1. The function of the coils is to carry the current whose magnetic field will induce a current in the pipe. This heats the pipe while the coils are not heated. The electrical resistance of the coils should be low and their heat conductivity high. Copper is generally used for coils. The conductors may be in the form of bars or preformed clamps that are hinged and bolted together, contactless solid conductor split coils, hollow tubes through which water flows for cooling, or stranded cable. The hinged and bolted bars greatly reduce the cost of installing coils, but may cause problems at the connections because of overheating or arcing if they are not tightened properly. The contactless solid conductor split coils reduce installation costs while eliminating concern regarding overheating and arcing. Water cooled flexible tubing can be as flexible as the standard air cooled cable. The air cooled cable can be used where water cooling is not required. All coils must be wrapped in the same direction around the pipe and polarity must match, otherwise, their magnetic fields will be in opposition to each other and heating will be difficult, if not impossible.

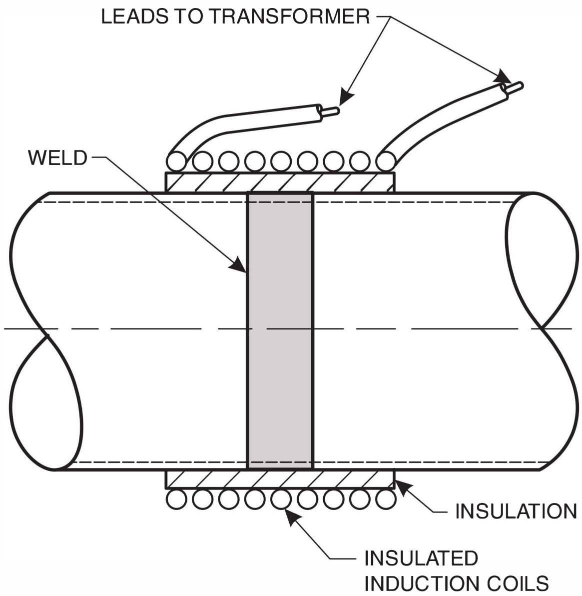


Figure 15.1—Schematic Depiction of Induction Coil Setup

15.4 Ampere Turns. The energy input to the pipe is approximately proportional to the ampere turns, which is the product of the current in the coils and the number of turns of the coil around the pipe. Both of these factors can be changed to regulate the energy input.

Current can be controlled effectively by changes in the taps on the transformer. Either the supply to the machine or the capacity of the machine determines the upper limit of the current. Either stopping or starting the flow of current or changing its frequency or amplitude, or both can also control current. Solid state, phase balanced sources are required to permit varying frequency and amplitude. A very simple but effective means of controlling the power is by means of a closed loop control system with feedback from a thermocouple attached to the pipe surface.

The amplitude of the current and the number of turns in the coils directly affect the power input. Since only the current can be conveniently varied once heating has been started, it is important to pre-plan these variables. If the applied frequency and voltage remain constant and the number of turns is decreased, the current in the coils will increase proportionately. However, for a given frequency and voltage, the number of turns can only be varied within a relatively narrow range. If too few turns are used, the current will exceed the capacity of the machine. If too many turns are used, the system may have insufficient capacity to heat the pipe to the desired temperature.

15.5 Location of Turns of the Coil. Current is induced in the pipe only in the metal under the coils. The width of the heated band is thus determined by the width of the coils. Should a wider heated band be desired, the turns can be spaced farther apart by the use of insulation between them or by leaving a gap in between the coils at the center of the heated band. Such a gap can be left because heat is conducted into this region from the metal heated on each side. When induction coils are used to preheat a joint, a gap must be provided in the coils in order that there be access for the welder. Often, the coils can be left in this position for postheating or PWHT, provided adequate insulation is used over the part of the pipe not covered with coils.

Stacking one layer of coils on top of another is not recommended, even if the coils are water cooled. Such stacking causes one layer of coils to induction heat the other layer. As such, this practice may lead to overheating the coil.

Cables and cable leads should not be coiled and should be as short as possible because additional undesirable inductance will be produced. Metal parts within coiled cables and leads can also be unintentionally heated.

When the wall thicknesses of the pipe on each side of the weld are not equal, such as where a thick-walled valve is joined to a pipe, the heat losses to the thicker valve by conduction will be significantly greater, as previously discussed in 5.6.3. The solution to this problem lies only partly in providing more insulation on the valve. More heat must be put into the valve by the use of more turns of coils on that side since the energy distribution is in proportion to the ratio of the number of turns. This would mean having more turns on the valve side. A shift of only one or two turns towards the heavier side may provide the needed change in temperature distribution.

For example, there might be six turns on the valve side and four on the pipe side. If the number of turns is increased, the extra ones are added to the side needing greater heat input. Note that adding turns will decrease the total energy input to the weld unless the current to the coils is increased. This is true because the percentage decrease in the current is greater than the percentage increase in the number of turns, so that the product of amperes and turns, which is the measure of energy input, is decreased. Therefore, increasing the number of turns decreases the total energy input, but provides more heat to the side receiving the increased number of turns. In all such cases of unequal heat losses and input, it is recommended to have separate control zones (i.e., separate coil and power supply) on each side in order to separately control current and thereby balance the temperatures more closely.

15.6 Suggestions for Setup. In this subclause, suggestions are discussed which are intended to be helpful to an operator faced with the necessity of setting up an induction heating installation. The example used assumes that the electric current is 60 Hz AC supplied by a transformer with taps on the secondary. This does not imply that other equipment cannot be used.

15.6.1 Equipment and Materials. The following equipment and materials constitute what is considered to be the minimum recommended for an effective induction heating installation:

(1) One transformer unit that has a secondary voltage of about 90 V, others may vary.

(2) Temperature controllers for closed loop feedback control from thermocouples.

(3) Input cables from the power source to the input side of the transformer.

(4) Cable leads from the transformer to the induction coils.

(5) Induction coils as necessary.

(6) Thermocouples and extension wire (see 8.2 and 8.5).

(7) A calibrated temperature recorder (see 8.6).

(8) Suitable insulation (see Clause 9).

(9) Heat resistant twine (nonmetallic material) to tie the insulation into place. Typical materials include glass tape and ceramic fiber rope.

Manufacturer's recommendation should be consulted.

15.6.2 Insulation Attachment. The insulation attachment is discussed in 9.4. Special attention is called to the need to apply insulation directly to the pipe under the induction coils.

15.6.3 Induction Coil Attachment. When attaching the coils, all turns must be wound over the insulation without touching any metal. All winding should be in the same direction. Care should be taken while wrapping to ensure that the insulation is not damaged and that the coils are neither too tight nor too loose. They should be properly spaced relative to the center of the weld so that the heated band is of the desired width and located to give an even temperature across the joint. Heat resistant twine can be used to tie the coils down and prevent shifting during operation. Micarta wedges have also been used successfully to keep the coil centered. Some smoke generation and charring of the Micarta is to be expected. Electrical insulating materials must be used to cover the connections between the coils and the cable leads and any joints within the coils.

15.6.4 Setup of Transformer. The transformer is connected to the power source with an input cable and to the coils with cable leads. The cables should be located so that no one will trip over them and so that they are not coiled.

Good safety practices should always be followed. Whenever anyone is working on coils or when heating operations are not in progress, the main power switch should be in the open position and tagged "open."

15.7 Relative Advantages and Disadvantages of Induction Heating. The relative advantages of induction heating are as follows:

(1) High heating rates are possible due to the high power density;

(2) Effective for rapid through-thickness heating since it does not rely solely upon conduction;

(3) Ability to heat a narrow band adjacent to regions that have temperature restrictions (it must also be recognized that such narrow band heating can induce stress);

(4) Local hot spots due to variations in heater watt density can be avoided more easily;

(5) The coils are relatively long-lived and less likely to fail during heating than some other equipment in the system; and

(6) The overall heating efficiency in terms of frequency conversion and coil efficiency, with correct output circuit design, can be greater than 90%.

The relative disadvantages of induction heating are as follows:

(1) The initial cost of the equipment can be higher than other appropriate heat sources; and

(2) Less ability to create control zones, especially around the circumference.

16. Electric Resistance Heating

16.1 General. Resistance heating occurs when an electric current is passed through conductors with high electrical resistance. It is commonly described as I^2R heating, where I = current and R = resistance. Manufacturers offer resistance heating elements in a wide variety of sizes and shapes to fit practically any geometry. Most are quite flexible and able to conform closely to the shape to be heated, making them useful in the shop or field. The equipment required for resistance heating includes heating elements, insulation, power supply, and temperature-monitoring and controlling devices. The degree of sophistication varies from manual operation with a single control zone (circuit) to fully automated operation with multiple control zones.

Electric resistance heating is fully applicable to hydrogen bakeout, preheat, postheating, and PWHT.

16.2 Heaters. Typically, resistance heating devices consist of high resistance conductors (hot section), low resistance conductors (cold tail), and surrounding insulators such as ceramic beads. A braid of metal capable of resisting high temperature exposure may further protect the ceramic beads. The ends of the conductors are fitted with lugs or similar devices to facilitate connection to the power circuit.

Since each heater has a limited current-carrying capacity, the current should be monitored by an ammeter. Monitoring of current is more important where multiple elements are used in control zones. In such cases, current monitoring can be used to identify the failure of an individual heating element and thereby enable remedial response to avoid the problems associated with resultant temperature gradients. The number of heaters required is governed by the mass to be heated, geometry of the area to be heated, required gradient control, the rate of heating and holding temperature, and the power rating of the individual heaters.

The following precautions are applicable for any type of resistance heater:

(1) Heaters should be matched to the output voltage characteristics of the power supply.

(2) For parallel hookups, heaters with resistances within approximately ±5% are normally used on areas where constant heat flux is desired. If newer elements are combined with older ones (whose resistance may have changed because of oxidation during use), the difference in resistance between individual heaters in a control zone should be limited to avoid nonuniform heat input.

(3) An ammeter should be used to check that the current supplied does not exceed the rating of the transformer/power supply or to identify failed heaters.

(4) All power should be turned off before heaters are connected to the power supply. This will provide for personnel safety and can prevent damage to the heater elements.

16.2.1 Finger Element Heaters. Finger element heaters are designed with dual solid nichrome conductors and a series of stacked ceramic tubular insulators that create the "fingers." These heaters fit around an entire pipe circumference or segments of a circumference. This style of conductor provides for an extremely reliable heater that has a typical current capacity limitation of 120 A. The heaters are typically powered by a welding power supply with a large number of elements in series because of the low voltage drop across each. The total amperage must not exceed that of the welding power supply.

The finger element is the forebearer of the more commonly used flexible ceramic pad heater (FCP) which is discussed in 16.2.3. Among other reasons, the increased use of the FCP can be attributed to the emergence of specifically designed power consoles that operate at a relatively common output voltage.

16.2.2 Braided Heaters. Braided heaters consist of a flexible inner core of stranded nichrome wires insulated with woven layers of high temperature yarn and covered with heat-resistant braided wire.

Braided heaters can be attached directly to the pipe with stainless steel bands and covered with insulation, or they can be placed into special wire mesh jackets with insulation to create a heating blanket. The latter makes it possible to attach the heaters and insulation to the pipe at one time. Braided heaters can be positioned either longitudinally or circumferentially around the pipe.

16.2.3 Flexible Ceramic Pad (FCP) Heaters. The FCP heater consists of a multi-stranded nichrome metal wire (hot section) joined (by welding) to a multi-stranded nickel wire (cold tail) which is inserted in ceramic beads (alumina) with pre-placed holes to form a pad. The beads for the hot section typically have two holes and are interlocking such that they can be made to contour readily to a cylindrical surface. The hot section is generally provided by manufacturers in various rectangular shapes (with a constant area) to accommodate different pipe circumferences. The length of the resistance wire generally remains constant to provide heaters with the same power density. Single hole tail beads typically emerge from the hot section. A different color tail bead generally marks the location of the weld between the nichrome and nickel wire. This allows the weld (junction between the hot and cold sections) to be placed outside the insulation. A connector is attached to the end of the cold tail. FCPs are installed in much the same way as braided heaters. A control zone typically consists of three heaters connected in parallel. Multiple control zones can be used in the axial or circumferential directions.

16.2.4 Wrap-Around Heaters. A typical wraparound heater consists of an insulated nichrome wire element surrounded on three sides by a 1 in [25 mm] thick ceramic fiber blanket housed in a stainless steel shell.

The heater is curved to fit snugly around a given size pipe. This means that each pipe size requires a different wrap-around heater. The preshaped body of the wrap-around makes it easier and faster to set up in the field. However, its rigid body design and relatively high cost limit its use to repetitive heat treatments in straight-run pipe of the same size.

16.2.5 Single-Strand (Rope-Type) Heaters. Heaters with a single conductor of stranded nichrome wire are of similar construction as braided heaters. They are available with silicon fiber insulators or ceramic beads similar to the FCPs.

Single-strand heaters can be wrapped around a pipe in much the same way as induction coils. They can also be formed into pads, including irregular shapes, to fit around and between nozzles and to compensate for unequal metal thicknesses.

16.2.6 Heater Attachment. The method of attachment of the heaters depends on the type used. Whenever the axis of the pipe is in a horizontal position and one element is used, the heater should be attached so that the center of the heater is at the bottom and the two ends are near the top. This should result in a small gap near the top of the pipe. Where multiple elements are used, gaps between elements should be evenly spaced. Once in place around the pipe, the heater(s) can be secured with a stainless steel strap or other suitable means. The application of wire in direct contact with FCP heaters is not recommended since shorting may result if the wire slips between the ceramic beads and makes contact with the conductor. Galvanized material shall never be used for heater attachment. Depending upon the circumstances, the difference in thermal expansion between the pipe and steel band may result in the thermocouples being crushed and shorted between the heater and the pipe. As a result, some allowance for expansion should be made, for example, by limiting the tightness of the band. Carbon steel bands are not recommended for direct contact with the heater since they tend to sag at normal PWHT temperatures, allowing the heaters to move. Insulation is applied over the heaters. Carbon steel wire can be safely used on the outside of insulation to secure it in place. The heaters are then ready to be connected to the power supply.

Gaps between heaters produce cold spots. The degree of temperature drop in the gaps is dependent on the width of the gap, the thickness of the material, the temperature of the material, and the length of the gap. The magnitude of the temperature drop is expected to increase as the:

(1) Width of the gap increases,

(2) Thickness of the material increases,

(3) Temperature of the material increases, and

(4) Length of the gap increases.

The metal surface under a heater is heated via conduction directly from the heater to the pipe, whereas the metal surface in the gap between heaters is heated via conduction through the pipe. The volume of heater adjacent to the gap affects the amount of temperature drop within the gap. Gaps between heaters can be accommodated with minimal temperature drop provided that they do not exceed the wall thickness of the pipe or 2 in [50 mm], whichever is less. In instances where gaps are used in excess of this recommendation, additional monitoring thermocouples should be used to ensure that the soak band achieves the desired temperature.

If braided heater blankets are to be used, care should be exercised to ensure that none of the heaters overlap the insulation as this could damage the heater. Once good fit is ensured, the blankets can be secured to the pipe, then insulation can be wrapped around the blanket and secured with wire. The heaters are then ready to be connected to the power supply.

16.3 Power Sources. Electric power needed for resistance heating can be provided by many sources, ranging from engine driven welding machines to a normal commercial supply. Either AC or DC equipment can be used. The selection of the system for any given application depends upon availability, portability, cost effectiveness, type of controllers, and matching the output voltage characteristics with the heaters.

Note: Additional precautions should be taken when using DC power supplies.

The total power requirement should be established to judge the adequacy of a power system. If sufficient power is not available, it may still be possible to successfully achieve the required temperature but at a reduced rate of heating. A detailed assessment of the power requirements for local heating would include quantifying the power required to:

(1) Heat the part at a specified rate to the desired temperature;

(2) Overcome conduction losses within the part;

(3) Overcome convection and radiation losses from sections of the part that are not insulated (both inner and outer surfaces); and

(4) Overcome conduction, convection, and radiation losses from the insulated sections of the part.

Quantifying each of these contributions to the required power is often impractical, and in some cases, impossible. A simplified, rule-of-thumb assessment of the power supply adequacy can be achieved by applying Equation (5).

$$\text{Required Power (kW)} = \frac{(M \times c_p \times R)}{(CF \times E)} \qquad (5)$$

where:

M = mass of metal to be heated (lb or kg)

c_p = specific heat (Btu/lb/°F or kJ/kg/°C)

Note: Specific heat varies with temperature. Use 0.20 Btu/lb/°F or 0.83 kJ/kg/°C for steel.

R = maximum rate of heating (°F/hr or °C/hr)

CF = conversion factor (3412 Btu/kW-hr or 3600 kJ/kW-hr)

E = insulation efficiency (use 0.4 for well insulated assemblies)

When selecting welding machines as power sources, it is important to recognize that most welding machines are rated at a duty cycle of less than 100%. For manual and semi-automatic pipe welding, which requires many starts and stops, there is no need to select equipment with a 100% duty cycle. However, when used for heating, the equipment may be continuously on line for many hours. Therefore, to prevent overloading or damaging the equipment, it is important to determine and not to exceed the current at its 100% duty cycle rating. In addition, the load voltage from the welding machine should match the design voltage of the heating elements.

The cables should not be any longer than necessary, and they should not be coiled, since both conditions reduce the availability of useful power. Ground and neutral connections to the power supply or heating circuit are to be made with cable. Use of structural steel as a conductor for a ground or neutral is not recommended.

16.4 Suggestions for Setup. The following suggestions are intended to help an operator faced with the necessity of setting up a resistance heating installation.

16.4.1 Equipment and Materials. The following equipment and materials constitute what is considered to be the minimum recommended for an effective electric resistance heating installation:

(1) Power supply, with contactor or primary switch

(2) Temperature controllers for closed loop feedback control from thermocouples

(3) Input cables from the power source to the input side of the transformer

(4) Cable leads from the transformer to the heating elements

(5) Heaters matching output voltage characteristics of power supply to provide the necessary number of circumferential and axial control zones

(6) Stainless steel banding to attach the heaters

(7) Thermocouples and extension wire (see 8.2 and 8.5)

(8) A calibrated temperature recorder (see 8.6)

(9) Suitable insulation (see Clause 9)

(10) Heat resistant twine, metal banding, or tie wire to secure the insulation

(11) Ammeter to measure current

16.4.2 Power Source. The leads should be connected with the power supply in the off position. Cable lengths should not be any longer than necessary and should not be coiled. All connections should be checked for tightness and tied off at both ends to take the strain off the heaters.

16.4.3 Startup and Operation. All dial selector knobs must be in the off or minimum output position before starting the power supply. This action will guard against an overloading which could burn out or severely damage the power supply or part. An ammeter should be used to monitor current for each control zone when the power supply is activated. The amperage should not exceed the power source rating. For variable current applications, the current should be gradually increased. For constant current, percentage-time applications adjust the percentage of time to suit the heating rate. When the hold temperature is reached the amperage or percentage on-time, depending on the type of power source, should be reduced to maintain this temperature.

At the completion of the hold period, the output (amperage from a variable current source or on-time from a constant current source) should be reduced to supply only enough current to keep the rate of cooling below the maximum specified. In some cases, the current can be shut off completely.

16.5 Relative Advantages and Disadvantages of Resistance Heating. The relative advantages of resistance heating are as follows:

(1) Standard heaters can accommodate a wide variety of part sizes and geometrical configurations.

(2) Continuous and even heat can be maintained throughout the welding operation (including during long breaks) from preheat through to postheating or PWHT.

(3) Temperature can be adjusted accurately and quickly.

(4) Welders can work in relative comfort and do not have to stop intermittently to raise preheat temperature.

(5) Nonuniform or gradient heat input can be obtained easily, such as may be required for the top and bottom halves of a pipe or where pipes are attached to heavier sections such as valves.

The relative disadvantages are as follows:

(1) Elements may burn out during a heat treatment. The possibility of this occurring is greatly reduced if elements are inspected/maintained before each use.

(2) Inadequate work practices may create the possibility for a resistance element to short itself out to the pipe, producing arcing spots.

17. Flame Heating

17.1 General. In local heating of welds with one or more flames (torches), the heating operation is much more of an art than a science. The amount and concentration of heat transferred to the weldment depends upon the:

(1) Amount of fuel consumed,

(2) Completeness of combustion,

(3) Adjustment of the flame,

(4) Distance between the flame and the weldment,

(5) Manipulation of the flame, and

(6) Control of heat losses to the atmosphere.

Flame heat has limited applicability for hydrogen bakeout, preheat, and postheating, and is not usually considered applicable for PWHT. Weldments may be severely damaged by improperly applied flame heating.

17.2 Heat Sources. Burning a fuel gas mixed with air or oxygen produces heat for flame heating. If the weldments are of considerable mass, or if the work is to be done fairly quickly, these gases should be burned with oxygen rather than air. However, the use of oxygen requires closer torch control to prevent oxidizing the steel or damage from flame impingement.

When air is used, the volume should be large enough to produce nearly complete combustion. The air may be forced into the fuel stream under pressure or, sometimes, simply aspirated into the flame.

17.3 Torch Tip Sizes. The torch tip size should be as large as is practical and convenient for the job. The larger size tips and flames not only produce more heat more quickly, but also tend to distribute it more evenly. The use of welding or cutting torch tips should be avoided since they increase the risk of burning or cutting the metal.

17.4 Heated Band. In order to get a good, even heat in the soak band, the heated band may need to be extended further than that described in 6.2. Overheating local areas should be carefully avoided. The thicker the pipe wall, the more important it is to allow sufficient time for heat to conduct through it, and it may also be advisable to apply heat to the internal surface of heavy wall pipe. It follows that it is also important when using flame heating to measure the temperature carefully and in enough regions to ensure that thermal gradients are not excessive.

17.5 Flame Adjustment. Neutral or slightly reducing flames should be used. An oxidizing flame should not be used.

17.6 Flame Attitude. The flames should be kept close enough to the pipe to get maximum heat transfer and to get the shielding effect of the flame's outer area, but not close enough to get any melting effect. The sharp, pointed, inner cones of the flames should never touch the pipe.

The flame or flames around the pipe should be manipulated so as to distribute the heat as evenly as possible. Uneven heat distribution will cause distortion, warpage, and residual stress.

On larger sizes of pipe, more than one torch should be used. This will help to distribute the heat. When more than one operator is working on the heating operation, each person's role should be planned in advance.

17.7 Protection from the Elements. The pipe to be heated must be well protected from moisture and wind.

17.8 Holding. When the weld area has been brought to the proper temperature, it can be held at that temperature with lower heat input by continuing to manipulate the torches around the pipe or by holding them at some greater distance from the pipe.

17.9 Cooling. When the weld area has been brought to the proper temperature and held there for the correct length of time, it should be covered with insulation and allowed to cool slowly.

17.10 Suggestions for Setup. The following suggestions are intended to help an operator faced with the necessity of setting up a flame heating installation.

17.10.1 Equipment and Materials. The following equipment and materials constitute what is considered to be the minimum recommended for effective flame heating:

(1) Adequate fuel supply with air or oxygen supply. Fuel supply bottles should not be drawn down at a rate that exceeds the bottle's capacity.

(2) Hoses of sufficient length to provide fuel and air/oxygen, allowing sufficient excess for manipulation of the heater around the pipe.

(3) Torch with sufficiently large tips to distribute the heat evenly.

(4) Thermocouples and extension wire (see 8.2 and 8.5).

(5) A calibrated temperature recorder (see 8.6).

17.10.2 Temperature Measurement. This and any heating process should be held to the same standards. Those standards are to ensure that the required temperatures are attained with the controls necessary to meet the objectives of the heating operation. Due to the highly variable nature of the flame heating process, it is strongly recommended that thermocouples, as described in Clause 8, be used to monitor temperature. It is recognized that current practices may not be to use thermocouples with flame heating.

17.11 Relative Advantages and Disadvantages of Flame Heating. The relative advantages of flame heating for local heating of welds are low cost and portability.

The relative disadvantages of flame heating are as follows:

(1) Minimal precision and repeatability

(2) Minimal uniform temperature distribution

(3) The great amount of operator skill it requires

(4) Risk of damaging the material

18. Gas-Flame Generated Infrared Heating

18.1 General. This method relies upon radiation as the principal mechanism for transferring heat from the source to the pipe. Fuel gas is burned with air in a specially designed burner which then radiates the energy to the pipe.

This process is applicable for preheat and hydrogen bakeout, and has limited applicability for postheating and PWHT.

18.2 Fundamentals. Infrared radiation is generated by all hot bodies and is electromagnetic in character, just as are light and radio waves. Some wavelengths are more effective in actual heating than others. Wavelengths in the range of 2.0 μm to 6.0 μm appear to be most effective.

Since infrared energy behaves just as light does, its intensity falls off as the square of the distance between the emitter and the receiver. In addition, when the electro-magnetic energy strikes a body, part is absorbed and part is reflected. Any surface modification to metals such as polish, scale, rust, and so forth, varies the reflectivity and therefore, the absorption.

Finally, since the process is one of radiation transmission, the area of the receiver that "sees" the transmitter should be as effectively disposed as possible, and losses due to stray radiation should be kept to a minimum.

18.3 Burner Arrangement. Gas-flame generated infrared burners can be flat-faced or contoured to match the shape of the part to be heated. For larger diameter parts, it is possible to use multiple flat-faced burners to approximately match the part contour.

18.4 Process Control. One of the significant virtues of gas-flame generated infrared energy is its ease of control and application. Because of the electromagnetic nature of the heat, it is transmitted from the source to the pipe or part surface instantaneously. Heat transmitted is determined by the distance between the heat source and the part being heated and by the volume of fuel generating the heat. Therefore, the only control required is that of regulating the gas flow because the distance is generally constant for a given application. Controllers for automatic regulation are available.

18.5 Sheltering of Thermocouples. Due to radiant heat transfer, it is important that thermocouples be covered with insulating putty to "shelter" them from the radiant energy. However, the amount of putty should be limited to prevent blocking too large an area from radiant heat transfer. It is expected that concerns regarding the need to "shelter" thermocouples will be eliminated for thermocouples directly attached by capacitor discharge welding. See Clause 8 for recommendations regarding thermocouples.

18.6 Suggestions for Setup. The following suggestions are intended to help an operator faced with the necessity of setting up a gas-flame generated infrared heating installation.

18.6.1 Equipment and Materials. The following equipment and materials constitute what is considered to be the minimum recommended for effective gas-flame generated infrared heating:

(1) Burners matched for the pipe size to be heated.

(2) Temperature controllers for closed loop feedback control from thermocouples.

(3) Adequate fuel and air or oxygen supplies.

(4) Hoses of sufficient length to provide fuel and air/oxygen to the burner.

(5) Thermocouples and extension wire (see 8.2 and 8.5).

(6) A calibrated temperature recorder (see 8.6).

18.7 Relative Advantages and Disadvantages of Gas-Flame Generated Infrared Heating. The advantages of gas-flame generated infrared heating are as follows:

(1) Fast response time. This method will generally allow heating at rates limited only by the need to reduce the through-thickness temperature differential in the pipe itself.

(2) Use of relatively economical fuel.

(3) Fast cool down. Little or no extra mass is brought to temperature. Thus, the part or work can cool as fast as its own heat capacity and thermal conductivity will allow, provided the procedure specification permits such rapid cooling.

(4) Quick turn-around. The expeditious setup afforded by equipment designed for specific pipe sizes coupled with rapid heating and cooling enable quick turn-around.

The disadvantages of gas-flame generated infrared heating are as follows:

(1) Initial equipment cost is high.

(2) Separate "furnaces" must either be fabricated or available for each pipe diameter.

(3) Equipment cannot be left in place during welding operations.

(4) Care must be exercised to avoid overheating the surface layer of the part due to the rapid rates of heating which are possible.

19. Radiant Heating by Quartz Lamps

19.1 General. This method relies upon radiation as the principal mechanism for transferring heat from the heat source to the work and is similar to gas flame infrared. Electrical quartz lamps radiate the energy to the work. This method can provide for accurate control of time and temperature.

The quartz lamp heating elements are usually located outside the pipe itself. The heat is radiated to the outside surface of the pipe and is conducted through the pipe thickness. Thermocouple temperature measurements are required to actuate a feedback control system.

The process is clean in the sense that no products of combustion are available to react with or contaminate the surface. There is no odor, and little waste heat, and thus, no need for forced ventilation of the working area to achieve operator comfort.

This process is applicable for hydrogen bakeout, postheating, and PWHT, and has limited applicability for preheat.

19.2 Description of the Heating Method. Radiant heating by quartz lamps is a process using electric current to heat a tungsten electrode to a temperature high enough to emit infrared waves. This temperature is in the range from 4000°F to 5400°F [2200°C to 3000°C].

The quartz lamp device is designed to encapsulate the tungsten wire with argon in an envelope of quartz. The filament electrical characteristics are such that voltages of 120, 240, or 480 V can be applied. Lamps range in length from 2 in to 38 in [50 mm to 970 mm], with the most frequent lengths, for purposes of local PWHT, being in the range of 5 in to 10 in [130 mm to 250 mm]. Thus, a 10 in [250 mm] lamp might have a voltage of 240 V, or 24 V/in [0.94 V/mm] and be conducting a filament current of four to eight amperes. This gives an input power density of 0.1 kW/in to 0.2 kW/in [3.9 W/mm to 7.9 W/mm] of lamp. The lamps can also be used at twice "rated" voltage at lower duty cycles for higher temperature applications. This gives approximately 2.7 times rated power output. However, the lower power level is adequate for most PWHT applications and will give appreciably longer lamp life. The quartz tube passes the infrared radiation with an efficiency of approximately 86 percent.

A second important part of the apparatus is the reflector, which redirects the heat and radiates in all directions, focusing it toward the work. Infrared radiation is not converted to heat until it strikes an absorbing surface. Metallic reflectors are chosen to be reflective rather than absorbent. Heat, which starts in the wrong direction, is channeled properly by reflectors, as indicated in Figure 19.1, and strikes the work material. The process is aided if the work material is not too reflective. That is, the reflector should reflect or reradiate; the work should absorb. Ceramic reflectors depend on reflection plus re-radiation. The lower reflectivity of ceramic reflectors causes a temperature increase, but low thermal conductivity keeps the surface temperature high so that the energy is directed back toward the workpiece by re-radiation.

The usual alignment of equipment for heating of a pipe would be to arrange a sufficient number of these filament-reflector units around the circumference of the pipe. The filaments would be aligned parallel to the pipe axis, so that side by side reflectors approximately 1 in to 2 in [25 mm to 50 mm] away from the pipe outer surface completely fill that circle. This is shown in Figure 19.2.

The third fundamental element of the system is temperature sensing and feedback control. Quartz lamp radiant heaters have the potential for very rapid heating and cooling. Without careful sensing and control, steep thermal gradients and detrimental overheating can be experienced. Thus, properly installed and protected thermocouples and programmed time-temperature devices are desired for overall control. Life of the devices depends to a great extent on protecting them from overheating.

Reflectors, quartz lamps themselves, and the "end seals" (i.e., the electrical connections to the lamps at either end) are all sensitive to overheating. This requires proper selection of the cooling medium and design of the overall device for cooling.

19.3 Heater. The radiant heater consists of quartz lamps and reflectors.

19.3.1 Quartz Lamps. Table 19.1 describes length, electrical characteristics, and power output for the lamps commonly used for local heating. Suppliers should be consulted prior to final selection of lamps for specific applications. Quartz lamps come in two basic designs: the simple tungsten filament and the iodine cycle lamp. The latter, as noted in Table 19.1, has a higher power output per length of lamp and is used primarily for more concentrated heating tasks than those of concern in this document. If the end seals experience temperatures greater than 650°F [345°C], high temperature seals should be specified.

At rated power output, lamps should have a life of approximately 3000 "on" hours or several hundred typical four-hour thermal cycles. A modulated current control system will extend the life of lamps when compared to an on-off control system.

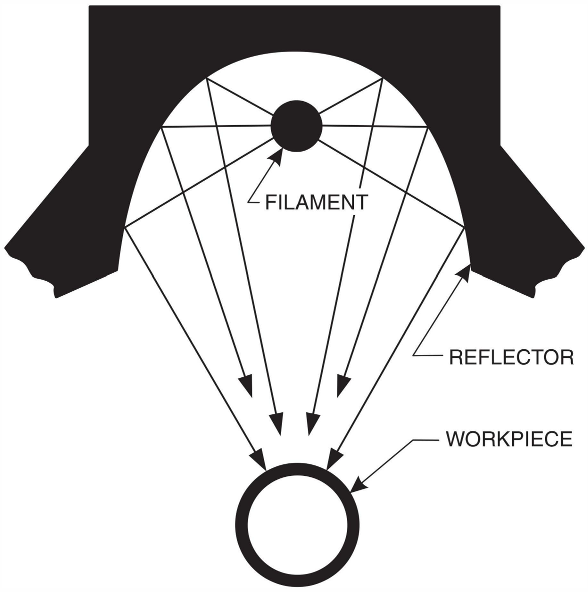


Figure 19.1—Relative Position of Quartz Filament, Reflector, and Workpiece

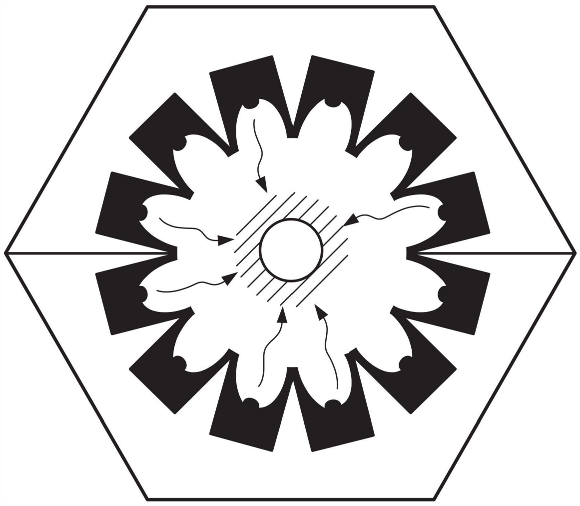


Figure 19.2—"Infrared Furnace" of Quartz Lamp Reflector Units Clam-Shelled or Assembled Around a Pipe

Table 19.1
Typical Quartz Lamps

Lighted Length		Rated Volts, V	Power, W	Power Density	
in	mm			W/in	W/mm
Tungsten Filament Lamps					
5	[127]	120	500	100	[4]
6	[152]	144	1200	200	[8]
10	[254]	240	1000	100	[4]
10	[254]	240	2000	200	[8]
16	[406]	240	1600	100	[4]
13–3/4	[349]	384	3200	230	[9]
Iodide Cycle Lamps					
2–1/2	[63]	120	1000	400	[16]
3	[76]	120	500	170	[6.6]
6	[152]	208	1250	210	[8.2]
9–3/4	[248]	480	6000	620	[24]

Note: These lamps can be used with any of a variety of reflectors, and the reflector package may or may not be designed to accommodate circulating water or gas flow cooling to make a heating unit with the desired temperature-time capability for the work load.

19.3.2 Reflectors. Reflectors are available in ceramic, gold, or polished aluminum. Gold is generally reserved for applications requiring higher temperatures than those encountered in local heating of welds. For the latter, aluminum or ceramic is adequate. The advantage of the ceramic reflector is that, although its initial efficiency is somewhat lower than metal reflectors, the efficiency remains constant throughout service. If the ceramic is dulled, exposing it to high temperature to drive off any condensed contamination can rehabilitate it. This will happen to some extent in normal operation, giving the ceramic a stabilizing, self-cleaning feature. The aluminum reflector should have an efficiency of up to 95% depending primarily on cleanliness and polish. The ceramic has an efficiency of 90%.

The metal reflectors, particularly aluminum, will generally require some cooling, either water or forced gas. This adds to the complexity of the setup. Air used to cool reflectors can cool the pipe if it is not protected. Ceramic reflectors may be used without cooling.

19.4 Thermal Cycle Control. The primary method for measuring temperature as an input to the feedback control is a thermocouple. The method for attaching the thermocouple is described in 7.5 and 7.8. The thermocouple should be protected from direct radiation from the lamps. Concerns regarding the need to protect thermocouples from direct radiation will be eliminated for thermocouples directly attached by capacitor discharge welding. The temperature signal from the thermocouple is compared to a desired signal and the lamp power input is varied accordingly. Control devices can be as simple as on-off, but the preferred method adjusts power to match the actual versus desired temperature differential to control heating rate, hold time, and cooling rate. This would include a variable reactance or proportional voltage control feature, similar to temperature controls used on a permanent furnace. In a sense, one builds a furnace around a pipe for radiant quartz lamp heating.

19.5 Effect of Work Surface Condition. As indicated previously, the work must be an infrared absorber rather than an efficient reflector. Thus, blackening the surfaces will enhance efficiency of the radiant process. Variations in blackness or reflectivity are the primary reason for the requirement for feedback control for each PWHT cycle.

Variations in piping surface condition can be expected. Therefore, a repetition of the same power-time cycle will not necessarily produce the same temperature-time cycle. A difference in heating rates can be experienced when comparing an oxidized with a nonoxidized surface. The oxidized material, being a more efficient absorber, heats appreciably faster. Oxidation, which occurs during the PWHT cycle, assists the thermal efficiency of the procedure.

19.6 Suggestions for Setup. The following suggestions are intended to help an operator faced with the necessity of setting up a quartz lamp infrared heating installation.

19.6.1 Equipment and Materials. The following equipment and materials constitute what is considered to be the minimum recommended for effective quartz lamp infrared heating:

(1) Specific quartz lamp(s) for the pipe size to be heated.

(2) Adequate electric power supply.

(3) Temperature controllers for closed loop feedback control from thermocouples.

(4) Cables to bring power from the supply to the lamp(s).

(5) Thermocouples and extension wire (see 8.2 and 8.5).

(6) A calibrated temperature recorder (see 8.6).

19.7 Relative Advantages and Disadvantages of Quartz Lamp Radiant Heating. The relative advantages of quartz lamp radiant heating are as follows:

(1) Fast response time. This method will generally allow heating at rates limited only by the need to reduce the through-thickness temperature differential in the pipe itself.

(2) Efficiency. Quartz lamp and reflector efficiencies are both quite high. Most of the heat goes into the work.

(3) Cleanliness. No combustion products are brought in contact with the work. Inert gas may be flushed through the work area during heating. Operator comfort is high since waste heat is low.

(4) Fast cool down. Little or no extra mass is brought to temperature. Thus, the part or work can cool as fast as its own heat capacity and thermal conductivity will allow, provided the procedure specification permits such rapid cooling.

(5) Quick turn-around. An established procedure can be performed with expeditious set up and processing.

The disadvantages of quartz lamp radiant heating are as follows:

(1) Initial equipment cost is high.

(2) Quartz lamps are fragile and sensitive to contamination. They must be kept clean and protected from rough handling.

(3) Separate "furnaces" must either be fabricated or available for each pipe diameter. However, this can be nullified by using a single large size furnace or by using lamp units as building blocks.

(4) Equipment cannot be left in place during welding operations.

(5) Care must be exercised to avoid overheating the surface layer of the part due to the rapid rates of heating which are possible.

20. Comparison of Heating Processes

No one local heating process is superior for all applications. The process best suited to any given job depends upon the circumstances. In certain situations, it may even be desirable to use several processes together. Table 20.1 briefly summarizes important aspects of the heating processes discussed in Clauses 15 to 20 and indicates their applicability for hydrogen bakeout, preheat, postheating, and PWHT. In addition to the processes discussed in Clauses 15 to 20, high-velocity gas combustion is a heating process that offers many advantages for large diameter pipe or pressure vessels. Detailed information regarding the use of high velocity gas combustion has been reported (Reference A29) elsewhere.

Table 20.1
Comparison of Heating Processes

Attribute	Induction	Electric Resistance	Flame	Exothermic	Gas Infrared	Quartz Infrared
Applicability to hydrogen bakeout	Yes	Yes	Limited	Very Limited	Yes	Yes
Applicability to preheat	Yes	Yes	Limited	No	Limited	Limited
Applicability to postheating	Yes	Yes	Limited	Very Limited	No	Yes
Applicability to PWHT	Yes	Yes	No	Very Limited	No	Yes
Main Advantages	A, B	C, D	E, F	E, F	A, F	A, F
Main Disadvantages	G, H, I	J	K	I, M, N	G, I, O	G, I, O, P

Key to Advantages:
A = high heating rates
B = ability to heat a narrow band adjacent to a region that has temperature restrictions
C = ability to continuously maintain heat from welding operation to PWHT
D = good ability to vary heat around the circumference
E = low initial equipment cost
F = good portability and ease of setup

Key to Disadvantages:
G = high initial equipment cost
H = equipment large and less portable
I = limited ability to create control zones around the circumference
J = elements may burn out or arc during heating
K = minimal precision, repeatability, and temperature uniformity
L = no adjustment possible once started
M = limited ability to vary heating rate, hold time, and cooling rate
N = available systems currently limited to one weld configuration
O = separate equipment required for each diameter
P = equipment is fragile and sensitive to rough handling

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Annex A (Informative)

List of References

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Annex B (Informative)

Discussion of Issues and Recommendations Regarding the Heated Band

This annex is not part of this standard but is included for informational purposes only.

This annex discusses two issues, through-thickness temperature gradient and induced stress, that must be considered when determining the required heated band width.

B1. Through-Thickness Temperature Gradient

Shifrin concluded (Reference B1) from experimental work 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 width is at least 5t (where t = wall thickness of the pipe) 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.

In the decades since it was published, the Shifrin work (or variations on it) has served as the basis for the majority of standard practice with regard to heated band width for local heating as it relates to the attainment of minimum temperature within the soak band. For example, an approach has been to specify the heated band width as the sum of the soak band width plus 2.5t on each side of the soak band. This type of approach is still widely used today. However, concerns have been expressed (Reference B2) that the 5t width is not sufficient, especially as the internal radius increases with no internal insulation.

Hill has reported (Reference B3) on the effect of the heated band width on the PWHT soak band temperature achieved at the 6:00 position on the inner surface for 6.625 in [168 mm], 12 in [305 mm], and 18 in [457 mm] diameter pipes oriented horizontally. It was suggested that an empirically derived ratio, H_i, 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 and convection from the inner surface. Equation (B1) describes this empirically derived ratio. Solving Equation (B1) for the heated band width results in Equation (B2).

$$H_i = \frac{A_e}{2A_{cs} + A_i} \qquad \text{(B1)}$$

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)

$$\text{Heated band width} = \frac{H_i\left[\dfrac{OD^2 - ID^2}{2} + (ID)(SB)\right]}{OD} \qquad \text{(B2)}$$

where:

H_i = ratio of heat source area to heat loss area
OD = outside diameter of pipe
ID = inside diameter of pipe
SB = width of soak band

One set of conditions examined utilized a ratio of H_i = 1.19, two circumferential control zones, with control temperatures of approximately 1150°F [621°C] at the 12:00 and 6:00 positions, on an 18 in [0.46 m] diameter, 1 in [25 mm] wall thickness pipe. For these conditions, a temperature difference of 120°F [67°C] occurred between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 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 45°F [25°C] would occur, thereby ensuring achievement of the minimum temperature, 1100°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 that the recommended ratio was empirically derived. As such, it is founded upon certain conditions inherent to the tests that lead to that recommendation, such as the number of control zones, the hold temperature, and the orientation of the pipe (i.e., horizontal versus vertical). For example, data is reported for one and two zone control on an 18 in [0.46 m] diameter, 1 in [25 mm] wall thickness pipe using a ratio of H_i = 4.81. For one zone of control, a temperature difference of 92°F [51°C] is reported between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 position, 2t from the centerline of the weld), while for two zones of control the difference was 70°F [39°C]. It should also be noted that for this size pipe, a minimum of three circumferential control zones are recommended.

As the number of control zones is increased, lower empirical H_i ratios would be appropriate. With multiple control zones it is also possible to have different control temperatures for each zone. The use of different control temperatures for each zone would also affect the empirically derived H_i ratio. In addition, the empirically derived H_i ratio is based on a soak band size of 4t, which may be larger than that required by the applicable fabrication code. Therefore, the H_i ratio of 5 may be conservative for situations in which a larger number of control zones are used or a smaller soak band size, or both, is required.

Murakawa and Wang have reported data (Reference B4) that suggest the relation between ΔT (through-thickness temperature difference) and the H_i ratio is dependent upon thickness. They also question fundamental assumptions inherent to the ratio. Their preliminary conclusion for situations with one control zone is that the ratio may be too large for small thicknesses and too small for large thicknesses. In addition, they suggest that a combination of techniques such as multiple circumferential control zones may provide a more economical approach.

The hold temperature also affects the empirically derived H_i ratio. Temperature differences between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 position, 2t from the centerline of the weld) are reported for hold temperatures between 500°F to 1300°F [260°C to 704°C] with a ratio of H_i = 2.28. The temperature difference varied from 21°F to 64°F [12°C to 36°C] as the hold temperature increased. This data suggests that a ratio of H_i = 2 may be appropriate for lower temperature heating processes such as hydrogen bakeout, preheat, and postheating when the temperature is below approximately 800°F [427°C].

Although not reported in the paper (Reference B3), the authors have also tested the use of a nonuniform width 360-degree heated band. In these tests, it was found (Reference B5) that a heated band at the 6:00 position that is approximately 1.6 times as wide as that at the 12:00 position was required to generate uniform circumferential temperature with one zone of control for pipe in the horizontal position. By using such an approach, lower H_i ratios can be used to achieve the desired temperature uniformity. However, as discussed in Annex Clause B2, the effect of such a heated band on induced stresses and distortion would also have to be considered.

Hill (Reference B3) also discusses modification of the ratio calculation to account for insulation on the inner surface and adjacent heat sinks (heavier wall thickness pipe, valves, fittings, flanges, etc.). For example, when insulation is present on the inside surface, the A_i term in Equation (B1) can be removed from the denominator of the ratio.

As stated above, the H_i ratio is empirically derived. Therefore, its applicability to conditions (position of piping, wall thickness, temperature, number of control zones, etc.) beyond those used in the test must be carefully examined. Fundamental assumptions inherent to the ratio have also been questioned. Although it appears that the H_i ratio can not provide a unique solution, it does highlight the need for the through-thickness temperature criterion to account for all of the factors that contribute to heat loss.

B2. Induced Stresses and Distortion

Efforts to address the stresses resulting from local PWHT were first reported by Rose and Burdekin (References B6, B7). One basis for this work was to establish parameters that produced approximately the same degree of stress relaxation in the vicinity of the weld as would be achieved in a furnace. As an approximation, the hot yield strength (YS) of the material at PWHT temperature was used as the target level of stress relaxation. Having established the hot YS as an approximate target for stress relaxation, the Rose and Burdekin work then aimed at limiting the induced stress at the weld due to PWHT to something less than hot YS, thereby ensuring that the induced residual stress at the weld due to PWHT was no greater than the residual stress levels that would remain even if the PWHT were done in a furnace. As a result of this work, a heated band width as shown in Equation (B3) was proposed.

$$\text{Heated band width} = 5\sqrt{Rt}\text{, centered on the weld} \quad \text{(B3)}$$

where:
R = inside radius
t = thickness

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.

Concern has been expressed that a heated band size of $5\sqrt{Rt}$ may be overly conservative. For example, a supplement to a German standard (Reference B8) explains the basis for changing the heated band sizing requirement from $5\sqrt{Rt}$ to $4\sqrt{Rt}$. In summary, this supplement explains that the "run-out length" for stresses and moments induced by local heating according to the theory of shells is $2.83\sqrt{Rt}$. It therefore concludes that a heated band size of $4\sqrt{Rt}$ should provide an adequate margin of safety.

Annex C provides a detailed discussion that is in agreement with the German standard and previous work (Reference B9). Annex C concludes that a minimum heated band width in accordance with Equation (B4) can be used to adequately control induced stresses in the soak band for "code required" PWHT.

$$\text{Minimum heated band width} = SB + 4\sqrt{Rt} \quad \text{(B4)}$$

where:
SB = soak band width
R = pipe inside radius
t = wall thickness

This recommendation differs from international codes and practice in that it specifies the "run-out-length" from the edge of the soak band instead of the weld centerline. This approach was used to ensure adequate control of stresses throughout the soak band. The minimum width of the recommended heated band in Equation (B4) is of similar size to that used in international codes and practice as shown in Equation (B3). The magnitude of the difference depends upon the difference between the width of the soak band and $\sqrt{Rt}$.

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Annex C (Informative)

Discussion of Stresses Induced During Local 360-Degree Band PWHT

This annex is not part of this standard but is included for informational purposes only.

This annex elaborates on the issues relating to stresses induced during local 360-degree band postweld heat treatment (PWHT) which are discussed in the recommended practice and Annex B. The discussion that follows is intended to describe the basis for the recommendations made in the recommended practice and other documents. In particular, this annex discusses an approach to establishing the minimum heated band width, a means to control the axial temperature gradient by specifying the minimum temperature at the edge of the heated band, and the minimum gradient control band width.

In all cases the recommendations discussed in this annex assume a single 360-degree band of heaters. In addition, the arrangement of heaters and insulation are assumed to be fully capable of providing the required level of power and control to the component and will achieve the desired PWHT soak band and gradient temperatures. The fact that the recommendation for the minimum heated band width has been met does not guarantee that the selected heater arrangement will bring the component to PWHT temperature and maintain adequate uniformity.

C1. Heated Band Width

The reader has already been introduced to the concept that the magnitude of the bending stresses induced by the heater during PWHT is dependent on the width of the heater and the temperature profile along the pipe. Note that the temperature profile is just as dependent on the width of the heater as it is on insulation and environmental conditions. In particular, it has been stated that the thermally induced stresses at the weld (and under the heater) can be minimized by using a heated band width of at least 3 to 5 times $\sqrt{Rt}$. This recommended practice suggests that in order to address concerns about induced stresses the minimum heated band (heater) width be $4\sqrt{Rt}$ plus the width of the soak band. This recommendation minimizes the stresses induced by the heat transfer discontinuity at the edge of the heater and the stresses induced by the shape of the temperature profile under the heater and to a lesser extent in the gradient control band.

The parameter $\sqrt{Rt}$ appears in various international codes and is further emphasized in the work of Timoshenko (Reference C1), Rose (Reference C2), Burdekin (Reference C3), and others on cylindrical shells subjected to axisymmetric thermal loading.

The following discussion attempts to simplify and clarify the basic mechanisms that drive the complicated problem of thermally induced stresses in an axisymmetrically loaded cylindrical shell. In this and all further discussions (unless otherwise specified), the weld is assumed to be at the center of the heater and is narrow. The application of these concepts to a finite width weld and heat-affected area will follow in a summary of this clause.

List of Symbols

- R = the piping inside radius,
- t = the piping thickness,
- l = the heated half band width,
- E = modulus of elasticity,
- α = coefficient of thermal expansion,
- x = axial distance from the weld centerline,
- w = displacement of the piping, (positive inward),

$T(x)$ = the temperature distribution along the axis of the cylinder,

σ_x = bending stress,

υ = Poisson's ratio,

$\upsilon = 0.3$

$$D = \frac{Et^3}{12(1-\upsilon^2)},$$

$$\beta^4 = \frac{Et}{4DR^2} = \frac{3(1-\upsilon^2)}{R^2t^2}$$

C1.1 Thermal Stresses Induced by the Heater Edge Flux Gradient Discontinuity. A fundamental characteristic of any system heating a pipe by means of a finite width heat source are the bending stresses that are induced from the thermal heat transfer (flux gradient) discontinuity at the edges of the heat source. These stresses are manifested as thermally induced moments and shear forces in the pipe at the edges of the heater. The magnitude of these moments and shear forces is dependent on the size of the flux gradient discontinuity and the temperature profile on each side of the heater edges.

The stresses introduced in a cylinder by concentrated moments and shear loads are well understood and the character of the stress solution is independent of whether or not the loading mechanism is mechanical or thermal. Since the resultant stresses are self-equilibrating, they are local in nature and die out rather quickly. The local character of the bending stresses caused by a concentrated moment are proportional to the function given by Equation (C1), as is the bending component of the heater flux gradient discontinuity stresses. The decay functions for concentrated shear loads and other boundary conditions are similar and have the same decay rate (Timoshenko [Reference C1]).

$$\phi(\beta x) = e^{-\beta x}[\cos(\beta x) + \sin(\beta x)] \qquad \text{(C1)}$$

The constant β is dependent on the pipe's geometry and material properties. The derivation of Equation (C1) and its relationship to the discontinuity stresses is omitted to limit this discussion to the essential points.

Equation (C1) is plotted in Figure C.1 and may be interpreted as follows. Consider the plot to be proportional to the bending stress distribution induced in a pipe by a concentrated axisymmetric bending moment (or the bending effect caused by the edge effect at a single end of a heater) as a function of distance from the applied bending moment. In this case the axis coordinate zero is the location of the applied bending and the axis represents distance along the axis of the pipe from the same point, e.g., toward the weld. Two important factors make this figure different in character from that which a heater would cause. First, Figure C.1 does not include the effect of bending stresses caused by the opposite edge of the heater. Second, the effect of simultaneously occurring shear loads is not considered. Both of these omissions are considered in a subsequent and more detailed treatment in this annex. The opposite heater edge bending moment is treated by reflecting Figure C.1 about the ordinate axis, separating the two edges by the appropriate heater width and using superposition to add the stresses. To avoid the superposition effect, heated band widths at least twice (recognizing the figure represents the effect from one edge of the heater) that producing sufficient decay are required. Shear loads are not directly applied by the heater but are instead a manifestation of displacement compatibility requirements at the heater edges.

Recall that a heated band width of between 3 to 5 times $\sqrt{Rt}$ is being considered. At one end of the range, Japanese researchers (Reference C4) have considered the minimum induction coil width needed to avoid superimposing the bending stresses resulting from the temperature discontinuity at the edges of the coil. This was based upon the approach described by Timoshenko (Reference C1) and experimental measurements. They concluded that if the coil width is larger than $3\sqrt{Rt}$, effects from superimposing stresses from each edge could be avoided. Note that the Japanese work defines R_m as the mean radius instead of the inside radius as used by the recommended practice and this annex. Converting the Japanese recommendation to inside radius results in a heated band width somewhat larger than $3\sqrt{Rt}$. At the other end of the range is the traditional $5\sqrt{Rt}$ heated band width found in various international codes and is based upon the work of Rose (Reference C2) and Burdekin (Reference C3).

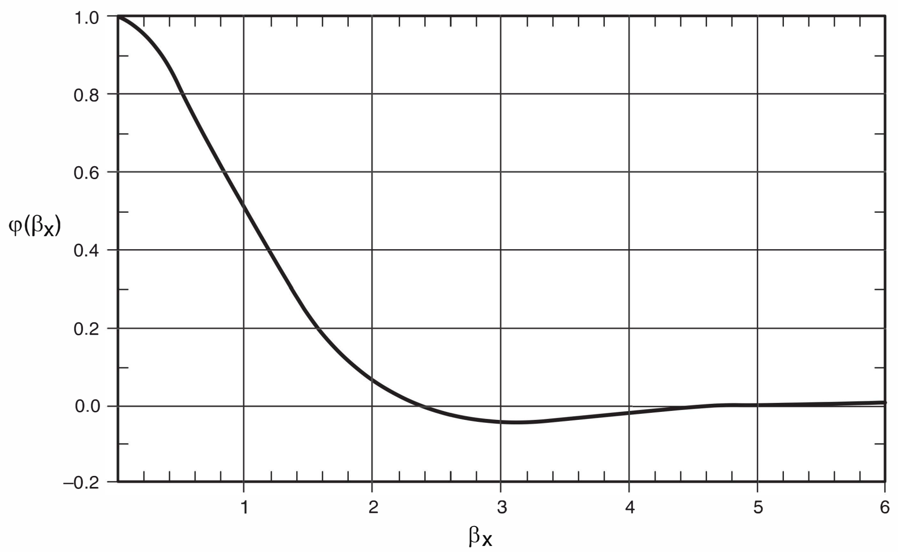


Figure C.1—Bending Stress Decay as a Function of βx, Where x is the Distance from the Edge of the Heater to the Centerline of the Weld

The function in Figure C.1 may be divided into two parts, one that defines a region of great change and the other defines the region in which the function has leveled out and decayed nearly to zero. The transition between these two regions occurs somewhere between $\beta x = 2$ and 3. The latter region is of interest because the local heater edge effect stresses will have largely decayed to zero at these distances. The soak band can be placed in the low stress region by selecting the heated band width appropriately.

For steel and other materials that have a Poisson's ratio of $\upsilon = 0.3$, βx equals $1.285/\sqrt{Rt}$. This then completes the relationship between βx and heated band width. The vales of $\beta x = 1.9$, 2.6, and 3.1 are calculated to correspond to heated band widths of 3, 4, and 5 times $\sqrt{Rt}$ respectively and neatly fall into the transition and low stress regions.

On the basis of the above discussions, it is reasonable to conclude that a minimum heated band width of $4\sqrt{Rt}$ plus the width of the soak band will provide a sufficient "run-out length" for stresses induced by the edge of the heated band. Further note that this result holds for all pipes with a heated band width of $4\sqrt{Rt}$ plus the width of the soak band, independent of material (for materials where Poisson's ratio, $\upsilon = 0.3$), geometry, or heater type.

This example demonstrates the first of two important connections between the $\sqrt{Rt}$ parameter and the heated band width. The second connection will be discussed in a following subclause about stresses induced under the heater. The heater edge induced thermal stresses will be revisited by way of an example in an upcoming discussion.

C1.2 Thermal Stresses Induced Under the Heater. Ideally, there will be no temperature variation under the heater. However, even with "properly controlled" PWHT, some temperature variation is expected under the heater. The following subclause focuses on the induced stresses that result from expected temperature distributions under the heater.

C1.2.1 Polynomial Temperature Distributions. The governing differential equation for the axisymmetric thermally induced deformation of a cylindrical shell is

$$w''''(x) + 4\beta^4 w(x) = -4\beta^4 \alpha R[T(x) - T_{ambient}] \qquad (C2)$$

It is instructive to examine the solution of this equation for the family of temperature distributions, T(x), that are given by polynomials of order 3 or less. By doing so, the simplest solution to Equation (C2) is obtained and an intuitive understanding of the parameters that drive the bending stress levels is gained. Subject to this condition, the solution to Equation (C2) for the thermally induced displacements is

$$w(x) = -\alpha\, R[T(x) - T_{ambient}] \quad (\underline{C}3)$$

Given that the bending stresses in the cylinder wall are determined from

$$\sigma_{xmax} = 6M_x/t^2 \quad (\underline{C}4a)$$

where:

$$M_x = -Dw''(x) \quad (\underline{C}4b)$$

and substituting the second derivative of Equation (C3) into Equations (C4) yields

$$\sigma_{xmax} = \frac{EhRT''(x)}{2(1-\upsilon^2)} \quad (\underline{C}5)$$

for polynomial temperature distributions of order 3 or less.

It is apparent from this result that the thermally induced bending stresses are proportional to the second derivative of temperature with respect to axial position. Note also that since the conductive heat flux is by definition proportional to the first derivative of temperature with respect to position, q = -kAT'(x), it can be stated that the thermally induced bending stresses are proportional to the first derivative of heat flux with respect to position. This is an important concept because many codes and recommended practices (including this one) discuss managing temperature profiles and limiting heater induced stresses with language that describes the temperature gradient (the first derivative of temperature) and not the gradient of the gradient (the second derivative of temperature). It is not the intent of this annex to characterize these descriptions as inadequate or improper. Its intent is, however, to point out that thermally induced stresses are more complicated to manage than many codes and standard references imply. Certainly it is much more practical to measure the temperature gradient than it is to measure the gradient of the gradient. With this in mind, statements such as "no harmful gradients" take on a clearer and more significant meaning to the heat treatment professional.

Returning to Equation (C5), clearly the bending stresses will be their greatest where the second derivative of temperature, (first derivative of heat flux) with respect to position, is the greatest. The physical interpretation of this is that the highest thermally induced stresses occur at locations where the greatest rate of change of heat transfer occurs. While this polynomial solution is too simplistic to apply to the heater edge, it does give some insight into how these stresses are generated.

C1.2.1.1 Ideal Temperature Heat Source. An ideal temperature heat source creates a uniform temperature distribution in the portion of a cylindrical shell it is heating. This constant profile is completely described by the polynomial $T(x) = T_0$. The stresses induced by this temperature field are zero at the weld provided that the heat source is sufficiently wide so that the stresses induced by heat flux gradient discontinuity at the heat source edge have negligible magnitude at the weld. If these stresses are not negligible they become the sole source of stress under the heat source.

C1.2.1.2 Ideal Flux Heat Source. An ideal flux source creates a parabolic temperature distribution in the portion of a cylinder it is heating. The reader can be satisfied that an ideal flux heater creates a parabolic temperature profile by reducing the full form of Fourier's heat conduction equation to one dimension (with no through-thickness consideration) and using internal volumetric heat generation to simulate the output of the heater. Since this distribution is a second order polynomial, the previous solution to Equation (C5) is applicable.

A parabolic temperature distribution can be completely defined by specifying temperatures at two locations. For purposes of this discussion, specify $T(0) = T_0$. and $T(1) = T_1$, where 21 is the heated band width. Any other reasonable pair of temperature points may be used to specify the temperature distribution. Hence, the parabolic temperature distribution and its derivatives can be written as follows:

$$T(x) = T_0 + (T_1 - T_0)\,\frac{x^2}{1^2} \quad (\underline{C}6a)$$

$$T'(x) = (T_1 - T_0)\,\frac{2x}{1^2} \quad (\underline{C}6b)$$

$$T''(x) = (T_1 - T_0)\,\frac{2}{l^2} \qquad \text{(C6c)}$$

To simplify the stress analysis, assume that the heat source is sufficiently wide so that the stress field induced by flux gradient discontinuity at the heater edges has negligible magnitude at the weld. If these stresses are not negligible they can be added to the subsequent analysis by superposition.

Substituting Equation (C6c) into Equation (C) gives the desired result for the thermal bending stress in a cylindrical shell subject to a parabolic temperature distribution.

$$\sigma_{x\max} = \frac{\alpha E R t (T_1 - T_0)}{l^2 (1 - \upsilon^2)} \qquad \text{(C7)}$$

With this result, the variation of the thermal stress can be studied for various heat source widths as a function of the parameters "R" and "t." Note that for parabolic temperature distributions, the thermal stresses are independent of axial position. Furthermore a review of Equations (C5) and (C6) reveals that "shallow" parabolas induce less stress than "steep" parabolas. This becomes an effective argument for maintaining reasonable temperature uniformity under the heater and for wide heaters.

C1.2.1.3 General Temperature Distributions. For the more general temperature distribution case, the thermally induced displacements will be in the form of a function that is dependent on position and temperature

$$w(x) = f[x, T(x)] \qquad \text{(C8)}$$

In order to determine the bending stresses it is necessary to calculate the second derivative of Equation (C8), [recall Equations (C4)]. Because the solutions are no longer polynomial, the solution for the thermally induced bending stresses will be more complex than that given by Equation (C5). However, the bending stresses' dependence on the second derivative of temperature with respect to axial position will be retained.

C1.3 Examples

C1.3.1 Example #1. Consider a piping section subject to the following temperature distribution:

(1) The pipe is at the ambient temperature everywhere except directly under the heater.

(2) The temperature of the pipe under the heater is uniformly 1000°F [538°C] above ambient.

Although this temperature profile is very idealized and will not occur in nature, it has some very interesting properties that make it a useful example for studying the thermally induced stresses caused by the edge of a heater.

The temperature distribution can be represented in a piecewise manner by two polynomials zero order (constants) and applying Equation (C5) provides evidence that the thermally induced stresses in the cylinder are zero. But this is not the whole story since Equation (C5) does not account for the stresses introduced by the flux gradient discontinuity at the edge of the heater. The reason for this is that the second derivative of the temperature profile (the first derivative of the heat flux) is equal to zero everywhere on the cylinder except at the discontinuity at the edge of the heater! At this point the heat flux and its derivatives are unbounded. This is the feature that makes this problem instructive; the stresses induced by the temperature profile are entirely due to the heater edge effect. It is now possible to qualitatively consider the edge effect of a finite width heater on the induced thermal stresses without interference from other induced stress sources.

An analytical solution to this problem is described by Timoshenko (Reference C1) and is presented here to demonstrate the localized nature of the resulting stress profile. Timoshenko's text provides a very detailed examination of the axisymmetric loading of cylindrical shells and is a highly recommended reference. A key result detailed in the text is the local nature of stresses introduced by self equilibrating loads such as the thermal loads being examined here.

The plots that follow are based on an 18 in [457 mm] outside diameter, 0.562 in [14.27 mm] wall thickness pipe constructed of low carbon steel subject to the previously described temperature profile. In the example, the effect of varying heated band widths is presented. The coefficient of thermal expansion, α, was assumed to be 8.03×10^{-6} in/in/°F [14.4×10^{-6} mm/mm/°C]. For simplicity the modulus of elasticity, E, was assumed to be temperature independent and was estimated to be 16.8×10^6 psi [116 GPa]. This assumption will result in moderate errors in the displacement solution and its derivatives but does not interfere with the solution's sensitivity to heated band width.

Figure C.2 shows the thermally induced bending stress profiles (at the inner radius of the pipe) for heated band widths that are integer multiples of $\sqrt{Rt}$ up to $5\sqrt{Rt}$. For convenience the horizontal axis has been scaled by a factor of $\sqrt{Rt}$.

The important characteristics of the stress curves in Figure C.2 include:

(1) There is a zero crossing in all of the curves at or near the edge of the heater.

(2) There are large localized stress peaks on each side of the edge of the heater within a distance of $0.5\sqrt{Rt}$ to $1.0\sqrt{Rt}$. The magnitude of these local stress peaks is largely independent of the width of the heater.

(3) If the heater is narrow enough, the two heater edge stress peaks that occur under the heater add algebraically and become a single stress peak at the center of the heater.

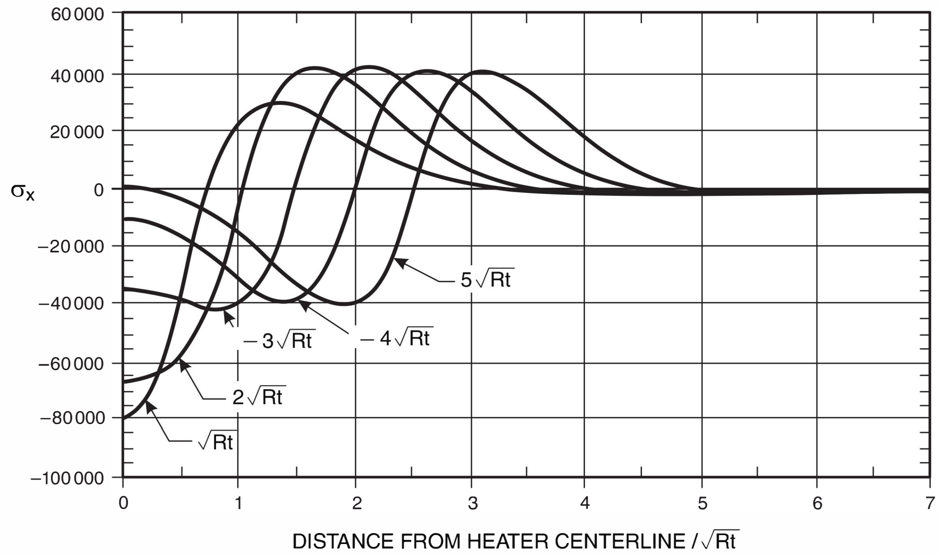
(4) There is always a local stress maximum or minimum at the center of the heater.

(5) The magnitude of the stress at the center of the heater is dependent on the width of the heater and ranges from zero for wide heaters to twice the magnitude of the stress peaks near the edge of the heater for narrow heaters.

(6) The stress values shown are high. Real temperature profiles will have lower peak stresses but the stress decay rate will be the same.

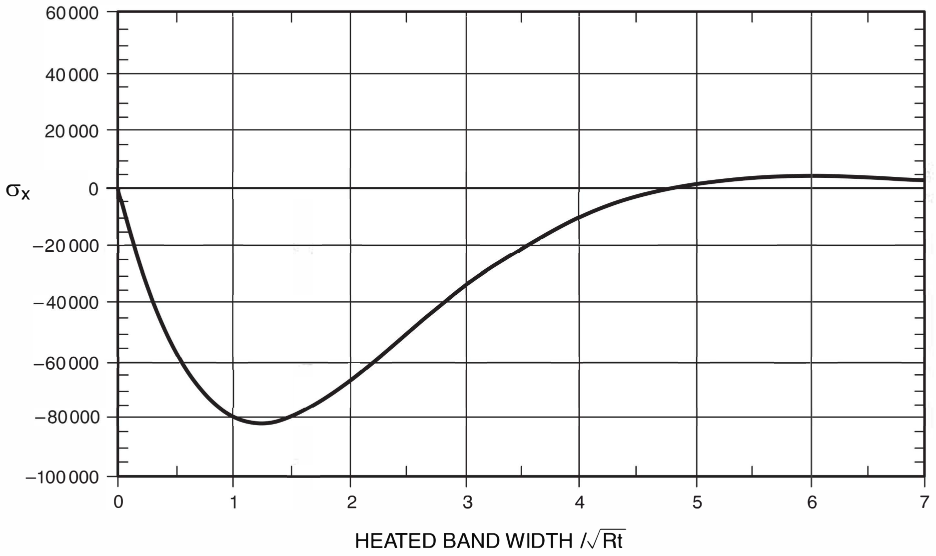
Figure C.3 is a plot of the same data showing the dependence of the bending stress at the center of the heater due to the heater edge effect as a function of the heater width. For convenience the axis has been scaled by the factor $\sqrt{Rt}$. Note that the induced stress at the weld centerline is very small for heated band widths of at least $4\sqrt{Rt}$ to $5\sqrt{Rt}$.

In addition to the expected result, the figure indicates that very narrow heaters can have very low induced heater edge effect stresses. Keep in mind that Figure C.3 shows only the stresses caused by the heater edge and not the stresses caused by heater temperature profile. The stresses induced due to very narrow heaters are normally very high (refer to the discussion in C1.2.1.2).



Note: The bending stresses are plotted as a function of distance from the heater centerline for heated band widths equal to $n\sqrt{Rt}$, where n is an integer and $1 \leq n \leq 5$.

Figure C.2—Bending Stress Distribution Induced by the Heater Edge, for Heaters of Various Widths



Note: The bending stresses are plotted as a function of distance from the heater centerline for heated band widths equal to $n\sqrt{Rt}$, where n is an integer and $1 \leq n \leq 5$.

Figure C.3—Bending Stress at the Heater Centerline Induced by the Heater Edge; for Heaters of Various Widths

Conclusions that can be made at this point are:

(1) The magnitude of the stresses in the piping at the heater centerline caused by the edges of the heater can be reduced by selecting an appropriately wide heater. Recall the earlier conclusion in C1.1 that a heated band width of $4\sqrt{Rt}$ plus the width of the soak band appears to provide an adequate "run-out length" for induced stresses. Based upon induced stresses going to zero for a heated band width of $5\sqrt{Rt}$ as shown in Figure C.3, one might conclude that this width is more appropriate. However, it is still concluded that a width of $4\sqrt{Rt}$ plus the width of the soak band will be adequate because "real" temperature profiles will produce lower stresses for this width.

(2) The magnitude of the stresses that occur near the edge of the heater is dependent on the characteristics of the temperature profile in the piping at the edge of the heater and is quite independent of the heater width.

(3) In the example shown in Figure C.2 there is clearly a "harmful temperature gradient" at the edges of the heater. Despite the fact that many codes specify temperature gradient limits, the thermally induced bending stresses in this example are caused solely by the gradient of the temperature gradient.

The analyst working on this heat treatment has some difficult decisions to make (ignoring the fact that the assumed temperature distribution is not a real profile). If the analyst's goal is to leave no residual stresses in the soak band, then they have the flexibility to select a wide heater to zero the heater edge effect stresses at the weld. On the other hand, if the analyst's charter is to minimize residual stresses everywhere, then they must begin to make compromises. This is because using a wide heater does not eliminate the peak stresses induced by the heater edge, they are only moved away from the heater center-line. It should be noted that the high induced stresses near the edges of the heater might cause no residual stresses if the material temperature at the heater edges is low enough so that no hot yielding occurs. This is very dependent on the piping material, geometry, the heater arrangement, insulation, and environmental conditions.

C1.3.2 Example #2. Consider the case where ideal flux heaters are used and the heated band width is determined by a suitable multiple of the cylinder's thickness, e.g., $2l = \lambda_1 t$ (recall that l is the half heated band width). Solving for 1 and substituting into Equation (C7) yields

$$\sigma_{x\max} = \frac{4\alpha E(T_1 - T_0)R}{\lambda_1^2(1-\upsilon^2)\ t} \qquad (C9)$$

Thus by specifying the heated band width to be proportional to the pipe thickness, the resulting thermal stresses at the heater centerline will vary proportionally to the radius and inversely proportionally to the thickness. Assuming that the pipe material and temperature profiles are the same, only pipes with the same radius to thickness ratio would have the same level of thermal stresses. It is difficult to recommend that the heater width be a suitable multiple of the pipe's 'thickness and still limit the thermal stresses over a wide range of radius to thickness ratios.

Now consider the case where the heated band width is determined by a suitable multiple of the square root of the product of the cylinder's radius and its thickness, e.g., $2l = \lambda_2\sqrt{Rt}$. Solving for l and substituting into Equation (C7) yields

$$\sigma_{x\max} = \frac{4\alpha E(T_1 - T_0)}{\lambda_2^2(1-\upsilon^2)} \qquad (C10)$$

Consequently, by specifying the heated band width to be proportional to the square root of the product of the cylinder's radius and thickness, the resulting thermal stresses at the heater centerline are independent of the cylinder's radius and thickness. Thus the magnitude of the thermal stresses is only dependent on the temperature profile, the material properties, and the selected proportionality constant. Given a suitable limiting value for stress, a reasonable and universal heated band width recommendation can be made based on a multiple of the square root of the cylinder's radius times its thickness.

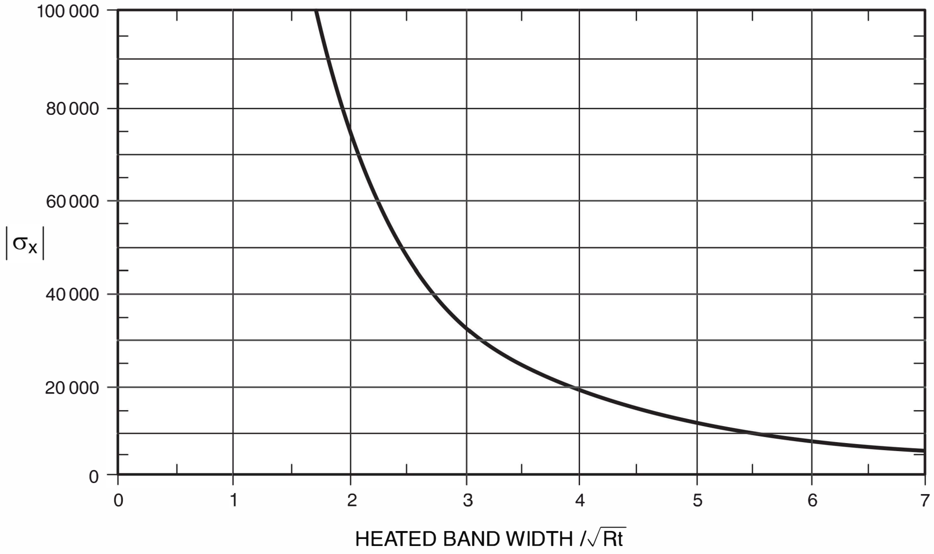
This is the second important connection between the heated band width and the parameter $\sqrt{Rt}$. The reason that this example is significant is that most flexible electric resistance heaters used in PWHT applications generate power uniformly over their entire area. This is identical to the way that the ideal flux heater provides power. The ideal flux heater approximation is a reasonably adequate model even with interfering effects such as surface contact resistance.

C1.3.3 Example #3. Figure C.4 is a plot of the bending stress induced at the center of the heater due to a parabolic temperature distribution as a function of heater width using Equation (C10) and the values shown below. The temperature at the edge of the heater was assumed to be 550°F [288°C], or one-half the temperature in the soak band which was assumed to be 1100°F [593°C]. For convenience the axis has been scaled by the factor $\sqrt{Rt}$. The plot does not include the stresses due to the edges of the heater. It should be noted that this example is presented for illustrative purposes only. The yield point of the material is being ignored, hence a portion of the stresses plotted in Figure C.4 exceed the yield strength. Note that the heater induced stresses are well above the hot yield strength of most steel at PWHT temperatures until the heated band width exceeds approximately $4.5\sqrt{Rt}$ to $5\sqrt{Rt}$. The material properties were the same as those used in C1.3.1, Example No. 1.

The reader is cautioned that the polynomial solution to the thermal stress problem is very attractive and begs to be used to estimate the magnitude of the stresses under a heater. However this is not the entire solution as even an ideal flux heater must be of finite width to be useful in the field. Thus the heater edge induced stress must not be overlooked.

C1.4 Translating Theory Into Practice. The topics discussed in this subclause all support the practice of recommending that the PWHT heated band width be at least as wide as some suitable coefficient times $\sqrt{Rt}$. The question becomes what is a suitable value for the coefficient? The German standard (Reference C5) discussed in Annex B concludes that a heated band width of $4\sqrt{Rt}$ is appropriate (based on a "run-out length" of $2.83\sqrt{Rt}$ due to the heater edge effect). This document has recommended a variation of the German rule in that the heated band width is suggested to be the width of the soak band plus $4\sqrt{Rt}$. The reason for this variation is that the width of the soak band (weld metal, HAZ, and sufficient adjacent base metal) can be significant. It is the recommendation of this document that the heater edge effect stresses not only "do no harm at the weld," but also "do no harm in the soak band." Thus the width of the soak band has been added to protect the weld metal, HAZ, and sufficient adjacent base metal.

With respect to stresses induced by the temperature profile under the heater, the given example supports the wider heated band widths. The results are sufficiently dependent on material properties and strengths at temperature that a conservative multiple of $\sqrt{Rt}$ is recommended for the heated band width. Certainly the example given does not support an argument for recommending a heated band width less than that specified in the German standard.



Note: The bending stress at the heater centerline is plotted as a function of distance from the centerline to the heater edge. The heater edge temperature is half the soak band temperature. For heated band widths equal to n $\sqrt{Rt}$, where $0 \leq n \leq 7$.

Figure C.4—Bending Stress at the Heater Centerline Induced by an Ideal Heater, for Heaters of Various Widths

Significantly missing from the above discussion is an estimate of the real peak magnitude of the heater edge effect stresses. To do so would have required making some limiting assumptions about the type of heaters and insulation used and the resulting temperature profile. Since this varies so much from component to component, the result would have been too narrow from which to make a universal recommendation. Historically recommendations about the heated band width based on heater edge effects have not been able to address this issue in a simple manner. The result is a conservative recommendation about protecting the weld from well-understood phenomena with a hard to establish peak magnitude. Whether the issue is heater edge discontinuity stresses or the stresses caused by the heater, analytical techniques such as the finite element method and a well defined acceptable stress criteria should be considered to properly assess the effect of narrower heaters.

Such an approach is currently being pursued by researchers (Reference C6) from Japan. They are utilizing an axisymmetric model based upon the thermal-visco-elastic-plastic, finite element method. Their modeling considers the effect of creep relaxation in a weld region containing an existing residual stress distribution from a representative weld. Their criteria for establishing the minimum width of the heated band is to limit the magnitude of residual stresses present after local PWHT to that produced by uniform PWHT (e.g., heating the whole component in a furnace). Piping with diameters in the range of 9.8 in to 39.4 in [250 mm to 1000 mm] and wall thickness between 1 in to 2 in [25 mm to 50 mm] have been considered. Results to date (Reference C6) suggest that a heated band width of the width of the soak band (for soak band width = 3t) plus $4\sqrt{Rt}$ could be used to meet the criteria of limiting the stresses present after local PWHT to that produced by uniform PWHT.

C2. Method to Control the Axial Temperature Gradient

As previously discussed in C1.2.1, it is the second derivative of temperature (the rate of change of the rate of change in temperature) which induces stresses under the heater. It has been explained that the use of a linear temperature gradient does not provide an adequate means to control these induced stresses. However, as discussed in C1.2.1.2, by specifying the temperatures at two points, a parabolic temperature distribution can be completely defined. Therefore, with knowledge of the minimum temperature at the edge of the soak band (T_0) and by specifying the minimum temperature at the edge of the heated band (T_1), a parabolic temperature distribution can be described. A parabolic temperature distribution appears to be a reasonable means to represent the type of heaters commonly used (e.g., electric resistance). Therefore, an approach, which establishes a minimum temperature at the edge of the heated band (heater) appears to offer a reasonable method to limit the stresses, induced under the heater.

Equation (C7) provides enough information to examine the effect of temperature at the edge of the heater and its effect on stress for a parabolic temperature profile.

C2.1 Example #4. An estimate of the minimum permissible temperature at the edge of the heated band can be made given a maximum stress allowable at the weld. This treatment is based on the stress formulation previously obtained for the ideal flux heat source, Equation (C7). This analysis assumes linearly elastic material behavior and that the heat flux gradient discontinuity stress can be neglected in the region of interest.

To keep the flux discontinuity stresses negligible, the heat source half width, 1, will be set to be $2\sqrt{Rt}$. Note that the width of the soak band is not included in order to simplify the analysis. Since the recommended minimum width of the heated band includes the soak band and this example does not, these results are marginally conservative. This in turn gives the following equation for stress:

$$\sigma_{x\max} = \frac{\alpha E T_0 (T_1/T_0 - 1)}{4(1-\upsilon^2)} \qquad \text{(C11)}$$

Solving for the ratio T_1/T_0 yields Equation (C12).

$$\frac{T_1}{T_0} = \frac{4(1-\upsilon^2)}{\alpha E T_0}\sigma_{x\max} + 1 \qquad \text{(C12)}$$

It is assumed that σ_{xmax} is twice the negative of the maximum allowable stress. By limiting the linear elastic model stresses (strains) to twice the hot yield, the resulting maximum residual stresses when cold can be expected to correspond approximately to the hot yield stress. This rule of thumb predicts residual stresses of about the same order of magnitude as can be expected from a uniform heat treatment in a furnace. Further elaboration on this problem requires an elastic-plastic analysis and is beyond the purpose and scope of this discussion.

The ratio T_1/T_0 provides an ability to estimate an acceptable drop in temperature to the edge of the heater. Equation (C12) was used to calculate the ratio T_1/T_0 for three materials, A516 Grade 70, 1-1/4Cr – 1/2Mo, and 2-1/4 Cr – 1 Mo steels, at a PWHT temperature of 1200°F [649°C]. These materials and this temperature were chosen because of the availability of the required yield strength, modulus of elasticity, Poisson's ratio and coefficient of thermal expansion data. The calculated ratio T1/T0 for these materials at 1200°F [649°C] was 0.48, 0.50, and 0.50 respectively. It is recognized that the validity of this approach rests on the rule of thumb approach for setting the maximum stress and that a limited amount of data has been evaluated. The ratio T_1/T_0 is certainly material dependent and ultimately a function of the chosen allowable stress at temperature.

Requiring that the temperature at the edge of the weld be at least or greater than a specific percentage of the temperature at the edge of the soak band is a satisfactory means of limiting the magnitude of the thermal stresses caused by thermal gradients under the heat source. The results of the calculations reported above supports the traditional recommendation to limit the minimum temperature at the edge of the heated band (heater) to be half the PWHT temperature.

C3. Gradient Control Band Width

The purpose of the gradient control band (GCB) is to minimize the variation of the pipe's temperature under the heated band (heater) and to minimize the heat flux gradient discontinuity stresses at the edge of the heater. To a large extent, the temperature profile under the heater is controlled by the width of the heater and the heater power. Other important factors that contribute to the temperature profile in the heated band are the heat losses to the environment from the pipe under the heater (which is typically un-insulated) and the losses from the adjacent (unheated) sections of pipe.

The GCB width is specified to minimize the heat losses caused by the unheated portion of the pipe and its effect on the temperature profile under the heater. In fact, with a single circumferential zone of control, the heat treater cannot control the temperature at both the heater centerline and its edges. This is because the heater power is the only control variable. The losses in the pipe under the heater combined with the losses in the pipe adjacent to the heater establish the boundary conditions that determine the temperature at the edge of the heater.

Because the inside of the pipe is typically inaccessible, the GCB insulation is normally only applied on the outside of the pipe undergoing PWHT. The important characteristics of the GCB insulation are its insulation value and its width. The insulation value and the width of the GCB insulation affect the temperature gradient at the edge and away from the heater.

This discussion will address the issue of selecting the appropriate width of the GCB from the standpoint of induced thermal stresses and will proceed based on the following assumptions:

(1) The temperature of the uninsulated portion of the pipe at the edge of the GCB is in the range of 350°F to 500°F [177°C to 260°C].

(2) The temperature at the edge of the heater is at least half, if not three-quarters of the soak band PWHT temperature.

(3) The temperature drop off from the edge of the heater to the edge of the GCB may be reasonably approximated by a linear temperature gradient.

Thus the temperature gradient may be reasonably estimated to be in the range of one quarter to one third of the soak band PWHT temperature divided by the width of the GCB extension beyond the edge of the heater (w_{GCB}). Using the one third value as more conservative for stress analysis purposes gives

$$T'_{GCB} \cong \frac{T_{PWHT}}{3w_{GCB}} \qquad \text{(C13)}$$

A solution presented by Timoshenko (Reference C1) for a temperature profile varying linearly with distance and then transitioning to a uniform temperature profile in an axisymmetrically loaded cylinder will serve as the basis for the following stress evaluation. The solution is given by

$$\sigma = 0.706\, \alpha\, E \sqrt{Rt}\, T'_{GCB} \qquad \text{(C14)}$$

The term T'_{GCB} is the temperature gradient in the GCB beyond the heated band and is estimated as described above. Equation (C14) predicts stresses twice that given by Timoshenko (Reference B1) because Timoshenko's example considers only a single "kink" in the temperature profile instead of the two "kinks" described here. It is important to recognize that the stresses induced by this temperature profile are due entirely to the heat flux gradient discontinuity effect at each "kink" in the temperature profile. Equation (C14) is somewhat conservative in that it assumes that the two "kinks" are close enough to each other so that the peak stresses from each "kink" superimpose additively within the GCB extension beyond the heated band.

Substituting Equation (C13) into Equation (C14) and solving for w_{GCB} gives the following relationship for the length of the extension of the GCB beyond the heated band.

$$w_{GCB} = \frac{0.706 \alpha E \sqrt{Rt}\, T_{PWHT}}{3\sigma_{allowable}} \qquad \text{(C15)}$$

Equation (C15) states that under the given assumptions, the width of the GCB beyond the edge of the heated band necessary to limit the thermally induced bending stresses in the same region to a specified limiting value is equal to some constant times the parameter $\sqrt{Rt}$. Equation (C15) is offered to support the concept of a GCB width that is a multiple of $\sqrt{Rt}$. This approach is similar to that described by Tahara (Reference C7).

Solving Equation (C15) for induced stress puts the equation in a form that permits the induced thermal stress to be estimated based on the component's material properties and the width of the GCB extension beyond the heater edge. Taking the material properties at the mean temperature of the GCB, say 600°F to 700°F [316°C to 371°C], and using a GCB extension length of $2\sqrt{Rt}$ yields thermally induced bending stresses that are likely to be below yield for many piping materials. This leads to the recommendation that the total width of the gradient control band be equal to the width of the heated band plus $4\sqrt{Rt}$.

Another important issue is the achievement of full PWHT temperatures within the soak band. In particular, the temperature on the inside surface of the pipe is of great concern as discussed in Annex A. It is difficult to establish an analytical approach to sizing the GCB width based on through temperature concerns because of the great variability of the factors that most significantly affect the temperature uniformity of the pipe. These factors are the losses from the inside of the pipe and the losses from the gradient control band insulation. The result is that recommendations appear to be based upon experience and not upon readily apparent analytical techniques.

The British BS 5500 (Reference C8) and the Australian AS 1210 (Reference C9) pressure vessel codes both recommend a total insulated band width (e.g., GCB) of $10\sqrt{Rt}$ on the basis that this width will usually ensure that the requirements for temperature uniformity will be met (including achieving full PWHT temperature in the soak band). The $\sqrt{Rt}$ factor in the recommendations implies stress based reasoning for both recommendations.

References

C1. Timoshenko, S., *Theory of Plates and Shells*, Chapter 15, McGraw-Hill, 1940.

C2. Rose, R. T., Stress in cylindrical vessels due to local heating stress relief of circumferential welds, British Welding Journal, pp. 19–21, January 1960.

C3. Burdekin, F. M., Local stress relief of circumferential butt welds in cylinders, *British Welding Journal*, pp. 483–490, September 1963.

C4. Tanaka, S., and T. Umemoto, "Residual Stress Improvement by Means of Induction Heating," Presented at *Proceedings of the Seminar on Countermeasures for Pipe Cracking in BWRs*, Vol. 1, EPRI WS-79-174, Heating," Paper No. 13, Electric Power Research Institute, Palo Alto, CA, 1980.

C5. *Procedure for the Heat Treatment After Welding* (in German), FDBR 18, January 1984.

C6. Murakawa, H., and J. Wang, unpublished research, Joining and Welding Research Institute, Osaka University, Osaka, Japan, October 1997 to April 1998.

C7. Tahara, T., "Local PWHT for Pressure Vessels," Presented at *Proceedings of the Annual Meeting on Corrosion and Materials*, API—Refinery Division, Nashville, Tennessee, May 1991.

C8. BS 5500, *British Standard Specification for Unfired Fusion Welded Pressure Vessels*, 1997.

C9. AS 1210, *Australian Standard Unfired Pressure Vessels Code*, 1989.

Annex D (Informative)

Procedure for Thermocouple Attachment by Capacitor Discharge Welding

This annex is not part of this standard but is included for informational purposes only.

D1. IMPORTANT: Disconnect the thermocouple wire from any temperature monitoring or control instrument prior to capacitor discharge welding!

D2. Prior to the start of use, the thermocouple attachment unit (TAU) should be fully recharged. If the battery light should appear while pressing the discharge button, the unit may require recharging.

D3. The area where the thermocouple wire is to be attached should be free of all foreign materials such as paint, grease, or oils. Remove surface scale and debris typically with a wire wheel, grinder, file, or wire brush. A smooth, flat surface with shiny metal will result in optimal welds. The area for the attachment of the ground should be cleaned in a similar manner.

D4. Place the welding ground between 4 in and 24 in [0.1 m and 0.6 m] from the immediate weld area.

D5. If applicable, adjust voltage to desired setting (typically 65 VDC). Some equipment may not have adjustment capability.

D6. Strip approximately 1/2 in [13 mm] of the outer insulation from the end of the thermocouple wire to be attached. Pull this outer insulation back approximately 4 in [100 mm] and bend the individual insulated wires apart such that they keep the outer insulation pulled back.

D7. Make sure all oxides have been removed from the surfaces of the pliers which will contact the thermocouple wire. Pull back the insulation on one of the thermocouple leads and hold the lead with the discharge pliers approximately 1/4 in [6 mm] from the end that is to be attached to the component. With the pliers holding the exposed wire, the insulation can be released and will move back to the point of contact with the pliers.

D8. Press the charge button on the TAU until the light signals ready.

D9. After the light appears, hold the thermocouple wire motionless and in contact with the desired location for attachment on the component. For automatic units, the discharge will occur automatically within approximately two seconds. For nonautomatic units, push the discharge button. In either case, a flash and pop should follow. Continue to hold the lead with the pliers for two to three seconds after the discharge to allow the weld to cool. After the pliers are released, pull the insulation back to the weld, thereby covering all of the lead.

D10. Repeat Steps D7 through D9 for the other thermocouple lead, positioning the second lead approximately 1/4 in [6 mm] away from the first lead.

D11. After completion of the welds, check their integrity by holding the thermocouple wire approximately 1/2 in [13 mm] from each weld and gently pulling on the wire. After checking both welds, pull the outer insulation back as close to the weld as possible.

D12. Should either of the wires detach upon gently pulling, remove the burned end of the wire(s), prepare the parent metal surface per step D2, and repeat steps D6 through D10.

D12.1 Removal of Thermocouples. During the equipment removal stage, the location of each thermocouple should be adequately identified. This is typically accomplished by circling the attachment area with a marker or chalk.

Light filing or grinding followed by inspection of the thermocouple attachment areas may be required. Care must always be exercised during filing or grinding to prevent removal of too much metal.

D12.2 Procedure and Performance Qualification. Neither qualification of this procedure nor performance qualification of welders is required by the fabrication codes listed below if the maximum energy input is limited to 125 Watt-seconds (Joules) in accordance with the equation listed below.

ASME Section III, Div. 1, paragraph NB-4311.2

ASME B31.1, *Power Piping*, paragraph 127.4.9 (A)

ASME B31.3, *Process Piping*, paragraph 330.1.3 (b)

Energy input = 1/2 CV^2 (Watt-seconds [Joules])

where:
C = capacitance in Farads
V = direct current voltage

Annex E (Informative)

Accuracy of Thermocouple Temperature Measurements

This annex is not part of this standard but is included for informational purposes only.

A number of factors determine the overall accuracy of a temperature measuring system. They include sensor, system connections, and instrumentation error contributions. The discussion in this annex is based upon the assumption that a type K thermocouple is attached to the workpiece by means of capacitor discharge welding (directly attached, separated junction thermocouple). The type K thermocouple is suitable for PWHT applications not exceeding 2300°F [1260°C]. The lead extending from the sensor to the measuring or controlling instrument will be of thermocouple extension grade and interconnecting plugs and sockets will also be made of the type K material. References are provided for various documents (References E1–E6) which discuss the issues addressed in greater detail.

E1. 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, the Thompson Effect, and position uncertainty.

E1.1 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 National Institute of Standards and Technology (NIST) standards. This error is expressed as a deviation from NIST standards. The deviation results from a variation in the material composition 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 (1150°F [621°C]), the inaccuracy due to wire composition is ±4.6°F [±2.55°C].

E1.2 Stability. Extended exposure of standard type K wire to temperatures of 1000°F [538°C] or more can lead to a shift of +6°F to +9°F [+3.3°C 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 1000°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.

E1.3 Remaining Factors. 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, the Thompson Effect, and position uncertainty) are not expected to be significant if good installation and routing practices are followed and normal local heating conditions are encountered. Each of the remaining factors is briefly defined below.

(1) Intermediate Metal—Effect of the workpiece as an intermediate metal at the hot junction of a directly attached, separated junction thermocouple.

(2) Green Rot—Effect of an oxide layer resulting from reducing atmospheres.

(3) Cold Work—Effect of alterations of the cross sectional area of thermocouple wire due to mechanical deformation.

(4) Noise—Effect of electrical interference picked up by the sensor.

(5) Thompson Effect—Effect of temperature gradients along the cable.

(6) Position Uncertainty—Effect of a deviation in the actual position of the junction versus the desired position of the junction.

E2. System Connections Error

The total error for the cable system (extension wire and connectors) to the instrument will result from initial calibration, stability, intermediate metals, green rot, cold work, noise, the Thompson Effect, and 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 can be neglected.

E3. 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°F to 2000°F [–18°C to 1093°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].

E4. 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].

E5. Improving Total System Accuracy

The system can be improved by properly maintaining and calibrating the recording instrument. This requires that a calibration device be utilized which has an accuracy four 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 in [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].

References

E1. *Manual on The Use of Thermocouples in Temperature Measurement*, ASTM Manual Series MNL 12, Fourth Edition, 1993.

E2. ANSI MC96.1, *Temperature Measurement Thermocouples*, Instrument Society of America, August 1982.

E3. Wang, T. P., "Thermocouple Materials," *ASM Handbook*, *Volume 2*, *Properties and Selection: Nonferrous Alloys and Special Purpose Materials*, Tenth Edition, pp. 869–888, 1990.

E4. Thermocouple Cable Lengths and System Accuracy, Product Bulletin #55, Thermo Electric Company, September 1994.

E5. Morrison, R., *Grounding and Shielding Techniques in Instrumentation*, John Wiley and Sons, 1967.

E6. Wang, T. P., "Accuracy, Stability, and Factors Affecting Calibration of Thermocouples," Presented at *Proceedings of the Measurement Science Conference*, 1992.

Annex F (Informative)

Information on Types of Insulation

This annex is not part of this standard but is included for informational purposes only.

This annex provides information regarding various types of thermal insulation that are commonly used during local heating operations.

F1. Glass Wool

Fiber glass wool is a silicate man-made vitreous fiber (MMVF) manufactured by a discontinuous process. As a result, a significant portion of the fiber sizes produced will be considered respirable. 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 that can readily become airborne. The softening point of the fibers is reported to be 1200°F [649°C], with a maximum recommended use temperature of 840°F [450°C] (Reference F1).

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

F2. Rock and Slag Wool

Rock and slag wool are silicate MMVF manufactured by a discontinuous process. As a result, a significant portion of the fiber sizes produced will be considered respirable. As the name implies, rock or blast furnace slags 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 that can readily become airborne. The maximum continuous service temperature is approximately 1200°F [640°C], with devitrification (transformation from amorphous to crystalline) beginning above 1337°F to 1517°F [725°C to 825°C] (Reference F1). If transformed to the crystalline state, fibers can fracture longitudinally and as a result, adversely change their diameter and aspect ratio, thereby increasing the number of respirable fibers. 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.

F3. Refractory Ceramic Fiber

Refractory ceramic fiber (RCF) is silicate MMVF manufactured by a discontinuous process. As a result, a significant portion of the fiber sizes produced will be considered respirable. 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 1832°F [1000°C] and begin softening in the range 3164°F to 3272°F [1740°C to 1800°C] (Reference F1). The maximum continuous use temperature is approximately 2000°F [1093°C]. If transformed to the crystalline state, fibers can fracture longitudinally and as a result, adversely change their diameter and aspect ratio, thereby increasing the number of respirable fibers. RCFs are more expensive than glass or mineral wool, but generally have the lowest thermal conductivity.

F4. 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. The continuous nature of the manufacturing process enables production of fibers diameters well in excess of that considered respirable. For high purity silica fibers, the maximum use temperature reported is 2012°F [1100°C], with devitrification beginning at 1832°F [1000°C] (Reference F1). Variation of these temperatures with purity is noted (Reference F1). If transformed to the crystalline state, fibers can fracture longitudinally and as a result, adversely change their diameter and aspect ratio, thereby increasing the number of respirable fibers. 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 intact 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.

F5. Fiber Respirability

Consult manufacturers 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.

Reference

F1. *Man-Made Vitreous Fibers Nomenclature, Chemistry and Physical Properties*, Revision 2, Thermal Insulation Manufacturers Association, Inc. (TIMA), now the North American Insulation Manufacturers Association (NAIMA), March, 1993.

Annex G (Informative)

Standard Procedure for Local Heating

This annex is not part of this standard but is included for informational purposes only.

Procedure No.: ____________________ Revision No.: __________ Date: ______________

Governing Code: ____

Workpiece Identification Number: ____

Material Specification: ____

Component Dimensions: ____

Thermocouple, Heater, and Insulation Layout Drawing Number: ______________________

Thermal Cycle

Heating Rate: ____________________ °______/hour (specify max. or min.) above ______________ ° ______

Hold Temperature Range: ____________________ ° to ______________________ ° ______

Minimum Hold Time: ____________________ hours Maximum Hold Time: ____________________ hours

Cooling Rate: ____________________ °______/hour (specify max. or min.) above ______________ ° ______

Steps

G1. Match procedure/drawings to workpiece, including verification of workpiece identification number. Check the appropriateness of specified thermal cycle to the material and application.

Completed by: ______________________________ Date: ______________

G2. Install and test power/control equipment, including power supplies, temperature controllers, and temperature recorders.

Completed by: ______________________________ Date: ______________

G3. Check validity of calibration date on all temperature recorders. Enter serial number and date next calibration due for each recorder.

Serial number: ____________________ Date Next Calibration Due: ______________

Serial number: ____________________ Date Next Calibration Due: ______________

Serial number: ____________________ Date Next Calibration Due: ______________

Serial number: ____________________ Date Next Calibration Due: ______________

Completed by: ______________________________ Date: ______________

G4. Install thermocouples (including spares) per drawing/sketch using approved methods. Direct attachment by capacitor discharge welding (Annex D) is recommended.

Completed by: ______________________________ Date: ______________

G5. Verify specified (per drawing/sketch) placement of thermocouples.

Verified by:___________________________________ (User's/Owner's Inspector) Date:________________

G6. Install heat sources and insulation per drawing/sketch using approved methods.

Completed by: ____ Date:________________

G7. Verify specified (per drawing/sketch) placement of heat sources and insulation before the start of heating.

Verified by:___________________________________ (User's/Owner's Inspector) Date:________________

G8. Install and connect thermocouple extension wire. Check operation of all thermocouples. Check for reversal of thermocouple polarity. Note that it may only be possible to detect a double polarity reversal visually.

Completed by: ____ Date:________________

G9. Install and connect power cables. Check operation of all heat sources.

Completed by: ____ Date:________________

G10. Obtain approval to begin the heating operation.

Approved by: ________________________________ (User's/Owner's Inspector) Date:________________

G11. Perform and document periodic checks during heating, including equipment operation (recorder and power supplies) and adherence to specified heating rate. If a deviation occurs during heating, follow approved corrective action. If it appears that achieving the hold temperature will be difficult and requires excessive time, the User/Owner's Inspector should be notified and a decision made regarding whether to continue heating.

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

G12. Verify the start of the hold period, e.g., all soak band thermocouples are within the required temperature range.

Verified by:___________________________________ (User's/Owner's Inspector) Date:________________

G13. Perform and document periodic checks during the hold period, including equipment operation (recorder and power supplies) and adherence to required hold temperature range. If a deviation occurs during the hold period, follow approved corrective action. A maximum time in the hold temperature range may be specified for certain materials. If it appears that the maximum time limit will be exceeded, the User/Owner's Inspector should be notified and a decision made regarding whether to continue heating.

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

G14. Verify completion of the hold period, e.g., all soak band thermocouples remained within the required temperature range for the minimum required time. Must be verified before the start of cooling.

Verified by:___________________________________ (User's/Owner's Inspector) Date:________________

G15. Perform and document periodic checks during cooling period, including equipment operation (recorder and power supplies) and adherence to specified cooling rate. If a deviation occurs during cooling, follow approved corrective action.

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

Completed by: ______________________________ Date:________________ Time: _______________

G16. Deactivate power/control equipment after the temperature is below that where cooling rate control is required.

Completed by: ____ Date:______________

G17. Remove all equipment after the temperature is safe for personnel. Cut thermocouple wires and mark locations of attached thermocouples for light filing/grinding.

Completed by: ____ Date:______________

G18. Note any deviations such as heating rate, hold time and temperature, or cooling rate that occurred during the thermal cycle. If no deviations occurred, enter "None."

____

____

____

____

____

Completed by: ____ Date:______________

G19. Complete and submit to User's/Owner's Representative appropriate documentation in accordance with Standard Documentation Checklist (Annex H).

Received by:__________________________(User's/Owner's Representative) Date:______________

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Annex H (Informative)
Standard Documentation Checklist for Local Heating

This annex is not part of this standard but is included for informational purposes only.

It is recommended that the following documentation be provided by the supplier of local heating services at the completion of work:

H1. ☐ Procedure (Annex G) with all required information completed

H2. ☐ Drawings/sketches for thermocouple, heater and insulation layout

H3. ☐ Thermocouple wire Certificates of Conformance

H4. ☐ Temperature recorder calibration records

H5. ☐ Hardness testing results (if applicable)

H6. ☐ Strip chart record of the entire thermal cycle with the following information

a. ☐ Date(s), time period and location work performed

b. ☐ Identification of contractor/personnel performing the work

c. ☐ Identification number of the workpiece

d. ☐ Temperature and time scales

e. ☐ Correspondence between thermocouple numbers on the chart(s) and drawing/sketch

f. ☐ Heating rate above specified temperature

g. ☐ Hold period temperature and time

h. ☐ Cooling rate above specified temperature

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Annex I (Informative)

Informative References

This annex is not part of this standard but is included for informational purposes only.

I1. Introduction

Extensive reference to local heating requirements found in common piping codes, standards, and practices is made to aid the user of this document. These referenced codes, standards, and practices are listed below. Except for hydrogen bakeout and postheating, specific hold temperature and time requirements are not discussed.

I2. Piping Fabrication Codes

(1) ASME Boiler and Pressure Vessel Code, Section III, Division 1—Subsection NB, Class 1 Components, *Rules for Construction of Nuclear Power Plant Components*

(Note: Although direct reference is made to Subsection NB and its related paragraphs, Subsections NC and ND for Class 2 and 3 components have essentially the same requirements.)

(2) British Standard Specification for Class I Arc Welding of Ferritic Steel Pipework for Carrying Fluids (BS 2633)

I3. Recommended Practices Regarding Service Environment

(1) Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments (NACE SP0472–95)

(2) Avoiding Environmental Cracking in Amine Units (ANSI/API 945)

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Annex J (Informative)

Requesting an Official Interpretation on an AWS Standard

This annex is not part of this standard but is included for informational purposes only.

J1. Introduction

The following procedures are here to assist standard users in submitting successful requests for official interpretations to AWS standards. Requests from the general public submitted to AWS staff or committee members that do not follow these rules may be returned to the sender unanswered. AWS reserves the right to decline answering specific requests; if AWS declines a request, AWS will provide the reason to the individual why the request was declined.

J2. Limitations

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

J3. General Procedure for all Requests

J3.1 Submission. All requests shall be sent to the Managing Director, AWS Standards Development. For efficient handling, it is preferred that all requests should be submitted electronically through standards@aws.org. Alternatively, requests may be mailed to:

Managing Director
Standards Development
American Welding Society
8669 NW 36 St, # 130
Miami, FL 33166

J3.2 Contact Information. All inquiries shall contain the name, address, email, phone number, and employer of the inquirer.

J3.3 Scope. Each inquiry shall address one single provision of the standard unless the issue in question involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the request along with the edition of the standard (e.g., D1.1:2020) that contains the provision(s) the inquirer is addressing.

J3.4 Question(s). All requests shall be stated in the form of a question that can be answered 'yes' or 'no'. The request shall be concise, yet complete enough to enable the committee to understand the point of the issue in question. When the point is not clearly defined, the request will be returned for clarification. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annexes) that bear on the issue in question shall be cited.

J3.5 Proposed Answer(s). The inquirer shall provide proposed answer(s) to their own question(s).

J3.6 Background. Additional information on the topic may be provided but is not necessary. The question(s) and proposed answer(s) above shall stand on their own without the need for additional background information.

J4. AWS Policy on Interpretations

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all official interpretations are approved by the technical committee that is responsible for the standard. Communication concerning an official interpretation is directed through the AWS staff member who works with that technical committee. The policy requires that all requests for an official interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the procedures that must be followed, some requests for an official interpretation may take considerable time to complete.

J5. AWS Response to Requests

Upon approval by the committee, the interpretation is an official interpretation of the Society, and AWS shall transmit the response to the inquirer, publish it in the *Welding Journal*, and post it on the AWS website.

J6. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The *AWS Board Policy Manual* requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

List of AWS Documents on Piping and Tubing

Designation	Title
D10.4	*Recommended Practices for Welding Austenitic Chromium-Nickel Stainless Steel Piping and Tubing*
D10.6/D10.6M	*Recommended Practices for Gas Tungsten Arc Welding of Titanium Piping and Tubing*
D10.7M/D10.7	*Guide for the Gas Shielded Arc Welding of Aluminum and Aluminum Alloys*
D10.8	*Recommended Practices for Welding Chromium-Molybdenum Steel Piping and Tubing*
D10.10/D10.10M	*Recommended Practices for Local Heating of Welds in Piping and Tubing*
D10.11M/D10.11	*Guide for Root PSS Welding of Pipe Without Backing*
D10.12M/D10.12	*Guide for Welding Mild Steel Pipe*
D10.13/D10.13M	*Recommended Practices for the Brazing of Copper Tubing and Fittings for Medical Gas Systems*
D10.14M/D10.14	*Guide for Multipass Orbital Machine Pipe Groove Welding*
D10.18M/D10.18	*Guide for Welding Ferritic/Austenitic Duplex Stainless Steel Piping and Tubing*
D10.22/D10.22M	*Specification for Local Heating of Welds in Creep Strength-Enhanced Ferritic Steels, in Piping and Tubing Using Electric Resistance Heating*

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