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Thermowell and Radiographic Testing Plug Design Recommendations and Typical Practices

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PRODUCT DESCRIPTION

Thermowells and radiographic testing (RT) plugs are used universally in power generation plants. This Electric Power Research Institute (EPRI) report provides recommendations and explains the design and installation practices for these products that are common to the power industry. Numerous instances of thermowell failure are addressed and examined for the purposes of optimization.

The report is intended to provide design, installation, and operation recommendations for power applications.

Background
Numerous field reports of thermowell and RT plug failures prompted EPRI to examine standard practices and designs being used in order to avoid field failure. Concurrently, in 2010, the only thermowell standard providing a pass/fail result to a thermowell design was significantly revised for the first time in 30 years in response to field reports of thermowell failures. This report covers the new American Society of Mechanical Engineers Performance Test Code 19.3 TW-2010 Thermowells standard and incidents of thermowell and RT plug failures and makes recommendations based upon these investigations of practical means to avoid similar failures.

Objective
- To explain current standard practices regarding thermowells and RT plug design, use, and installation.

Approach
A review of current publications, practices, and standards was completed and incorporated into the report along with input from member surveys.

Results
The report provides a straightforward analysis of many common issues facing owners/operators and designers whose systems incorporate the use of thermowells and RT plugs.

Applications, Value, and Use
This report seeks to provide guidance and recommendations for power plant designers, including operations and maintenance personnel tasked with the responsibility of designing, installing, specifying, or otherwise working with thermowells or RT plugs.

Keywords
Natural frequency
Protection tube
Radiographic testing (RT) plug
Thermocouple
Thermowell
Wake-frequency calculation

ABSTRACT

Thermowells and radiographic testing (RT) plugs are universally used in power generation plants. Their design, material selection, and proper installation are key to maintaining the safe and smooth running of any plant. Successful and unsuccessful practices for each are reviewed in this report.

Of particular note, in the summer of 2010, the only U.S. standard assessing the design strength of thermowells was significantly changed for the first time in 30 years. The numerous changes implemented by the standard were required by field reports of failure, including one significant incident involving a loss-of-cooling accident at the Monju Nuclear Power Plant in Japan.

This report addresses the changes instituted by the American Society of Mechanical Engineers Performance Test Code 19.3 TW-2010 Thermowells standard and discusses their impact upon common temperature measurement engineering practices.

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1
INTRODUCTION

Why Is the Guide Needed?

Radiographic testing (RT) plugs and thermowells are universally used in power plants and other industries. The core function of an RT plug is to seal the opening in a pipe left wall following an RT of welds as soon as pipe fabrication is complete. The core function of a thermowell is to position a sensor inside of a pipe to provide an accurate temperature measurement and enable the removal and replacement of the sensor without opening up the process.

The Electric Power Research Institute (EPRI) has been motivated by its member community to publish a guide addressing the proper design of an RT plug and thermowell, selection, and installation in response to field reports of failure for both of these products. Although the study is not exhaustive, this report seeks to identify practical methods and solutions to promote safe and effective design and installation.

The design, selection of materials, and proper installation of these products are key to maintaining the integrity of the pressurized system and, for thermowells, obtaining accurate and reliable temperature measurement. An effective design for these components requires the considerations of stress, corrosion, erosion, vibration, and installation technique. This report seeks to provide guidance and recommendations for power plant designers and operations/maintenance personnel tasked with the responsibility of designing, installing, or working with thermowells and RT plugs.

What Do RT Plugs and Thermowells Have in Common That Causes Them to Be Addressed in One Guide?

Thermowells and RT plugs are installed in high-pressure piping. As a consequence, each maintains the potential for pressure-related failure. Moreover, the products are fabricated from similar materials and share some methods of installation, so factors of installation, erosion, and corrosion are important for each. Thermowells and RT plugs fall into a category of piping connections that are not well addressed by the typical piping codes such as the American Society of Mechanical Engineers (ASME) B31.1 [1].

Should I Consider Additional Failure Modes for Thermowells?

Yes. Unlike RT plugs, thermowells project into the flow of the pipe. Consequently, thermowells exhibit susceptibility to additional modes of failure not present with RT plugs. These modes are referred to as *steady-state stress*, *dynamic stress*, and *velocity-induced resonance stress*.

What New Research or Guidance Is Available to Help Specify and Design Thermowells?

For many years, thermowell design has been subject to a pass/fail test established by the ASME, predicting success or failure of a given thermowell installation by comparing a proposed thermowell design to anticipated process characteristics. In 2010, this standard was replaced due to field reports of thermowell failures that were not predicted by the previous standard. These failures included a significant incident involving a loss-of-cooling accident at the Monju Nuclear Power Plant, resulting in a plant shutdown.

The new ASME/American National Standards Institute (ANSI) 19.3 TW-2010 standard [2] reflects a comprehensive change to the entire ASME/ANSI 19.3 (2004) [3] standard and can result in more conservative (shorter and fatter) thermowell designs. The guide will explain many of these changes, provide tools to apply the design standard, and detail the consequent impact on temperature measurement accuracy and responsiveness. It will also provide some details on a few problematic applications such as steam blow and circulating water lines.

What Could Possibly Be New in the World of RT Plugs?

For many years, the *de facto* mechanism for performing a nondestructive examination of pipe welds has been radiographic/X-ray testing, referred to under the ASME Codes as *RT*. Over the last few years, the primary shift in this area has been the migration toward ultrasonic testing (UT) of welds, which does not require pipe penetration and plugging.

For piping where RT testing is preferred and in legacy installations where RT plugs are in use, the guide details a number of differing plug designs, detailing some of the known disadvantages and advantages of each.

References

1. ASME B31.1-2012, Power Piping.
2. ASME PTC 19.3 TW-2010, Thermowells.
3. ASME PTC 19.3-2004, Part 3: Temperature Measurement, pars. 8−19.

2
THERMOWELL DESIGN

Thermowells are universally used in power applications. A thermowell serves to protect its installed temperature sensor from failure and enable the removal and replacement of that sensor without opening up the process or negatively impacting the sensor's ability to indicate the temperature of the process fluid. The thermowell also provides proper positioning of the temperature sensor within the piping to assure accurate and reliable measurement [1].

None of these goals can be accomplished if the thermowell is inappropriately designed. The consequences of thermowell failure can range from a minor irritant to a major safety hazard (see Figure 2-1). This section covers the fundamental and controlling principles of thermowell design as well as some pitfalls to avoid that are commonly encountered and capable of resulting in thermowell failure.

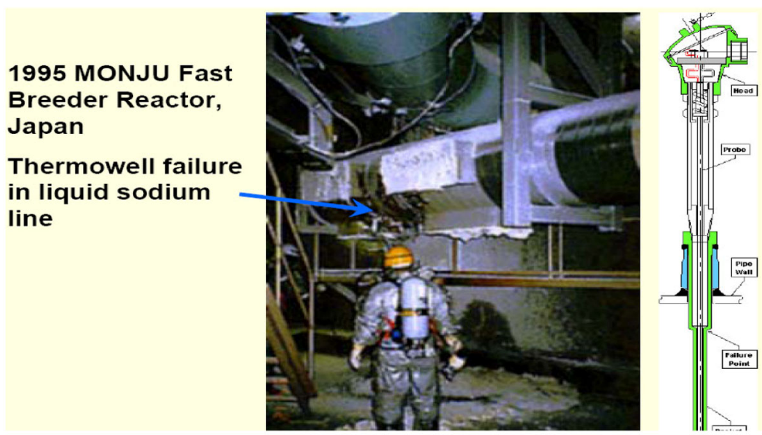


Figure 2-1
An operator preparing to replace a failed thermowell

A Case for Thermowell Fundamentals

For years, many companies have held internal standards that they cling to with little thought other than *it's the way it has always been done*. An example of this in the case of thermowells is the adherence to a design specification that mandates an immersion halfway into the pipe, plus 0.5 in. (12.7 mm) so that the sensing element is in the center of the pipe. Another commonly used rule prescribes that the sensing element be located in the middle one-third of the pipe flow (see Figure 2-2).

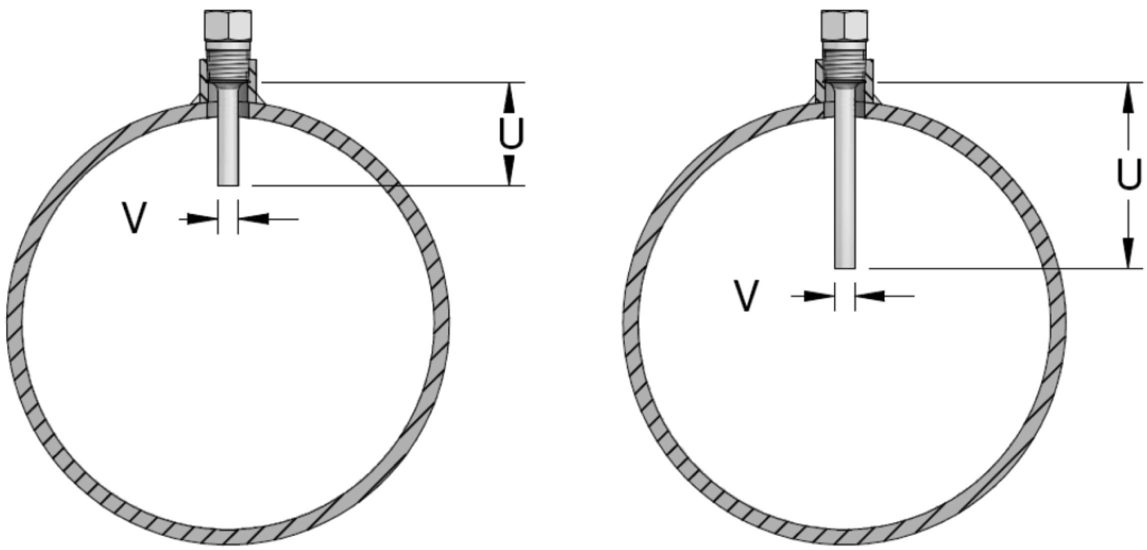


Figure 2-2
Typical thermowell design analysis (Is the U-length long enough to reach the middle one-third of the pipe?)

In many cases, the middle one-third of the pipe may be a perfectly good rule. Immersion into the middle third will avoid laminar areas of lower temperature that may exist in processes that are not well mixed. Moreover, the farther the thermowell is immersed into the process the lower the effects of conduction error on the temperature measurement.

However, be aware that depending on process conditions there are a number of other factors that can cause a standard thermowell to suffer mechanical failure at insertion lengths less than one-third of the pipe. These include flow-induced vibration (wake-frequency failure), dynamic (oscillating) and steady-state stress, pressure, corrosion, erosion, material selection, and improper installation technique [2].

Who Is Responsible for Thermowell Design?

The ASME Code clearly states that the responsibility for designing and specifying a suitable thermowell rests with the designer of the system into which the thermowell is being installed, as described in the following:

> Specification of a thermowell and the materials of construction are the sole responsibility of the designer of the system that incorporates the thermowell.
>
> Specification of a thermowell, including details of its intended installation and all intended operating conditions, is the responsibility of the designer of the system that incorporates the thermowell. The designer of that system is also responsible for ensuring the thermowell is compatible with the process fluid and with the design of the thermowell installation in the system. [3]

The Code clearly states that the final responsibility for the suitability of a thermowell for power plant applications rests with the engineer designing the boiler, steam line, heat recovery steam generator, turbine, and so on. Ostensibly, this responsibility would be shared in cases where system design is the shared responsibility of the end user and system supplier.

The standard goes on to state that the responsibility for ensuring compatibility of the process with the system is the responsibility of the end user:

> Sole responsibility for ensuring compatibility of the process fluid with the system rests with the end user. [4]

What Is a Thermowell and What Is Not?

The American Society for Testing and Materials (ASTM) has defined the term *thermowell* as follows:

> Thermowell, n. – a closed-end reentrant tube designed for insertion of a temperature-sensing element, and provided with means for a pressure-tight attachment to a vessel. [5]

In this instance, the ASTM definition of *thermowell* leaves a bit to be desired. Thermowells have a surprising degree of diversity, and not everything that looks like a thermowell is actually a thermowell [6].

Protection tubes, for example, meet the ASTM definition for *thermowell*. Moreover, protection tubes are often casually referred to as *thermowells*. However, protection tubes are not considered thermowells for purposes of the ASME thermowells design standard [7], and they were not included in the 19.3 standard that preceded it [8].

Protection tubes differ from thermowells in that they are typically manufactured from ceramic materials such as mullite or alumina or a metal pipe. Ceramic protection tubes (see Figure 2-3) are often necessitated in furnaces and other applications where the extremely high temperature would cause most metals to simply melt.

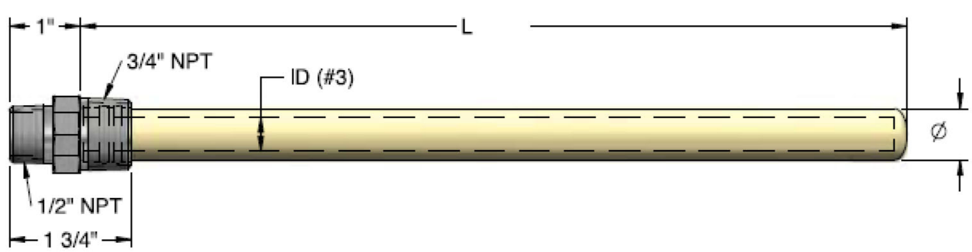


Figure 2-3
Typical ceramic protection tube

Metal protection tubes are typically manufactured from seamless pipe with a plug or machined tip welded on to close the hot end (see Figure 2-4). These make particular sense in low-velocity, low-pressure applications, especially where a combination of expensive exotic metals and long immersion lengths would make a thermowell prohibitively costly.

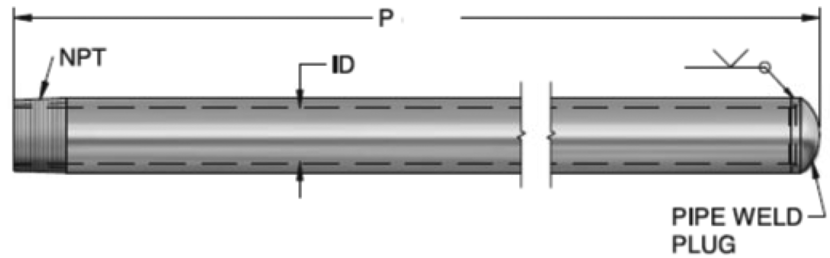


Figure 2-4
Typical metal protection tube with a welded plug at one end

A disadvantage posed by the protection tube is the increased response time associated with this design. The temperature sensor indicates its own temperature, not the temperature of the process. Compared to a thermowell, a protection tube has much larger air gaps between the sensor and the inside wall. This translates into much slower response times because air is a much poorer conductor of heat than metal, often changing a response time from seconds to minutes.

A solution devised to solve the response time problem for protection tubes is the fast-response protection tube (see Figure 2-5).

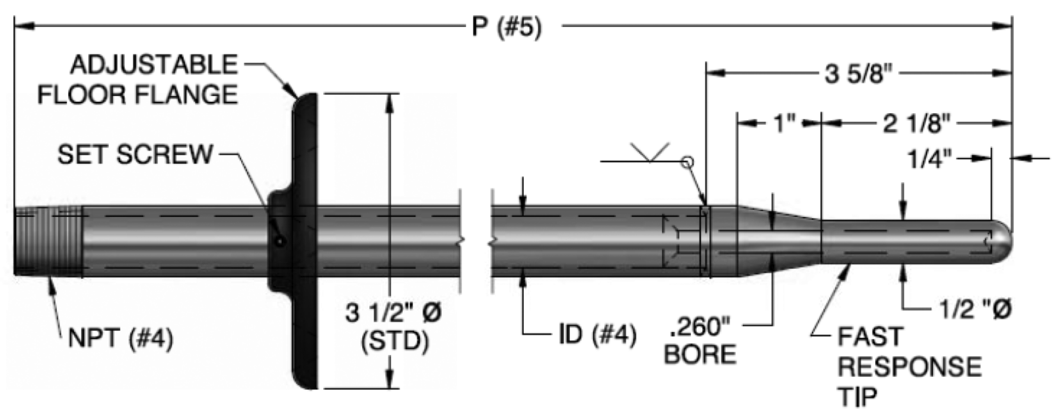


Figure 2-5
Fast-response metal protection tube

The fast-response design essentially consists of a thermowell welded on to the end of a protection tube. This design enables the sensing element of the temperature sensor to be installed in a small bore thermowell without requiring the material consumption or increased cost of a thermowell.

By contrast, thermowells are constructed of solid drilled-out bar stock (see Figure 2-6) [9]. Under the ASME standard, there are no welds in a thermowell, except in the case of flanged wells where a weld is often used to attach the flange to the thermowell shank.

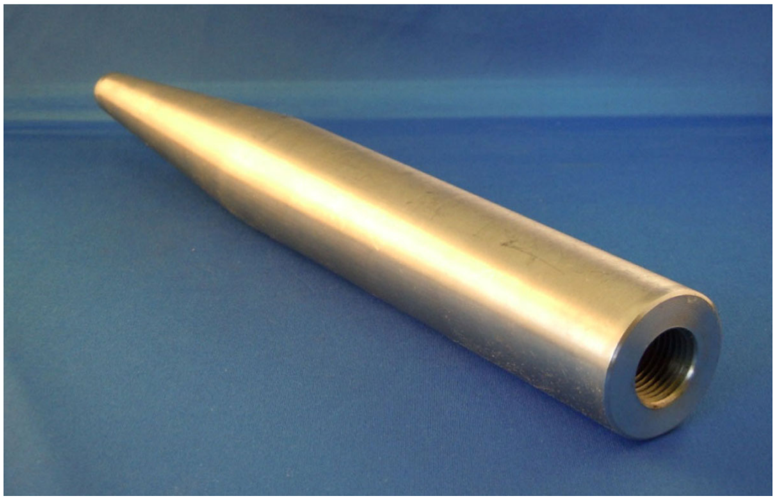


Figure 2-6
Typical weld-in thermowell, shaped and gun-drilled from solid bar stock

Although each of these designs—protection tube, fast-response protection tube, and thermowell—has its advantages and disadvantages that must be considered, for design purposes, it is important to know that all protection tubes and fast-response protection tubes are outside of the scope of the ASME 19.3 TW-2010 Thermowells standard. Moreover, welded-tip thermowells and butt welds along the thermowell shank are also outside of the scope of the ASME standard, as well as all thermowells with velocity collars, fins, spirals, coatings, sleeves, or knurled surfaces [10].

A final important note is that only thermowells that meet specific dimensional and manufacturing tolerances stated in the 19.3 TW standard can be evaluated by application of the 19.3 TW design calculations; not all do [9]. See Appendix A for a more detailed explanation.

Common Thermowell Process Connection Types

Thermowells are frequently categorized by process connection type. The most commonly encountered thermowell process connection types in a power application include threaded, weld-in, socket weld, and flanged (see Figure 2-7) [11].

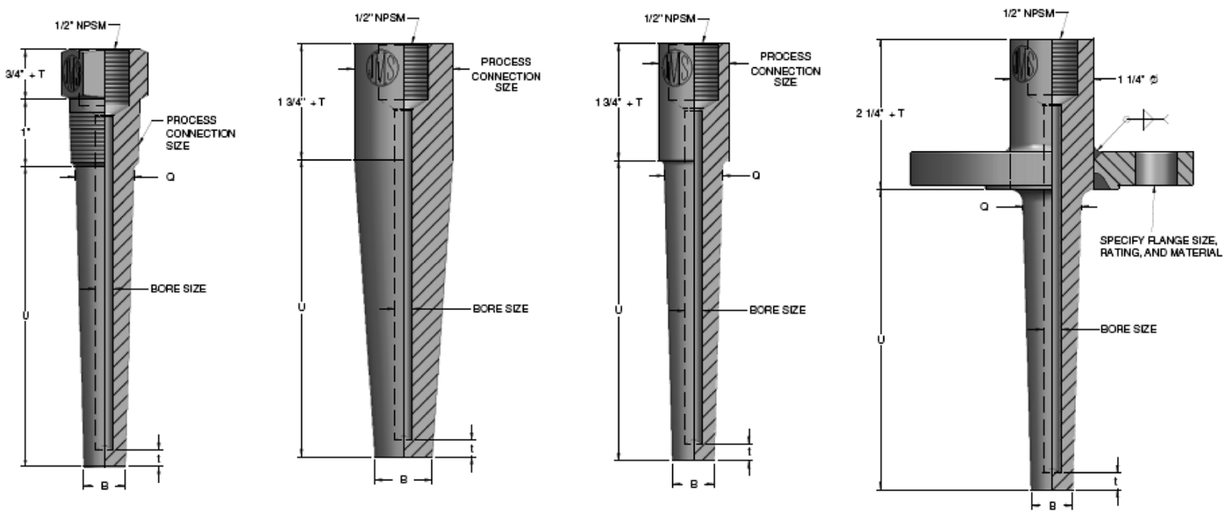


Figure 2-7
Common process connections: threaded, weld-in, socket weld, and flanged

Threaded thermowells are typically threaded into a thread-o-let that is welded into the pipe or threaded directly into a pipe wall that has been tapped for this purpose. Weld-in thermowells are typically installed by boring a hole and using a full penetration weld to attach the thermowell to the pipe wall. Less frequently, a boss is also used to attach a weld-in thermowell to a pipe.

Socket thermowells have a shoulder machined to fit a sock-o-let, which itself is typically welded into a pipe wall. Less frequently, socket thermowells will be directly welded into a process. Flanged thermowells come in typical flange facings of raised face, flat face, ring joint, or lap joint (van stone) and mated to receiving flange on a nozzle in the piping. Because the flange is typically welded to the thermowell shank (except in the case of a lap joint that is machined from a solid bar), the flange and thermowell shank should be constructed from the same material. The impact of the selection of the process connection on the strength of a thermowell design is addressed in the ASME Code section of the guide. Practices for proper installation of thermowells are addressed in the section on thermowell installation.

Common Thermowell Shank Styles

The most common thermowell shank styles are straight, tapered, and stepped (see Figure 2-8) [11].

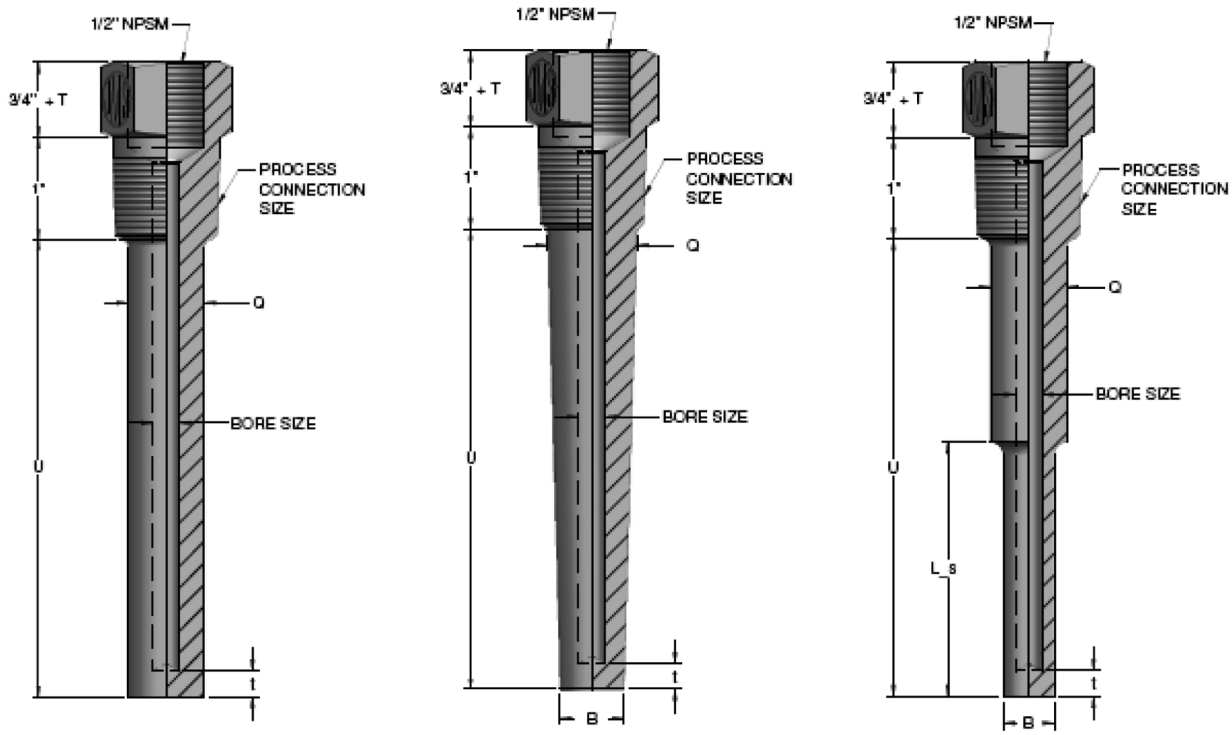


Figure 2-8
Threaded thermowells (from left to right) having straight, tapered, and stepped shanks

The name for each style is fairly straightforward. A straight shank is straight. A tapered shank tapers from a major diameter at the root of the thermowell just below the process connection to a smaller diameter at the tip. A stepped thermowell is straight for its entire length until the last 2.5 in. (63.5 mm) at the tip, where it steps down to a smaller diameter, typically to a 0.5-in. (12.7-mm) outside diameter (OD).

Each thermowell design has its own set of advantages and disadvantages, as shown in Table 2-1.

Table 2-1
Comparison of thermowell shank styles

	Straight	Tapered	Stepped
Strength	Strongest (often)	Strongest (sometimes)	Strong
Response Time	Fast	Faster	Fastest
19.3 Coverage	Not clear	Yes	No
19.3 TW Coverage	Yes	Yes	Yes

Tapered wells are the most common shank construction style [12].

Straight, tapered, and stepped designs are the only shank styles within the scope of the ASME thermowells standard. Thermowells with shank supports such as velocity collars, angle iron, spirals, and so on are excluded (see Figure 2-9) [10].

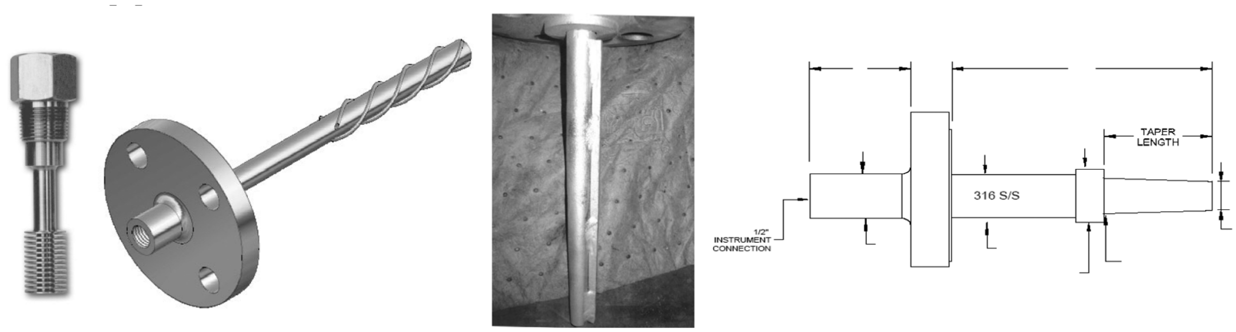


Figure 2-9
Shank styles not permitted by ASME 19.3 TW

Thermowells having shanks that are coated or sleeved (see Figure 2-10) are also outside of the scope of the ASME standard [10].

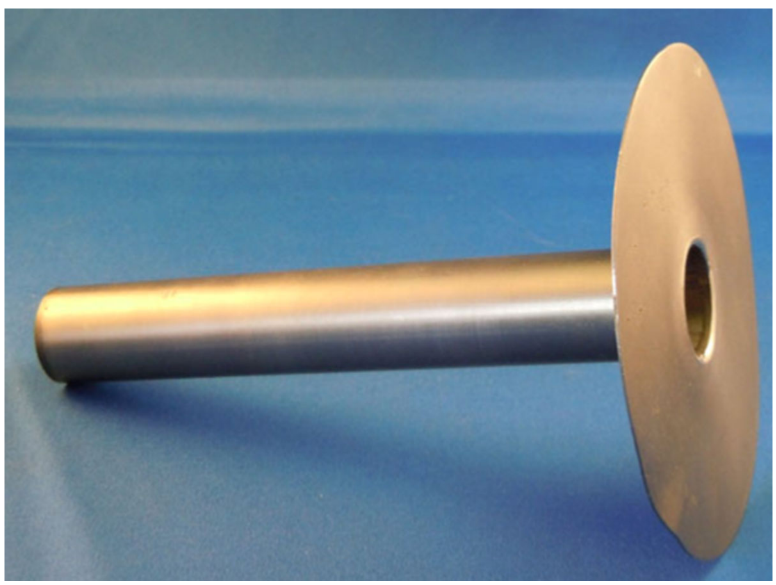
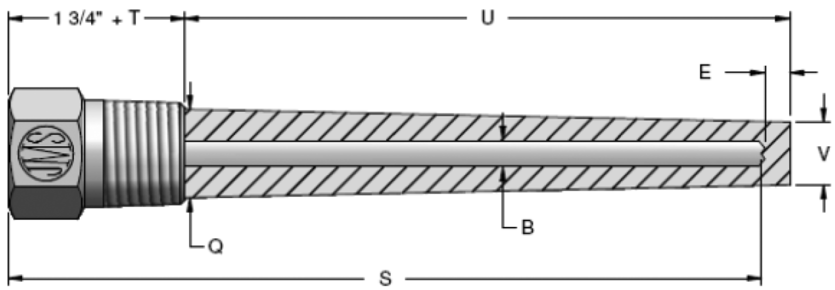


Figure 2-10
Tantalum sleeve to attach to the wetted portion of a flanged thermowell

Common Thermowell Dimensions and Symbols

To properly specify a thermowell, it is necessary to have a grasp of the pertinent dimensions and terminology. The most commonly applied standard providing dimensions for thermowells is the ASME B40.9 standard [13] but it is hardly alone. Even within the ASME standard there are discrepancies as to the proper letter callout for basic thermowell dimensions such as the root diameter. The confusion between standards is not helpful to the user because the lack of uniformity can lead to some confusion as to what is being described in a specification. Standards organizations are making some effort to consolidate references, but it is unlikely that these discrepancies will disappear from technical literature anytime in the near future. To minimize confusion, the specification should reference a specific standard establishing the dimensions at issue. The most common reference for thermowell dimensions is the ASME B40.9, now incorporated into the B40.200-2008 standard (B40.9) (see Figure 2-11).



Symbols	Dimension
B	Bore Diameter
E	Tip Thickness
Q	Base Diameter
S	Bore Depth
T	Lagging Extension
U	Insertion Length
V	Tip Diameter

Thermowell Terminology

Figure 2-11
Typical threaded thermowell with dimensions per ASME B40.200

A list of commonly referenced dimensions by standards is indicated in Table 2-2.

Table 2-2
List of thermowell dimensions by standards

	Insertion Depth	Lag Length	Root OD	Tip OD	Tip Thickness	Bore ID	Overall Length	Bore Length
ASME 19.3 TW-2010	L	—	A	B	T	D	—	—
ASME 19.3 (2004)	L	—	A	B	—	D	—	—
ASME B40.8 (2008)	U	T	—	—	—	D	Z	W
ASME B40.9 (2008)	U	T	Q	V	E	B	L	S
API 551	U	T	Q	V	E	B	—	—
PIP PCFTE000 (November 1997)	U	—	Q	V	—	B	H+U	A
PIP PCFTE100 (July 2008)	U	T	—	—	—	—	—	—
IEC 61520	U	T	F	B	X	d1	—	—
SAMA (1963)	U	T	—	—	—	Y	—	—

API = American Petroleum Institute, ID = inside diameter, IEC = International Electrotechnical Commission, OD = outside diameter, PIP = Process Industry Practices, SAMA = Scientific Apparatus Manufacturers Association.

Impact of Standards Other Than 19.3 TW on Thermowell Design

There are a number of industry standards and guides published that address thermowell design. These range from ASME, Process Industry Practices (PIP), American Petroleum Institute (API), and others. There are some conflicts among the various documents that can be confusing.

ASME Standards Impacting Thermowell Design and Specification

The two major ASME thermowells standards are the 19.3 TW thermowells design standard and ASME B40.9 specifications standard. As discussed, 19.3 TW establishes design calculations, and the major contribution of B40.9 describes the common designs and names certain thermowell dimensions for the purposes of facilitating clear and concise specifications of a product.

However, note the following provided by the B40.9 specifications standard:

- B40.9 recommends that the instrument connection on the thermowell be a 0.5-in. (12.7-mm) national pipe straight mechanical female fitting to match the typical 0.5-in. (12.7-mm) national pipe thread (NPT) male sensor threads without galling or seizing.
- B40.9 prohibits the use of screwing threaded thermowells into a threaded reducing flange even if they are back-welded.
- B40.9 requires that concentricity of bore meet a minimum threshold of ±10% of the minimum wall thickness.

Although not limited to thermowells, the ASME Boiler and Pressure Vessel Code (BPVC), Section III, Division 1, Appendices, Appendix N, 1300 Series, Guideline for Evaluation of Flow-Induced Vibrations of a Cylindrical Structure in a Pipe provides guidance on the flow-induced vibration of banks or arrays of tubes and on the excitation of structural vibrations by turbulence.

PIP Standards Related to Thermowells

ASME standards have the greatest impact in design and specification of thermowells. However, they are not the only standards touching on thermowell design. The PIP consortium is a group of process companies and contracting engineers who work together to establish common practices and standards for the smooth running of a plant. In 2008, the PIP published three standards touching on thermowells, as follows:

- **PIP PCFTE100 (July 2008) Thermowell Fabrication Details**. This standard explains how to specify threaded, flanged, weld-in, and socket-weld thermowells. It also provides guidance in the form of maximum velocity ratings based upon fluid type (air or water) and insertion length. Because these recommendations are based upon the old 19.3 standard as it existed in 2008, these recommendations are now out of date and need to be revised to be brought current.
- **PIP PCETE001 (June 2008) Temperature Measurement Guidelines**. This standard recommends that wake-frequency calculations be performed in accordance with the ASME Performance Test Code (PTC) 19.3 and provides a standard list of immersion lengths that are deemed acceptable. This standard also acknowledges the importance of material selection, consideration of corrosion, erosion, and material compatibility factors. Of note, this standard recommends that thermowells be installed in elbows with the tip facing into the flow to minimize flow-induced vibration. This practice makes it very difficult to perform a wake frequency calculation per ASME 19.3 TW-2010.
- **PIP PCCTE001 (July 2008) Temperature Measurement Design Criteria**. This standard requires the following:
  - A wake-frequency calculation for every thermowell in accordance with ASME PTC 19.3
  - A plug and chain for all test thermowells installed without a resident sensor
  - Consultation from a materials specialist for all high-temperature, weld-in applications
  - Thermowells to be constructed from solid bar stock unless otherwise approved
  - Thermowell shanks to be tapered
  - Thermowells to be located a minimum of 10 diameters downstream from mixing liquids and 30 diameters downstream of gases or desuperheaters
  - Thermowells in horizontal vessels to be at least 18 in. (457.2 mm) long but not longer than one-half the vessel diameter

Presumably, when the next updates of these PIP standards are available, they will reference the 19.3 TW-2010 replacement to the 19.3 standard presently referenced for design purposes.

API Standard Relating to Thermowells

Similarly, the API 551 standard addresses thermowells primarily for petrochemical applications. The current edition of that standard preceded the publication of 19.3, and, although it referenced 19.3 for design, it attempted to compensate for its shortcomings by reducing the wake-frequency limit stated in 19.3 from 80% to 66% of natural frequency. An upcoming revision to this standard also incorporates 19.3 TW as the design reference for evaluating whether a given thermowell design is compatible with anticipated process conditions.

Canadian Registration Number (CRN) Impact on Thermowells

Thermowells installed in Canada are required to maintain a Canadian Registration Number (CRN) that primarily serves to confirm a minimum thread count and pitch. Although the registration number is referred to as *Canadian*, there is no central registry for approval throughout Canada. Instead, each Canadian province issues its own authorization for approval, and the standard procedure for obtaining approval varies widely between the provinces. To be installed in a given province, the thermowell must be stamped with a numerical designation for that province indicating that the manufacturer has had that design approved by the local provincial authority (for example, the numerical designation for the province of Alberta is 2). If the last character of the stated CRN number is a C, it indicates that the thermowell design has been approved by each Canadian province and can be installed anywhere in Canada.

National Association of Corrosion Engineers International

The National Association of Corrosion Engineers Mauritanian Ouguiya (MRO) 175 (primarily upstream oil-field equipment) and MRO 103 (primarily downstream chemical and refining operations) are each material specifications designed to avoid stress corrosion cracking in sour applications. These are rarely an issue in a power application. Generally, the user must consider the process condition and select materials per either standard. In rare cases, such as the Texas Railroad Commission or the Alberta Energy Conservation Board, these certifications are required by law. Where these are applicable, the manufacturer should supply material test reports certifying that the materials used comply with the appropriate standard. For flanged wells, post-weld heat treating may also be required.

International Electrotechnical Commission (IEC) Standards

The International Electrotechnical Commission (IEC) maintains a standard that is similar to the ASME B40.9 Thermowells standard in that it describes common European thermowell designs for assistance in clarifying standard specifications. The IEC standard does not attempt to provide design guidance for thermowells.

The IEC standard replaced the German Institute for Standardization (DIN) 43772 standard. The DIN 43772 standard provides some guidance as to thermowell immersion length for common process characteristics in much the same manner as the PIP standards. It is unknown whether there are any current plans for change to the DIN standard in light of the new ASME standard and the emergence of the IEC standard. The DIN standard focuses on European-style thermowells that differ slightly from designs typically used in North America.

Pipe Fabrication Institute, Scientific Apparatus Manufacturers Association, and Others

The Pipe Fabrication Institute (PFI) does not maintain a standard addressing thermowells. The Scientific Apparatus Manufacturers Association (SAMA) formerly maintained a thermowells standard titled "Bushings and Wells for Temperature Sensing Elements," applying primarily to thermowells for liquid-in-glass thermometers. This standard served primarily to define typical thermowell lengths and designs and is no longer maintained. For some time, the U.S. Atomic Energy Commission Division of Reactor Development and Technology created the NE C 7-18T standard titled "Thermowell Systems for Liquid Metal Service," which became inactive in 1982 and was canceled in July of 1996. The International Society of Automation spent years working to build a more appropriate thermowell design calculation than the 19.3 standard but abandoned the attempt before finishing the work.

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3. ASME PTC 19.3 TW-2010, Section 3-2: Specification of Thermowells, Section 9-1: Specification of a Thermowell.
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7. ASME PTC 19.3 TW-2010, Thermowells, Sections 1-2 Scope.
8. ASME PTC 19.3 1974 (2004), Temperature Measurement, Table 1.3: Well Dimensions.
9. ASME PTC 19.3 TW-2010, Thermowells, Table 4-1-1, Note 2.
10. ASME PTC 19.3 TW-2010, Thermowells, Sections 1-2 Scope, Sections 6-7(e): Thermowells with Support Collars.
11. Kerlin, T. W. and M. Johnson, *Practical Thermocouple Thermometry*, 2nd ed., ISA, Research Triangle Park, NC: 2012, pp. 79–85.
12. Johnson, M. and A. Gilson, "The New ASME Thermowell Standard and Optimal Thermowell Design." Paper No. 0040-000134, presented at the ISA Annual Conference, Automation Week, Mobile, AL (October 2011).
13. ASME B40.200-2008, Thermometers, Direct Reading, and Remote Reading (ASME B40.9-2001), Table 1: Standard Dimensions.

3
THE ASME 19.3 TW THERMOWELL DESIGN CODE SUMMARIZED

Thermowell design presents a common dilemma. The characteristics that increase a thermowell's mechanical strength tend to decrease the accuracy and responsiveness of its installed temperature sensor [1]. Thicker, shorter thermowells are mechanically superior to longer, thinner thermowell designs. Conversely, longer, thinner thermowells enable more accurate and responsive temperature measurements but are more susceptible to high vibration and breakage. See Table 3-1 for the advantages and disadvantages of various thermowell designs.

Table 3-1
Pros and cons of thermowell design choices [2]

Conflicting Requirements

Factor	Ideal for Measurement	Ideal for Strength
Length	Long	Short
	Conductance error reduced	Fluid force reduced; higher natural frequency
Thickness	Thin	Thick
	Reduced conductance loss; faster response	Less stress; higher natural frequency
Fluid velocity	High	Low
	Increased heat transfer, faster response	Reduced fluid force; lower Karman vortex frequency

The thermowell designer's job is to design the thermowell so that it is long and lean enough to enable the sensor to provide an accurate and responsive temperature indication while ensuring that the thermowell is not so long and thin that its design poses a risk to its own mechanical integrity or the operation of its installed sensor. The ASME 19.3 TW-2010 Thermowells standard addresses all of the major aspects associated with assuring the mechanical integrity. It compares the proposed thermowell design to the anticipated process conditions and evaluates the likelihood of failure due to steady-state stress, oscillating (dynamic) stress, flow-induced failure (wake-frequency failure), and pressure. Corrosion and erosion factors can also be factored in when the data are available.

The 19.3 TW-2010 Thermowells standard provides an objective means for an engineer to balance these two competing interests for common thermowell designs. It also establishes an unequivocal priority between the two, stating that "In all cases, the mechanical strength requirements shall control" [3].

When Should the Requirements for PTC 19.3 TW Analysis Be Applied?

PTC 19.3 TW can be used to analyze any service. However, the typical practice in the power generation industry is to generate formal PTC 19.3 TW calculations for primarily steam or high velocity gas services. Applications requiring long insertions are also evaluated as a typical practice.

Where designs have already been analyzed or proven historically, reevaluation of the design is likely unnecessary. The use of standardized thermowell sizes and geometries that have been proven can eliminate the necessity of performing a sophisticated analysis for every application.

PTC 19.3 TW itself carves out exceptions to its application based upon low-fluid velocities where certain material and dimensional characteristics are maintained. In these instances, calculations of wake-frequency limits, steady-state stress, and oscillating stress need not be performed. PTC 19.3 TW classifies a low-fluid velocity application as having a maximum velocity of 2.1 ft/s (0.640 m/s) [4].

A Brief History of The ASME 19.3 TW-2010 Standard

In the mid-1950s, power plant operators were seeing a rash of thermowell failures in steam lines causing damage to their turbines. In 1959, J.W. Murdock published an article proposing a thermowell design calculation intended to prevent turbine damaging thermowell failures in steam lines. In 1974, this paper was abbreviated and adopted as the ASME PTC 19.3-1974 Code. The PTC 19.3 calculation enabled the comparison of a specific thermowell design to anticipated process conditions in a steam line by the establishment of a simple, four-page calculation yielding a pass/fail result [1]. That same year, Professor John Brock of the Naval Postgraduate School's mechanical engineering department issued an 85-page review of the PTC analysis, pointing out perceived shortcomings of the methodology prescribed by PTC 19.3-1974 [5]. Despite this thoughtful commentary, from the period of its initial adoption in 1974 to its last approval in 2004, little change was made to the PTC 19.3 standard [1].

Due to the unique status and simple approach of PTC 19.3, over the years it became the most common tool used to assess the likely integrity of a thermowell regardless of application type. The original intended scope of steam lines was forgotten, and it was applied across a broad range of applications and industries from circulating water lines to liquid-sodium applications and beyond. This was unintentionally enabled in part by limitations and ambiguities contained in the standard itself. Despite broad implementation by end users and engineering firms, field failures of thermowells cropped up and persisted on an intermittent basis in nonsteam applications, even among thermowells assessed by and built to the 19.3 standard.

Among many noted thermowell failures, perhaps the most famous involved a sodium line at the Monju nuclear reactor in Japan, where a catastrophic thermowell failure resulted in a liquid-sodium line leak. The thermowell at issue passed a PTC 19.3 evaluation but failed in practice. This single instance of thermowell failure resulted in a liquid-sodium line leak, a fire, and a plant shutdown that lasted for 10 years. To date, reports estimate that the shutdown associated with this thermowell failure has resulted in costs exceeding 1 trillion Japanese yen (greater than 10 billion U.S. dollars) [6].

The Monju plant was not alone in experiencing thermowell failures due to flow-induced vibration unaccounted for by the 19.3 calculation. The United States had its own share of liquid-sodium line leaks caused by flow-induced vibration (see Figure 3-1) [2].

Figure 3-1
Failed thermowell at sodium component test installation operations 35 miles (56.33 km) outside of Los Angeles, CA [7]

Significant instances of thermowell failure have not been limited to liquid-sodium lines, as shown in Table 3-2.

Table 3-2
Fully documented thermowell failures [2]

Year	Fluid	Psig	*T* / °F	Damage Assessment
1960's	Steam(x7)	1700	1050	***Turbine Loss***
1970's	Steam	150	400	Damaged Well
1983	B.F.W.(Nuclear)	1000	250	Leakage
1985	Off-Gas	100	300	***Fire***
1993	Gas Pipeline	600	70	Leakage
1994	Acid	50	390	Leakage
1995	Gas Processing	657	264	Leakage
1999	Gas Pipeline	1080	70	High Vibration
2004	Heavy Water	1990	500	Leakage
2004	B.F.W . (Nuclear)	2235	500	Sensor Loss
Liquid Sodium Failures				
Year	**Fluid**	**Psig**	***T* / °F**	**Damage Assessment**
1972	Liq. Sodium(x1)	20	800	***Major Fire***
1995	Liq. Sodium(x6)	50	500	***Major Fire***

1 psig = 108.22 Pa
F = 9/5(C) + 32

In less dramatic circumstances, thermowell failures historically suffer from poor reporting [8]. When they occur, they are simply noted in maintenance notes as a sensor replacement. Even as incidents such as those described in the previous table were being investigated, engineering [9] and academic [5] criticisms of the old standard pointed out the following concerns among others, that the ASME PTC 19.3:

- Failed to adjust Strouhal number with Reynolds number
- Covered outdated thermowell geometries
- Relied on tabular coefficients that could not be extrapolated accurately
- Failed to address in-line vibration
- Failed to assess oscillatory stress independent of steady-state bending stresses
- Provided no fatigue factor for oscillatory stress or a stress intensification factor for fatigue at the thermowell root
- Performed the installed natural frequency calculation in a crude manner without including any effects of foundation stiffness, fluid, or sensor mass

Some publications [9] and even standards [10] actually referenced the 19.3 standard and then, not trusting its result, handicapped it. The opportunity for improvement was clearly identified [11]. After approximately five years of work, in July of 2010, the ASME PTC 19.3 TW-2010 standard was published to address these shortcomings and received ANSI-approval.

What Aspects of Thermowell Design Did ASME 19.3 TW-2010 Change?

In many applications, 19.3 TW is now significantly more conservative than its predecessor, resulting in maximum allowable thermowell immersion lengths much shorter than previously allowed under the old 19.3 regime. This consideration is primarily due to consideration of in-line resonance and oscillating (dynamic) stress. As will be discussed in the section on low-density gas applications, in a small minority of cases where viscosity values are available, 19.3 TW may actually permit longer immersion lengths due to 19.3 TW's ability to tailor the Strouhal number to a particular application, instead of relying upon a default value.

Other changes include accommodating modern geometries such as straight and step shanks, an unlimited velocity range, a predicted life cycle, rules regarding manufacturing tolerances, dimensional limitations, and consideration of corrosion and erosion factors. For the first time, 19.3 TW made clear that support structures such as velocity support collars are ill-advised and outside of the scope of the standard,[1] primarily due to impracticalities regarding their manufacturing and installation. For the first time, 19.3 TW recognized that all thermowells are not equal in terms of their rigidity and susceptibility to vibration. Values such as the sensor mass, fluid mass, and process connection design are for the first time incorporated into the calculation of the installed natural frequency of the thermowell. A table listing the various changes from the old standard to the new is provided in Appendix B.

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[1] *ASME/ANSI* 19.3 TW-2010, Tables 4-1-1 and 4-2-1.

What Data Are Required to Apply ASME 19.3 TW-2010?

To evaluate the thermowell, the process connection type, shank style, materials of construction, bore diameter, unsupported length, root diameter, tip diameter, and tip thicknesses all need to be established (see Figure 3-2). Technical information such as moduli of elasticity at operating temperatures and maximum allowable working stress are also required and should be established based on ASME B31.1 Power Piping values or other appropriate values where available. Likewise, material density values can be obtained from the *ASM Materials Handbook,* certified material test reports, or other sources. Manufacturers provide standard fillet radii, which are adjustable for custom thermowells; although in practice, fillet radii have little impact on the calculation result unless the thermowell process connection is flanged. Free software, including automatic reference to these standards, is available online and easily discoverable through an Internet search. However, like any Internet resource, the software must be used with some caution. Certificates of validation from the software provider should be made readily available upon request. See Appendix C.

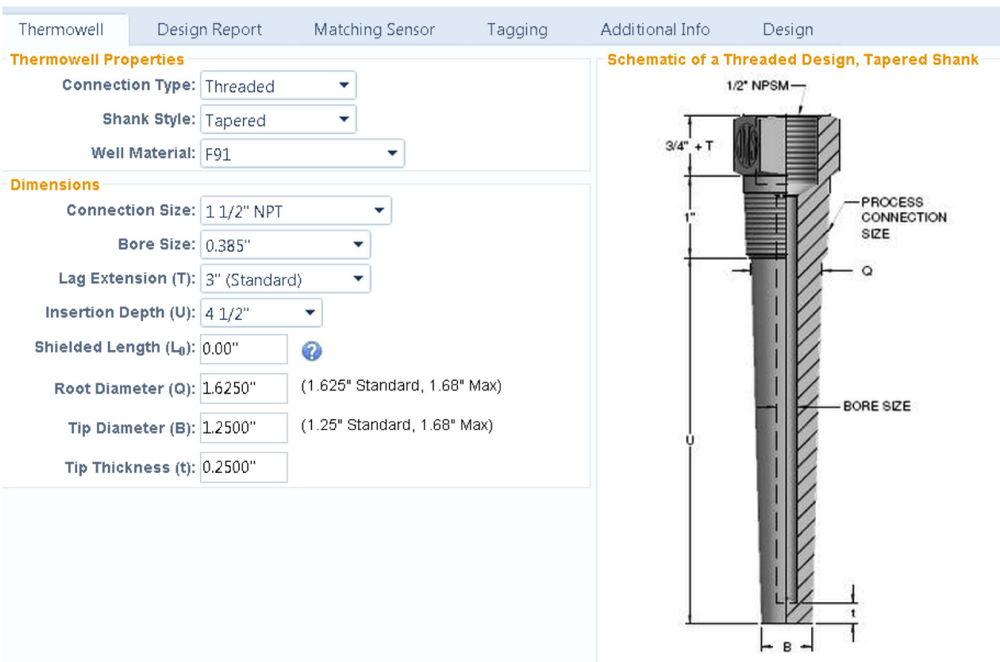

Figure 3-2
Typical input for thermowell characteristics for a 19.3 TW calculation

Process characteristics must also be established in order to perform a wake-frequency calculation (see Figure 3-3). The required characteristics are process maximum temperature, maximum pressure, density, velocity, and viscosity where possible.

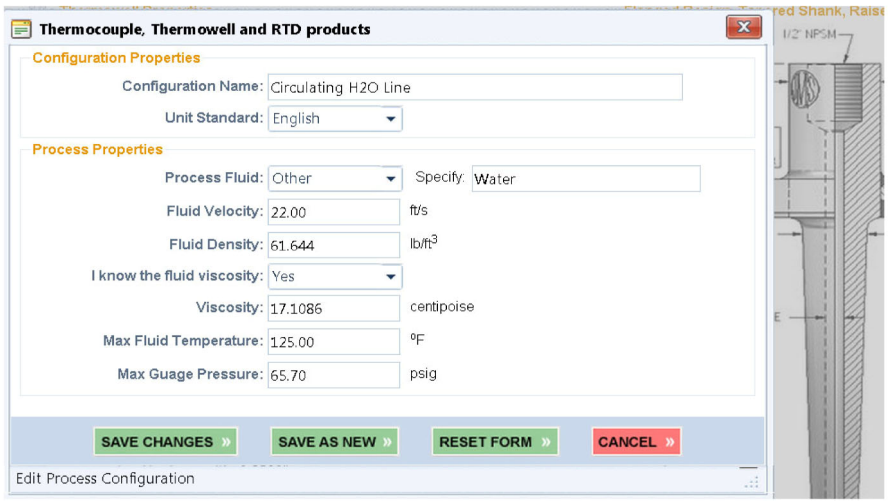

Figure 3-3
Typical process conditions required for a 19.3 TW calculation

Where steam and water lines are the process fluid of interest, the ASME Steam Tables are available to calculate density and viscosity values. As shown in Figure 3-4, as soon as these values are established, velocity can be calculated based upon flow rate, where the inside diameter (ID) of the pipe is established.

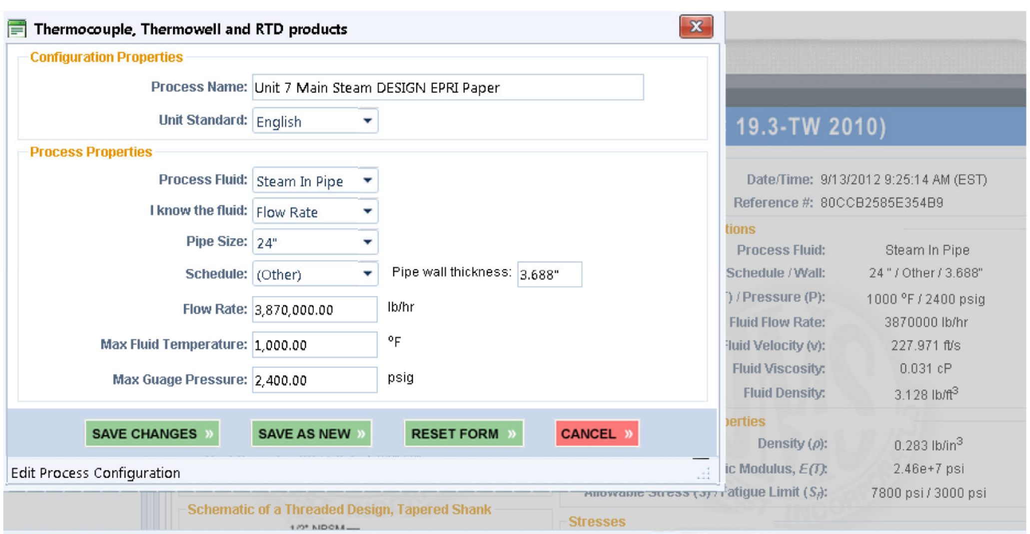

Figure 3-4
Typical process conditions input showing flow with velocity calculated on the right (227.971 ft [69.486 m]/s)

Important Cautionary Notes Regarding the Use of Flow Values to Establish Velocity

Where velocity is being calculated using mass flow with steam tables and pipe ID, it is possible to assess conditions at the highest pressure and temperature and still not evaluate the worst case condition for the thermowell. This surprising result derives from the success or failure of a thermowell design often being far more sensitive to velocity considerations than it is to those of temperature or pressure. The highest velocity case does not always correspond with the highest pressure or temperature case.

For example, consider a 24-in. (609.6-mm) main steam line with a wall thickness of 3.688 in. (93.675 mm) and a constant flow rate of 3,870,000 lb/hr (1755402.47 kg/hr). At the pipeline design conditions of 1000°F (537.78°C) and 2400 psig (16,648.74 kPa), steam density is 3.128 lb/ft^3 (50.106 kg/m^3) and the resulting velocity is 228 ft/s (69.494 m/s). At 991°F (532.78°C) and 2194 psig (15,228.42 kPa) (an operating condition, but not the piping design condition), steam density is 2.856 lb/ft^3 (45.748 kg/m^3) and the resulting velocity is 250 ft/s (76.2 m/s). This is due to the lower pressure at the operating condition when compared to the design condition. The same mass flow produces a higher volumetric flow (and higher velocity) at the operating condition.

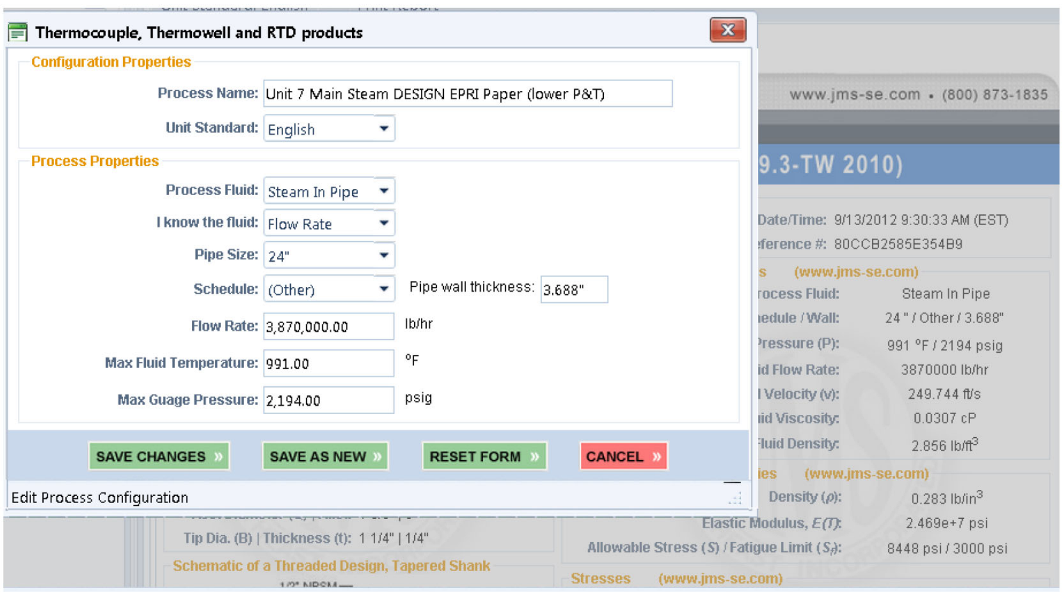

Figure 3-5
Typical process input for steam application calculating velocity based on flow, pipe ID, pressure, and temperature in which the lower pressure and temperature result in a higher velocity—worst case

In this example, the worst case for thermowell design is the design with a lower pressure and temperature (see Figure 3-5).

For this reason, when building a conservative design case where process conditions are based upon mass flow rates, it is often helpful to identify the maximum velocity condition and apply that velocity to the highest pressure and temperature case (see Figure 3-6). This represents a conservative analysis. If the design case does not pass using the worst-case velocity with the design temperature and pressure, it may be necessary to run two cases. One case is run using the worst-case velocity at the pressure and temperature corresponding to that velocity (see Figure 3-5). A second case is run at the velocity associated with the design temperature and pressure (see Figure 3-4).

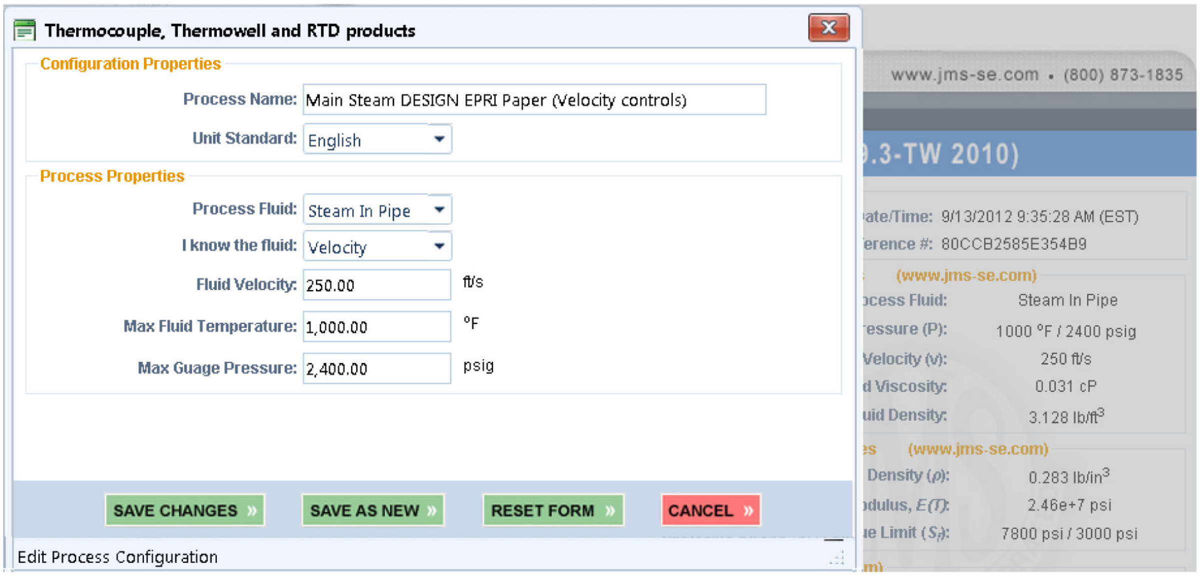

Figure 3-6
Process input using velocity rather than flow with steam tables

Another troublesome case is where the velocity value for a liquid system is calculated based on pump runout. Pump runout may determine the highest actual average flow in the piping system. However, it will not necessarily establish the highest velocity at the actual thermowell location due to local obstructions, flow stratification downstream of elbows or tees, or other factors.

An Important Practical Note Regarding Viscosity

Viscosity is not always a known characteristic of a process fluid, but it is necessary to establish the Reynolds number applicable to a given design. The standard does not require a viscosity value to perform its calculation. If the viscosity value is unknown, the standard prescribes a conservative Strouhal number, and the acceptable immersion length is limited by this lack of knowledge. Where viscosity is available, the 19.3 TW standard sometimes permits a longer immersion length due to a tailoring of the Strouhal number or application of a low-density gas limit where applicable.

Drilling Down—Wake Frequency and Installed Natural Frequency Under the ASME 19.3 TW Code

When it comes to vibration, thermowells are not all that different from smoke stacks, cooling towers, or suspension bridges. All of these objects have a natural frequency at which they will resonate. As fluids pass these structures, circular flow patterns are created in the wake downstream of the cylinder. These flow patterns, referred to as the *von Karman vortex effect*, swing from one side to the other, causing an oscillating bending force on the structure. When the frequency of these vortices approaches the natural frequency of the structure, a condition called *lock-in* occurs. In a lock-in condition, the structure's frequency will increase or decrease to resonate with the frequency of its vortices. As soon as resonance is achieved, the amplitude of the structure's vibration increases exponentially, risking the mechanical soundness of the structure itself. The effect can be disastrous (see Figure 3-7).

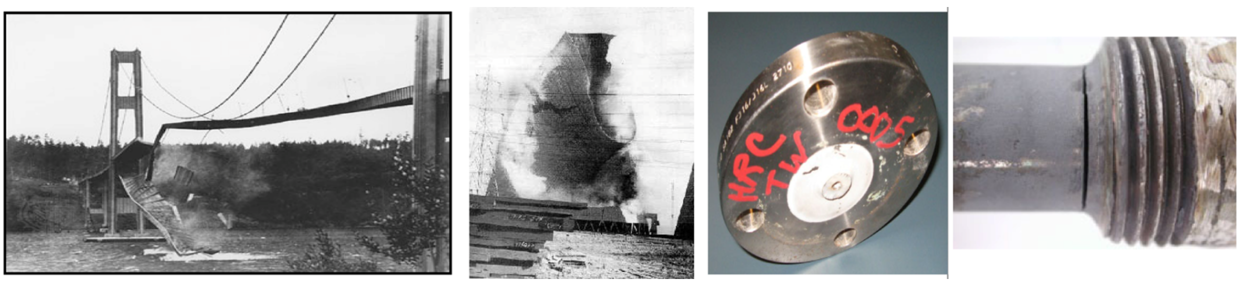

Figure 3-7
Suspension bridges, cooling towers, and thermowells adversely impacted by wake frequency

The von Karman vortex effect and the lock-in phase surrounding resonant frequencies were well known to the drafters of the original PTC 19.3 design methodology. The data available in 1974 appeared to indicate that the only thermowell vibration of significance for the purposes of design was vibration occurring in a plane transverse to the flow of the process fluid. To that end, the drafters sought to avoid transverse resonance by rejecting any thermowell whose wake frequency was calculated to exceed 80% of the natural frequency of the thermowell. Murdock and others involved in the creation of the standard were of the opinion that the 80% limit was a conservative limit necessary to avert the dangerous lock-in condition that was known to cause thermowell failures. This approach was successful at avoiding a lock-in for steam applications due to transverse resonance [2].

The criteria for passing or failing a thermowell design due to wake frequency were established by the PTC 19.3, as follows:

$$f_w/f_n \leq 0.8 = pass$$
$$f_w/f_n > 0.8 = fail$$

where:

f_w = wake frequency in hertz

f_n = natural frequency of the thermowell in hertz

The flaw in this strategy was the failure of the 19.3 standard to recognize that a thermowell does not vibrate in a single dimension transverse to the flow. Under normal design conditions, as a process fluid such as steam or water passes a thermowell shank, the shed vortices cause the thermowell to vibrate in a Lissajous or figure-eight pattern. Physically, this pattern can be approximated as vibration occurring in-line with and transverse (perpendicular) to the flow of the process fluid (see Figure 3-8).

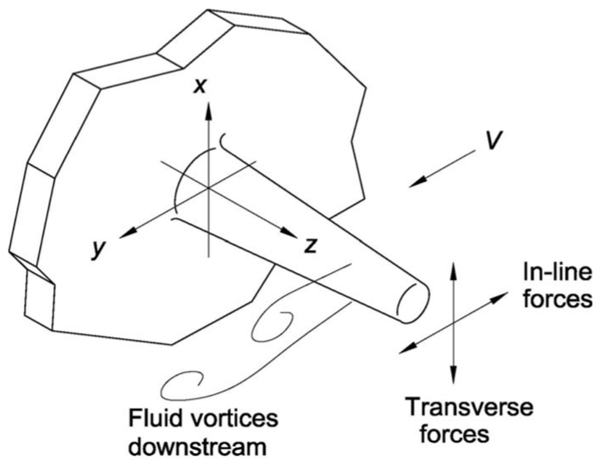

Figure 3-8
Directional forces corresponding to wake frequency

For all of the modifications to the form and substance of 19.3 in the 19.3 TW standard, by far the most significant factor impacting thermowell design is the recognition of the need to avoid in-line resonance—the factor identified as the root cause of the Monju failure.

The 19.3 standard conceived of thermowell vibration as occurring in a single-plane transverse to the flow. Resonance was judged as possible whenever the wake frequency approached 80% of the natural frequency of the installed thermowell. Indeed, transverse vibration is a real danger, and its occurrence should be avoided, if possible, because it can be catastrophic for the thermowell. However, a thermowell does not vibrate in a single plane. In reality, the thermowell vibrates in an oscillating fashion that includes an in-line component. The in-line component locks in and can begin to resonate with the shed vortices at wake frequencies spanning 40% to 60% of the installed natural frequency of the thermowell (see Figure 3-9).

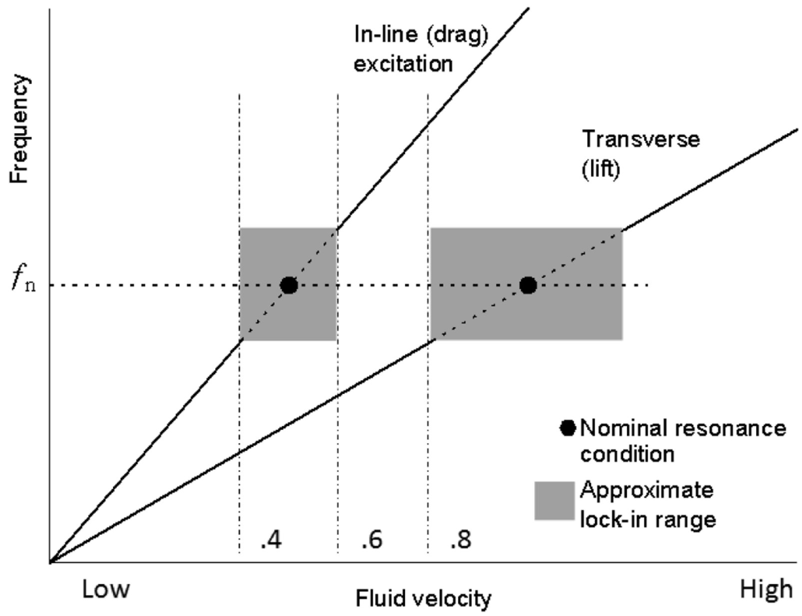

Figure 3-9
Lock-in zones for in-line (left box) and transverse (right box) resonance

If the ratio between a thermowell's installed natural frequency and wake frequency fall into the span of 40% to 60%, the thermowell will lock-in on the resonant frequency, and a spike in amplitude will occur as if the exact frequency of in-line resonance had just been struck. When thermowell vibration approaches the frequency of the shed vortices, the amplitude of vibration increases dramatically (see Figure 3-10). This exerts tremendous force and stress against the thermowell's base. In many cases, this stress is fully capable of causing the thermowell material to fracture or even shear off at the point of greatest stress—the thermowell root.

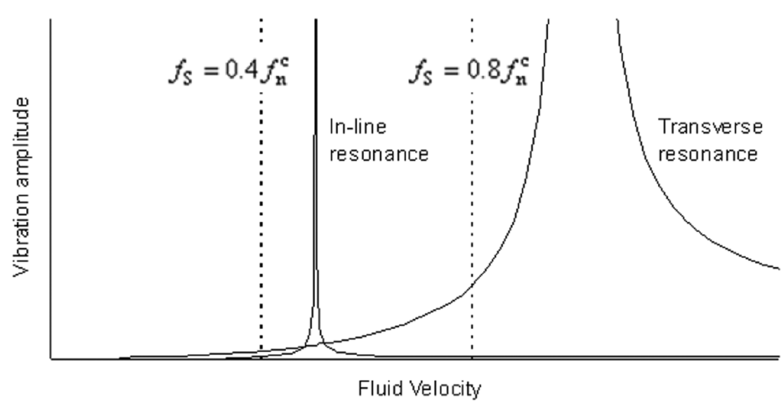

Figure 3-10
Increase in amplitude of vibration arising from a lock-in for in-line and transverse resonance

Recognition and avoidance of dangers posed by in-line resonance is critical to proper thermowell design, but the practical effect of reducing the wake to a natural frequency limit from 0.8 to 0.4 can be very significant. Under the 19.3 TW standard, the danger of thermowell resonance must be considered at velocities much lower than previously considered as problematic by the 19.3 standard [12].

Because process fluid speeds cannot generally be slowed down to accommodate the ideal length of a thermowell, the effect is a reduction in the maximum allowable unsupported lengths for many thermowells. This reduction challenges engineers involved in the design of thermowell applications to update their standards to reflect appropriate immersion lengths based upon a more conservative mechanical standard or to bulk up their thermowells to enable a sufficient immersion length.

Calculation of Wake Frequency Under 19.3 TW Versus 19.3

It is not possible to simply halve the result of the old standard because 19.3 TW changes the method of calculating both the natural frequency and wake frequency (f_s). Both the old 19.3 standard and the 19.3 TW calculate wake frequency as follows:

$$f_s = N_s V/B$$

where:

N_s = Strouhal number

V = velocity

B = thermowell tip OD

Whereas 19.3 used a fixed value for the Strouhal number equal to 0.22 (dimensionless), the new standard allows reductions in the Strouhal number to be achieved where viscosity is provided and the calculated Reynolds number is less than 500,000. A review of approximately 100 calculations based upon power and industrial processes revealed that the greatest reduction in the Strouhal number is approximately 20% [12].

Impact of Shank Style on Wake Frequency

Because the old 19.3 standard limited its scope to tapered thermowells, many users came to believe that tapered thermowells were inherently stronger than other shank styles [1]. There is some truth to this because the off-the-shelf tapered thermowell will typically have a larger root dimension than a similar stepped or straight shank, typically making it more resistant to flow-induced vibration.

The new 19.3 TW standard applies to all three shank styles and can have a significant impact on whether a given thermowell length meets the requirement of the 19.3 TW standard. A larger thermowell tip often (but not always) results in a stronger thermowell design because the tip diameter plays a very large role in the calculation of the wake-frequency value.

Because the tip diameter is the sole denominator in the equation calculating the wake frequency, changes to that value can have a pronounced impact by lowering the wake-frequency value. For that reason, where the process connection size is limited a straight thermowell of custom dimensions will often enable longer possible immersion lengths than a tapered thermowell of a matching process connection size. This also explains the reason it may be helpful to increase the size of a thermowell tip to obtain longer immersion into a process.

Impact of Velocity on Calculation of Wake-Frequency Value

Velocity is one of two factors constituting the numerator for the purposes of establishing wake frequency. As covered in the previous section regarding the calculation of velocity based upon flow rates, this accounts for the thermowell designs often being much more sensitive to changes in velocity than they are to changes in pressure or temperature. As the velocity increases, the wake frequency increases proportionately.

Calculation of Installed Natural Frequency Under 19.3 TW Versus 19.3

Initially, natural frequency has been experimentally assessed by mounting thermowells in a vice and striking them, feeding the output of a strain gage into an oscilloscope. The 19.3 standard attempted to calculate the natural frequency of a thermowell without the consideration of stepped or custom shank tapers, the process fluid's mass, or the mass of the installed sensor. By contrast, 19.3 TW addresses each of these factors because each impacts a thermowell's tendency to vibrate. Moreover, 19.3 TW addresses the manner of the installation for the thermowell because it necessarily impacts its rigidity and susceptibility to vibration by taking the natural frequency that would exist with an ideal rigid base and multiplying that value against a correction factor. This change in method merited a change in nomenclature. The standard no longer stops at the evaluation of the natural frequency of a thermowell. It addresses the *installed* natural frequency.

Impact of Process Connection Type on Installed Natural Frequency Value

The 19.3 TW standard accounts for the flexibility of each process connection type in evaluating the likely success or failure of the thermowell. This factor is referred to in 19.3 TW as the compliance factor (H_c) that reduces the value of the installed natural frequency. The more rigid the support, the higher the H_c, the more likely the design is to meet the requirement for wake frequency purposes under 19.3 TW. Threaded wells are deemed to have the least rigidity of the various process connections. This is reflected by an equation that results in a lower multiplier for the threaded thermowell connection than for other process connections.

Calculation of threaded thermowell H_c, as follows:

$$H_c = 1-0.9(\mathrm{A/L})$$

where:

A = root diameter of thermowell

L = unsupported length of thermowell

By contrast, the calculation of H_c for weld-in, socket weld, and flanged thermowells is calculated, as follows:

$$H_c = 1-0.61(\mathrm{A/L})/[1+1.5(b\,/A)]^2$$

The addition of variable *b* (fillet radius) introduces the potential for consideration of the fillet radius spanning from the process connection to the thermowell shank. Although all thermowells have some degree of fillet radius, not all are given credit under the 19.3 TW standard for having this fillet. Accordingly, for purposes of calculating H_c, a fillet radius of zero is used unless the thermowell is flanged. So the preference is quickly established: threaded wells are the least rigid, followed by weld-in and socket-weld thermowells, and flanged thermowells are rated as the most rigid.

For example, consider three thermowells that maintain the following identical characteristics aside from their process connection:

A= OD at root dimension = 1.5 in. (38.10 mm)

L = unsupported length of thermowell = 4.5 in. (114.30 mm)

b = fillet radius = 0.125 in. (3.175 mm)

A threaded thermowell with these characteristics maintains an H_c of 0.7.

$$H_c = 1-0.9(1.5/4.5)=1-0.3 = 0.7$$

A weld-in thermowell with these characteristics maintains an H_c of 0.797.

$$H_c = 1-0.61(.333)/[1+1.5(0)]^2 =1-.203 = 0.797$$

A flanged thermowell with these characteristics maintains an H_c of 0.839.

$$H_c = 1-0.61(.333)/[1+1.5(.125/1.5)]^2 =1-0.203/(1.125)^2 = 1-0.161 =0.839$$

Calculation of the installed natural frequency is resolved by multiplying the natural frequency of the thermowell against its compliance factor. The impact of the process connection choice is readily apparent.

$$f_n^c = (f_n)(H_c)$$

Exceptions to the 0.4 Wake Frequency Limit Provided by 19.3 TW

The 19.3 TW standard provides a standard limit of f_s/f_n^c<0.4. As a general rule, the lock-in zone for in-line resonance (defined by 19.3 TW as a wake frequency band ranging from 40% to 60% of the installed natural frequency of the thermowell) should be avoided all together. However, the Code carves out exceptions that allow thermowells to engage resonance in certain instances and to varying degrees. A summary of these exceptions include the following:

- **Low-density gas where in-line and transverse resonance zones are suppressed**. For Reynolds numbers (Re)<$⟦10⟧^5$ and Scruton numbers (N_{sc})>64, in-line and transverse resonances are suppressed, and the shedding frequency can exceed the natural frequency; although care must still be taken to ensure the thermowell's integrity against higher-order thermowell resonances. The prevention of these higher-order resonances are outside of the scope of the 19.3 TW standard.

- **Low-density gas where in-line resonance is suppressed**. For low-density gases with $Re<[\![10]\!]^5$ and $N_{sc}>2.5$, in-line resonance is suppressed. Accordingly, the wake-frequency limit is established to avoid transverse resonance of the thermowell. In such cases, the wake frequency (f_s) need only be constrained to less than 80% of the installed natural frequency (f_n^c).
- **Cyclic-stress test permitting transient passage through in-line resonance**. Where the thermowell passes a cyclic-stress test established by 19.3 TW for operation at in-line resonance, the thermowell may pass through but not rest at a condition of in-line resonance. Accordingly, in such cases, the wake frequency for a steady-state operating condition must fall below 40% of the installed natural frequency or balance in the zone between in-line and transverse resonance (6% to 79% of installed natural frequency).
- **Test where the thermowell fails cyclic-stress and the risks of failure are acceptable**. Finally, if the thermowell fails the cyclic-stress condition for operation at in-line resonance, $f_s<0.4\,f_n^c$, unless the following conditions hold:
  - The process fluid is a gas.
  - Exposure to resonance occurs on startup and shutdown only.
  - The sustained peak stress is less than the fatigue limit adjusted for the number of cycles.
  - The peak stress at in-line resonance is less than the fatigue limit adjusted for the number of cycles at in-line resonance, where the number of cycles may be estimated from the anticipated number of startup and shutdown events in the thermowell's lifetime.
  - The process fluid is not corrosive and will not reduce the fatigue resistance of the thermowell material.
  - The risks attendant to thermowell failure to people and property are deemed sufficiently limited as to be acceptable.

In all of the cases, although brief, passing through resonance can cause sensor damage. A logic tree for the determination of which limit applies is provided in Appendix D.

Low Density Gas Exception—Requirement for Viscosity Value

In brief, low-density gases are defined as those applications where the Scruton number exceeds 2.5 and the Reynolds number is less than 100,000. Where those conditions are met, the in-line resonance phenomenon is suppressed and the controlling limit is $f_s/f_n^c<0.8$.

To establish whether an application involves a low-density gas, it is necessary to establish a Reynolds number that requires a viscosity value. Accordingly, to get the benefit of the higher ratio applicable to a low-density gas, the designer must be able to verify the viscosity of the process gas.

Cyclic-Stress Exception—Beware of Passing Through In-Line Resonance

Given specific characteristics, 19.3 TW permits a kind of balancing between in-line and transverse resonance conditions. This is allowed where the thermowell passes a cyclic-stress test at in-line resonance. Essentially, the cyclic-stress test evaluates whether a thermowell is likely to fracture or mechanically fail as it transitions through an in-line resonance condition. This middle zone between the in-line and transverse lock-in zones is defined mathematically as a wake frequency to an installed natural frequency ratio greater than 0.6 but less than 0.8. The 19.3 TW standard will not provide a passing result to any thermowell that enters transverse resonance.

Although balancing between in-line and transverse lock-in zones is permitted by the standard, this practice is not recommended because slight increases or decreases in velocity can cause the thermowell to fail. Conservative engineering counsels that, unless in-line resonance is suppressed due to a low-density gas, if at all possible one should design a thermowell so that its steady-state condition maintains a wake frequency that is less than 40% of the installed natural frequency.

Appendix E shows a thermowell design that passes at a velocity of 38.71 ft/s (11.80 m/s). That same thermowell fails at 34 ft/s (10.36 m/s) and at 45 ft/s (13.72 m/s). In other words, for this thermowell to survive installation, the process conditions must be maintained consistently within a narrow 11 ft (3.35 m)/s (7 mph [11.27 km/hr]) band. This passing value is a trap for the unwary due to the common engineering habit of designing thermowells for peak conditions where stated velocities are often significantly higher than those anticipated for normal operation.

Accordingly, where the wake frequency to installed natural frequency ratio falls between 60% and 80%, the practice of assigning a maximum velocity and evaluating the thermowell against that is no longer considered sufficient to assess success or failure. In this scenario, the minimum and maximum operating ranges should be established and evaluated to ensure that at no point is the thermowell exposed to the risk of a steady-state condition within a lock-in zone for in-line or transverse resonance. In nearly all of the cases, the simpler (and better) solution is to select a maximum insertion length that results in a design where the thermowell is not ever required to pass through a state of in-line resonance. Because of the peculiar and varied relationships involved in balancing between phases, engineers should be particularly careful anytime they are designing a thermowell that they expect will fall between the lock-in zones for in-line resonance and transverse resonance [13].

Practice Note: Avoid Software Remedies that Provide a Pass/Fail Result Without Indicating Whether that Result Was Reached Due to the Cyclic-Stress Exception

Some software has the ability to identify when a positive wake-frequency calculation result is based on unreliable conditions, such as passing a cyclic-stress test. When designing a spreadsheet or using a software to perform wake-frequency calculations, care should be taken to ensure that where the design meets the requirement because of the cyclic-stress test only, a warning is presented that any reduction in velocity or insertion length could cause damage to the thermowell (see Figure 3-11). This is reinforced in that, although the thermowell is not damaged by passing through in-line resonance, the installed sensor may fail as a result of the high vibration that it encounters.

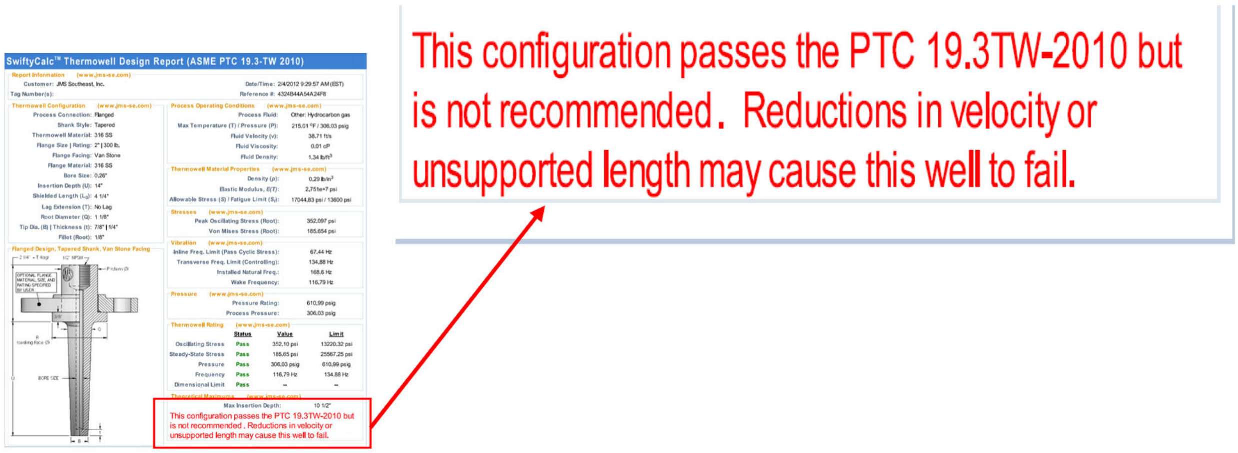

Figure 3-11
Example of an appropriate warning generated in response to a pass result contingent upon parking between resonance zones

Drilling Down—Oscillating (Dynamic) and Steady-State Stress Under the ASME 19.3 TW Code

Peak stress occurs at the support plane (root) of a tapered or straight-shank thermowell. For a stepped thermowell, peak stress must be evaluated at both the root and base of the step. Assessment of stress is another point of fundamental departure between the Codes. Whereas the 19.3 simply required that the sum of static and oscillatory stress not exceed the maximum allowable stress, 19.3 TW requires that an independent assessment be performed for both the steady-state and dynamic (oscillating) stress for all applications where velocities exceed 2.1 ft/s (0.64 m/s).

Under the 19.3 TW standard, steady-state stress is defined as the combined effect of hydrostatic fluid pressure and nonoscillating drag on the thermowell. The maximum permitted stress provided by the standard applies the von Mises criteria for failure. The von Mises criteria is a well-established structural analysis method for combining multiaxial loads into an equivalent tensile stress. According to the 19.3 TW standard, the von Mises stress must not exceed one-and-a-half times the value of the maximum allowable working stress of the material as specified by the governing code.

Dynamic stress results from periodic drag forces that cause the thermowell to deflect back and forth with and transverse to the flow of the process fluid. The limit of acceptable dynamic stress is temperature derated from the maximum fatigue stress amplitude limit at room temperature. Where information is provided, an environmental factor can also be introduced to consider effects such as corrosive services using ASME B31.1 Appendices IV and V as a guide.

Fatigue Failure Can Occur Due to Steady-State Stress or Dynamic Stress

Steady-state stress is due to a combination of hydrostatic fluid pressure and non-oscillating drag on the thermowell. It exerts a maximum stress (*Smax*) in the direction of the thermowell axis, on the downstream side of the thermowell where the thermowell attaches to the support plane. The thermowell's robustness against steady-state stress is determined by the von Mises criterion, as follows:

$$\sqrt{\frac{1}{2}[(S_{max} - S_r)^2 + (S_{max} - S_t)^2 + (S_t - S_r)^2]} \leq 1.5S \qquad \textbf{Eq. 3-1}$$

where *Sr* and *St* are the radial and hoop stresses at the thermowell root, and *S* is the maximum allowable stress, whose value may be fixed either by the governing code or by testing. For a step thermowell, the von Mises criterion should be evaluated at both the support plane and root of the step.

Dynamic stresses result from periodic lift and drag forces on the thermowell. The peak oscillatory bending stress is taken to be a function of these lift and drag stresses, as follows:

$$S_{o,max} = K_t \cdot (S_d^2 + S_L^2)^{1/2} \qquad \textbf{Eq. 3-2}$$

where *Kt* is a stress concentration factor equal to 2.2 when the dimensions of the fillet at the base of the thermowell *b* are not known and determined on the basis of the ratio of *A* (the root diameter) to *b* when they are. *Kt* should be set to a minimum of 2.3 for threaded wells. To prevent thermowell failure, *So,max* needs to be less than the fatigue endurance limit modified by temperature and environmental correction factors, as follows:

$$S_{o,max} < F_t \cdot F_e \cdot S_f \qquad \textbf{Eq. 3-3}$$

where *Sf* is the allowable fatigue limit in room-temperature air and should be evaluated at the design cycle limit of 10^{11} fatigue cycles except as intended use dictates otherwise. *Fe* adjusts for the effects of a corrosive process fluid on the fatigue limit, if necessary, and *Ft* for the effects of process temperatures above room temperature.

Drilling Down—Evaluating Pressure Ratings Under the ASME 19.3 TW Code

Under the 19.3 TW standard, a pressure calculation is established to evaluate whether the thermowell is likely to suffer tip or wall collapse due to the process pressure. For flanged wells, 19.3 TW also requires application of the working pressure temperature ratings established by ASME B16.5. As long as the process pressure is lower than the pressure limit of the wall, tip and (where applicable) flange, the thermowell meets the requirement. To counter the risk of shank collapse, PTC 19.3 TW includes a basic hoop-stress calculation to evaluate the suitability of a thermowell as a pressure boundary.

Pressure failures of thermowells are very rare. However, the same cannot be said for the protection tube. Protection tubes are typically fabricated by welding a process connection and machined plug to the end of a piece of seamless pipe (see Figure 3-12). Because protection tubes serve the same function as thermowells, they are often casually referred to as *thermowells*.

Figure 3-12
Collapsed Kanthal[2] protection tube caused by external pressure

In this case, the protection tube was manufactured from Kanthal material and exposed to a process having a temperature of 1850°F (1010°C) and pressure of 550 psig (3893.44 kPa). The unsupported length below the flange was 48 in. (1219.20 mm), the tip diameter was 1.05 in. (26.67 mm), the wall thickness was 0.110 in. (2.794 mm), and the ID was 0.83 in (21.08 mm).

At 1850°F (1010°C), the creep strength of Kanthal is 150 psig (1135.54 kPa). Despite the relatively high velocity, wake frequency was not the cause of failure. Failure resulted directly from the process pressure of 550 psig (3893.44 kPa) far in excess of Kanthal's creep-strength material rating [14].

The 19.3 TW standard calculates wall pressure ratings for thermowells (P_c) as the following:

$$P_c = 0.66S\frac{2.167}{2B/(B-d)} - 0.0833$$

where B = OD of thermowell at tip, S = maximum allowable working stress (psi), d = 0.83 in. (21.08 mm) diameter. Applying the 19.3 TW calculation to these facts predicts failure because the process pressure of 550 psig (3893.44 kPa) is greater than P_c, as shown in the following:

$$P_c = 0.66S\frac{2.167}{2B/(B-d)} - 0.0833 = 99 - \frac{2.167}{2.1/(.22)} - 0.0833 = 99 - 0.227 - 0.0833 = 98.69 \text{ psig}$$
(781.77 kPa)

Corrosion, Erosion, and Material Compatibility

Care should be taken to ensure that materials appropriate to the process are selected. The material must not only be chemically compatible with the process, but also must be suitable for the stress, temperature, and pressure.

In cases where corrosion is a concern, the thermowell material should be chosen carefully for its resistance to corrosion and corrosion fatigue. Thermowell material must always be forged or bar stock and meet the requirements of the governing code. In addition, the maximum allowable

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[2] *Kanthal* is a registered trademark of Kanthal Group.

pressure and the maximum allowable velocity must be examined in view of the installation's potential for corrosion; and the Code requires they be calculated for the following cases: (a) the initial thermowell dimensions; (b) the initial thermowell dimensions with root diameter *A* reduced by a corrosion allowance *c*, approximating the case of heavy erosion at the root; and (c) the initial thermowell dimensions with tip diameter *B* reduced by *c*, approximating the case of heavy erosion at the tip. The corrosion allowance *c* is to be fixed by the designer. The maximum allowable pressure and maximum allowable velocity should be taken as the minimum of the values obtained for the three cases described. If either the operating pressure or the fluid velocity exceeds its maximum allowable value, thermowell failure may result. Additionally, the designer may assign an environmental factor (F_E), reducing the oscillating (dynamic) stress limit to account for the potential for material loss [15].

Practical Note: Remember Steam Blow Conditions When Evaluating Thermowell Suitability

For new power generation facility construction, high-velocity steam is routinely admitted through steam lines to clear any debris out of the line before commencement of power generation. Where weld-in thermowells are installed in the line during this procedure, these higher velocities must be considered [16]. Although 19.3 TW does not have a speed limit, as a practical matter, it is extremely difficult to validate designs where the steam velocities exceed 750 ft/sec (228.6 m/s). It is not unusual in steam-blow conditions to exceed 1000 ft/s (304.8 m/s).

Accordingly, where the thermowell under design is going to be installed into a line subject to steam blow, a proper design procedure may require changing the process connection from weld-in to threaded. In this manner, the thread-o-let can be plugged during steam blow and the thermowell installed subsequent to the conclusion of steam blow.

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4

EXAMPLES OF THERMOWELL FAILURE RELATED TO THE PRIMARY CAUSES ADDRESSED BY THE 19.3 TW THERMOWELL STANDARD

Case Study—Circulating Water Line Thermowell Failure Caused By In-Line Resonance and Oscillating Stress Predicted By 19.3 TW But Not By 19.3

The effectiveness of 19.3 TW was vividly brought to light in the course of troubleshooting the following thermowell application just before the publication of 19.3 TW. A power plant required a temperature gauge in a thermowell mounted in an 84-in. (2133.60-mm) diameter circulating water line. The thermowell was located along the outside edge of the cross-over line between the high-pressure and low-pressure condenser (see Figure 4-1). The velocity at this location based upon pump runout was estimated to be 10 ft/s (3.048 m/s). The location, dimensions (1.25-in. [31.75-mm] root and 0.75-in. [19.05-mm] tip), and insertion length (22 in. [558.8 mm]) were based on typical practices.

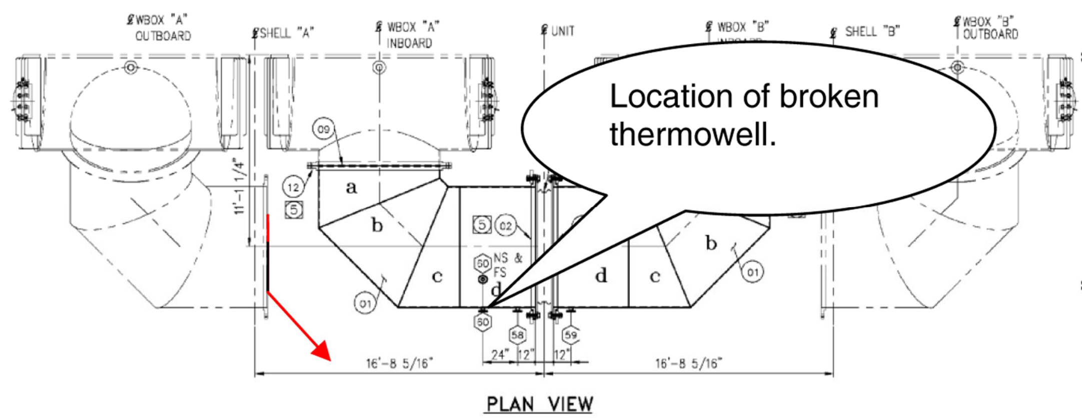

Figure 4-1
Thermowell installation location

After approximately one month of service, the thermowell failed (see Figure 4-2). Operators noticed that the temperature gauge was dripping water, not functioning, and that the needle was spinning freely. Upon removal, it was determined that the thermowell had snapped off near the base of the flange. The site team incorrectly speculated that this thermowell may have been manufactured from ceramic by mistake.

Figure 4-2
Broken thermowell 1

A root cause analysis revealed that instead of manufacturing the thermowell to the design specification, the supplier manufactured the thermowell to its own standard specifications (0.781-in. [19.837-mm] root and 0.625-in. [15.875-mm] tip). A classical PTC analysis was performed on the first thermowell and designated as failed due to transverse resonance. A new, beefier thermowell was specified (22-in. [558.80-mm] immersion, 1.5-in. [38.10-mm] root, 1-in. [25.4-mm] tip) to prevent recurrence. Additional steps were taken to reduce or capture manufacturing errors before shipment.

Two months later, the second thermowell failed. Reports from the site team were similar to the first incident. The gauge was leaking and not operating. Upon removal, it was revealed that the thermowell had not broken off completely but had cracked through to the bore (see Figure 4-3). A more thorough investigation commenced.

Figure 4-3
Broken thermowell 2

This time a computational fluid dynamic (CFD) analysis was performed to better assess the velocity at the point of thermowell installation (see Figure 4-4). This analysis indicated that the velocity of water at the point of installation was not 10 ft/s (3.048 m/s), but instead 20 ft/s (6.096 m/s). However, even with the higher velocity, the assessment by the traditional 19.3 wake-frequency methodologies showed that the installation should have been successful. The new 19.3 TW methodology was then applied. At the time, the new standard was still in draft form pending ANSI and ASME approval.

19.3 TW predicted failure for this thermowell installation based upon in-line resonance and oscillating stress. As a result, a shorter replacement thermowell was specified for which success was predicted by the draft 19.3 TW standard (16-in. [406.4-mm] immersion, 1.75-in. [44.45-mm] root, and 1-in. [25.4-mm] tip). With the new design, there have been no further reports of failure.

Subsequent to the investigation, several other plants were evaluated. A number of failures were predicted using the new methodology. One additional failure was reported from the field. Steps were taken to correct the compromised thermowell designs.

As a result, the following recommendations were made [1]:

- Avoid long thermowell installations just downstream (within 2 to 3 diameters) of elbows in circulating water lines.
- Generally limit insertion length of thermowells in circulating water lines to 16 in. (406.4 mm) or less.
- Carefully review specification documents and manufacturing drawings to ensure that specified thermowell dimensions are provided.
- Apply 19.3 TW calculations because older methodologies may not be as conservative.

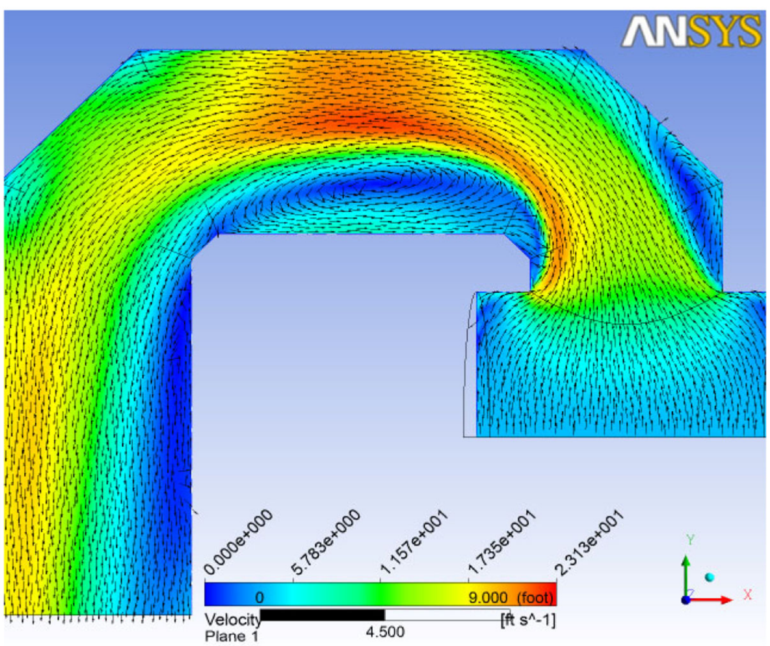

Figure 4-4
CFD analysis of a velocity profile inside a circulating water line, where red indicates high velocity and dark blue indicates low velocity

Velocity-Induced Vibration and Stress-Related Thermowell Failures Liquefied Natural Gas Line—Thermowell Immersion Longer Than Necessary

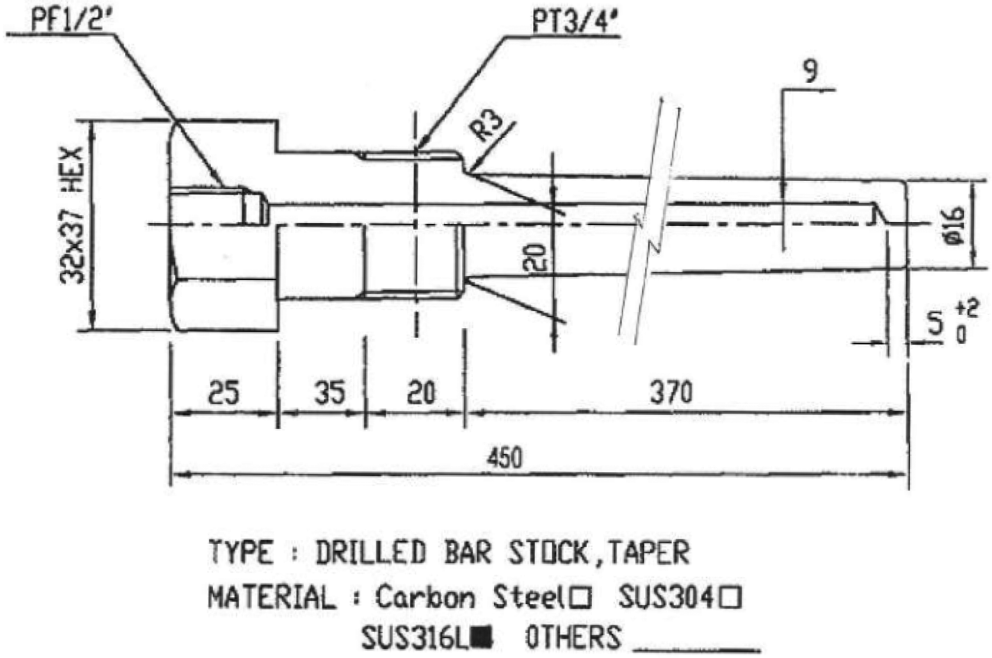

Figure 4-5
A 316L thermowell installed in a liquefied natural gas custody-transfer line

The thermowell shown in Figure 4-5 was installed in a liquefied natural gas (LNG) line to measure temperature for purposes of custody transfer on an ocean-going vessel. The unsupported length of the thermowell was 14.5 in. (368.3 mm). In the course of the custody transfer, the thermowell catastrophically failed, shearing off completely just below the threads (see Figure 4-6). The LNG in the line escaped and spilled onto the deck, resulting in a cryogenic fracture to the ship itself.

Figure 4-6
Failed thermowell

Significantly, the failed thermowell had a 14.5-in. (368.3-mm) U. The investigating body stated that at velocities of 7 ft/s (2.134 m/s) and greater, LNG is turbulent and the boundary layer is less than 0.5 in. (12.7 mm). Accordingly, a 2.5-in. (63.5-mm) thermowell would have provided tremendously enhanced mechanical strength with negligible impact on the accuracy of the temperature measurement. In this case, there was no need to attain the middle-third of the pipe. The effort to do so resulted in no advantage from a temperature measurement perspective and a significant disadvantage mechanically.

The thermowell failure depicted is typical of velocity-induced vibration. As the thermowell's installed natural frequency is approached by the frequency of the vortices being shed by its shank, the vibration amplitude increases tremendously, exerting the majority of the force at the root of the thermowell and resulting in a break. Proposed solutions to this application include shortening the thermowell and evaluating its design by application of the 19.3 TW standard. If no suitable design can be obtained, consider using a measurement of the pipe surface instead of an immersion measurement [2].

Velocity-Induced Vibration and Stress-Related Thermowell Failures Main Steam Line—Human Error Selecting Light Duty Well

Human error can also play a part in causing thermowell failure. The following thermowell was selected for a high-pressure, high-temperature, high-velocity main steam line (see Figure 4-7). The installed well lasted for approximately three weeks before failing.

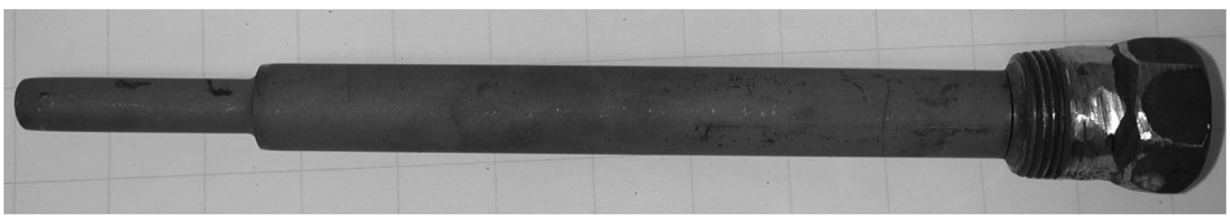

Figure 4-7
Step shank thermowell

Although a stepped thermowell can make an excellent choice for a fast response time and the longer immersion length to bring the sensing element closer to the center of the flow, the thermowell must be designed to withstand the process conditions that it is likely to encounter. Typical of thermowells suffering from flow-induced vibration, this thermowell cracked to the bore and was discovered before the shank, completely separating from the thread (see Figure 4-8) [3].

Figure 4-8
Failed thermowell: close-up of crack at support plane caused by velocity-induced vibration

Velocity-Induced Vibration and Stress-Related Thermowell Failures Liquid Sodium Line—Velocity Collar Insufficient to Avoid Failure

In an effort to get further into a process line, various strategies have been implemented to support a thermowell that is too long to endure the anticipated velocity conditions. Before the release of 19.3 TW, a number of designers would use a stiffening ring or velocity collar to attempt to brace the thermowell against the inside of the pipe nozzle (see Figure 4-9). The designers would typically theorize that use of the collar would shift the point of support to the hot side of the collar. The 19.3 TW standard has since stated that this practice is not recommended and is strictly outside of the scope of 19.3 TW. In practicality, for a collar to function correctly, it must have an interference fit with the nozzle. This is not practical to install and would make any subsequent removal of the thermowell nearly impossible.

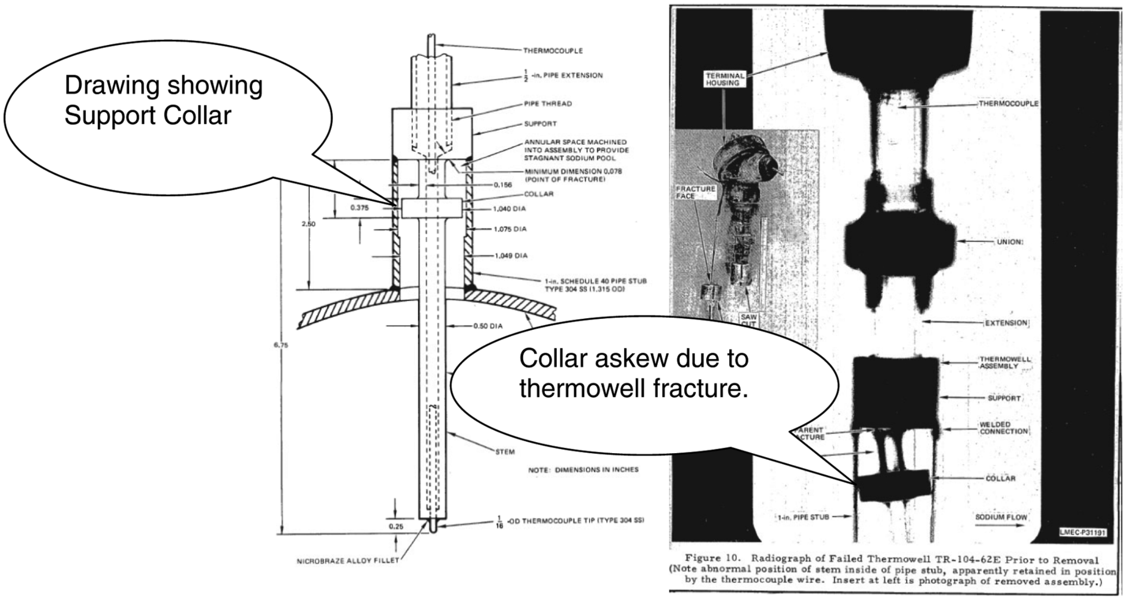

Figure 4-9
Thermowell with a collar support (left) and a radiographic image (right) of a thermowell failure above the collar

In practice, this design changes the entire natural frequency of the thermowell and rarely serves to support the thermowell in practice as well as it does in theory. The thermowell design in the figure was installed in a liquid sodium line 13 in. (330.2 mm) downstream of a butterfly-type control valve. Due to fatigue failure, the thermowell was completely severed at the stem to support the junction.

The sensor projecting from the thermowell tip was also completely severed (see Figure 4-10).

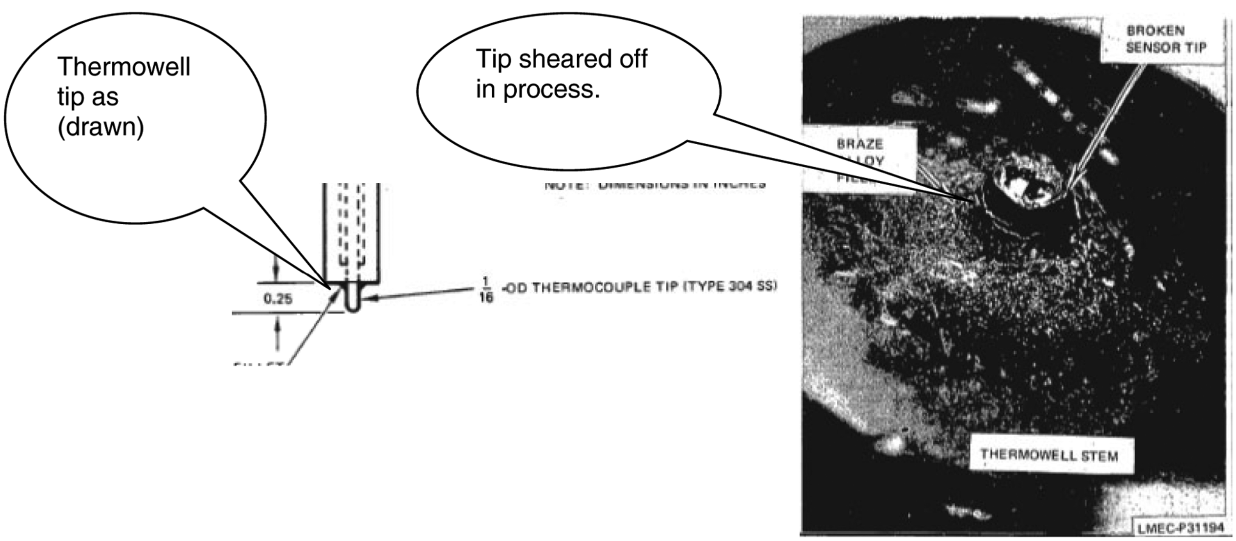

Figure 4-10
Thermowell with a protruding tip (left) and a photograph (right) of a thermowell showing a sheared tip

This thermowell failure resulted in a liquid-sodium leak and fire. The accident investigation revealed the root cause of failure as velocity-induced fatigue failure. To prevent further incidents, all thermowells were removed from locations immediately downstream of butterfly valves where the prediction of velocity caused by turbulence could be difficult to achieve. Moreover, the collar design was abandoned in favor of a more traditional weld-in design. All of the thermowells in the sodium line were removed and inspected. A number showed broken or damaged tips, but none showed the damage to the thermowell shank exhibited by the failed thermowell [4, 5].

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5

EXAMPLES OF THERMOWELL FAILURE RELATED TO THE SECONDARY CAUSES IDENTIFIED BY THE 19.3 TW THERMOWELL STANDARD

The PTC 19.3 TW standard primarily focuses on the stresses originating from the dynamics associated with fluid flow. However, it also incorporates other failure modes such as corrosion or erosion to a lesser degree by establishing factors to account for their impact on the thermowell design's ability to withstand predicted fluid-flow forces.

Thermowell failures come in a wide variety, from pressure-related to more obvious mis-installation errors. Although 19.3 TW is extremely helpful to thermowell design, it does not anticipate all possible causes of thermowell failure. For example, at least one source has also noted thermowell breakage occurring due to water freezing inside of the thermowell [1]. The 19.3 TW standard itself points out that failure due to turbulence-induced structural vibration, pulsed flow environments, or interactions of multiple thermowells in close proximity is outside of its scope [2]. This section will address instances of thermowell failure not directly attributable to fluid-flow dynamics. It also addresses some more obvious failures attributed to improper installation, manufacture, or design.

Pressure-Related Thermowell Failures

Pressure-related thermowell failures are extremely rare unless an installation error is at play. Professor John E. Brock of the Naval Postgraduate School and one of the original framers of the original PTC 19.3 questioned in 1974 whether there could be any reasonable pressure limit for a thermowell, as described in the following:

> There is no theoretical limit to the external pressure which may be applied... however we are also concerned with maintaining a reasonable approximation to the original internal dimensions so that the thermocouple assembly may be withdrawn and replaced even when pressure is applied." [3]
>
> Bridgeman conducted a number of tests on tubes of various steels having O.D. = 0.3125 in., I.D. = 0.0998 in. This corresponds to current industrial practice for high pressure installations. He subjected these tubes to as high as 412,000 psi external pressure. In each case the tube simply decreased in diameter, while maintaining its length almost exactly without change…. In one case, of a very soft steel under 412,000 psi, the central cavity appeared to close up completely. However, there was no failure or loss of pressure integrity. Thus for such thick wall cylinders non-symmetric distortion simply does not take place. [4]

In Brock's opinion, the only practical concern regarding thermowell failure is that the attaching weld might fail, as described in the following:

> The only case of high pressure thermowell failure of which the writer has knowledge seem unquestionably to be associated with failure of the attachment weld (after satisfactory operation for a number of years, incidentally). [5]

As it turns out, failure of the attaching mechanism is a serious concern.

Threaded Thermowell Pressure-Related Failures Due to Installation Error

Figure 5-1
Thermowell retrieved following ejection from a main steam line

As shown in Figure 5-1, the first instance of thermowell failure resulted from improper installation. The thermowell was properly sized and installed in a 3500 psig (24,232.98 kPa), 1000°F (537.78°C) main steam line. The bend in the shank and the chip at the tip occurred when the thermowell ejected from the process and struck structural steel in the building. From the picture, it is possible to count approximately three threads of engagement before the application of a seal weld (see Figure 5-2).

Threaded thermowell connections are designed to have the threads retain the design pressure. However, depending on the connection size, between six and eight threads are generally required to be in contact with the process connection threads whether the thermowell is installed into a thread-o-let or the process pipe is drilled and tapped. The seal weld primarily serves to prevent the thread from backing out and acts as additional leakage protection. When used, the seal weld should be of a material suitable for the thermowell and the process pipe. Dissimilar metal welds should be avoided.

It is also well known that above 900°F (482.22°C), the threaded hole can elongate (creep) causing the threads to lose their engagement. Oxidation of the threads over time can also reduce the threads' load carrying cross section. At 1000°F (537.78°C) and 3000 psig (20,785.60 kPa), this thermowell fell into the category of applications where a seal weld is required, but, in this case, the threads were never given the opportunity to do their job. This thermowell became a dangerous projectile when it blew out while the line was hot (see Figure 5-3). Fortunately, there were no injuries [6].

Although unusual, this instance of failure is not unique. In a poll of EPRI members, one operator recounted an instance where a thermowell with a thread smaller than its boss was simply seal welded into place without any thread engagement, resulting in failure.

In yet another plant a welded thermowell lasted a bit longer before it failed in the same manner. In this case, the thermowell was threaded a little further in, but only half of its full engagement.

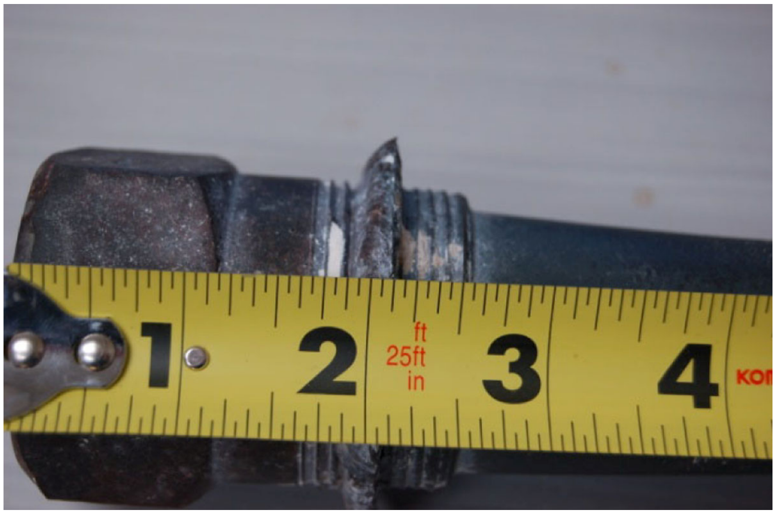

Figure 5-2
Thermowell ejected from a steam line showing insufficient threads of engagement

Figure 5-3
Ejected thermowell (left) and the damage (right) caused by the thermowell ejection

The lesson to be learned is that no matter how well designed a thermowell may be, it must be properly installed. The consequences of failure to properly install a thermowell in a high-pressure steam line can be disastrous [7].

Weld-In Thermowell Pressure-Related Failure Due to Installation Error

Threaded thermowells are not the only thermowell type susceptible to ejection when poor installation technique is implemented.

Figure 5-4
Thermowell and boss into which it had been welded

During a hot start, the weld-in thermowell, as shown in Figure 5-4, ejected from its location and landed three-and-a-half floors beneath its original installation. A second thermowell installed in the soot-blower system was stripped and found to have cracks in its weld (see Figure 5-5).

Figure 5-5
Installed thermowell exhibiting unsafe cracking at the weld

The thermowells at issue were primarily stainless steel thermowells, welded into boss material of 2.25Cr-1Mo using a groove and fillet technique (see Figure 5-6) with stainless steel weld filler material—a dissimilar metal weld.

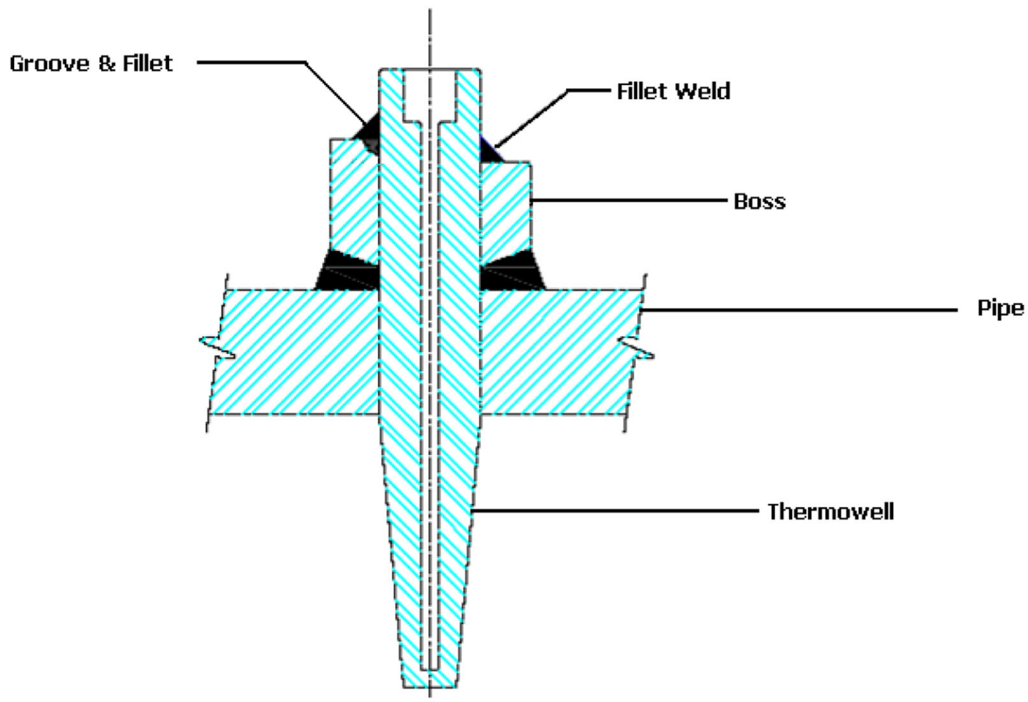

Figure 5-6
Two different methods of weld attachment: groove-and-fillet weld procedure (left) used before the failure, and a fillet weld (right) used following the failure

The groove-and-fillet weld created two significant problems. First, it is a difficult weld to accomplish properly due to difficulty of access. Any lack of penetration or discontinuity forms the perfect crack initiation site. Second, the dissimilar weld required expensive post-weld heat treating, resulting in a nonzero possibility of high-temperature-induced damage. Accordingly, the decision was made to adopt a straight-fillet weld procedure, as indicated on the right side of the installation diagram. Moreover, replacements required thermowells manufactured with matching material and matching weld material, resulting in similar metal welds and significant cost savings approaching $5,000 per well by avoiding heat treating [8].

Pressure-Related Failures—Summing Up

Pressure failures unassociated with corrosion or erosion are extremely unusual. When they do occur, they are typically caused by poor installation technique, creep, thread oxidation, or weld failure. To avoid these concerns, fittings and thermowells of matching alloy to the pipe and header are preferred. Seal welds should not be relied upon as a primary pressure barrier. Plant maintenance personnel should be aware that the need for installation repair could stem from deterioration of the threads. To avoid pressure collapse or breach of the working pressure temperature rating for flanged thermowells, the thermowell design should be compared against the 19.3 TW-2010 standard for compliance [9].

Where repair to an existing thermowell installation is made, some power plants are notching a groove into the side of the thermowell and welding filler material into that notch so that the notch can serve as a kind of mechanical lock to deter ejection from the process [8]. The best solution is proper design, selection of materials, and installation technique. For thermowells of matching F22 or F91 materials, reports have been received describing continuous use with no problems even for wells in units with more than 300,000 hours [7].

Erosion- and Corrosion-Related Thermowell Failures

Coal Pulverizing Small-Particle Erosion Failure

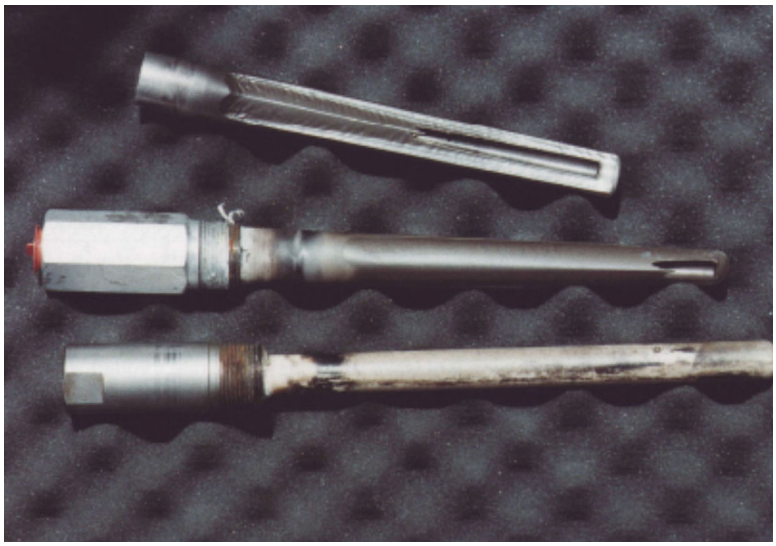

Figure 5-7
Failed thermowells (top two) caused by corrosion in a coal-pulverizing line despite the use of Stellite[3] coating (The protection tube [bottom] survived without failure despite longer exposure.)

These three thermowells (see Figure 5-7) were each installed into a coal-pulverizing line where the major length of the thermowell shank was directly exposed to high-velocity, small-particle erosion. The top two wells were coated with Stellite to increase the lifespan of the thermowells. Although the Stellite material is much harder than steel, the coating process leaves microscopic imperfections or cracks that are inevitably revealed in a process where billions of grains of powder are blasted against the thermowell shank. As soon as an imperfection is exploited by the coal powder and bare metal is revealed, the thermowell quickly erodes, as demonstrated in the figure.

The top two thermowells had been installed in the thermowell line for six months and three months, respectively. Small-particle erosion completely opened the thermowell shanks. Shortly thereafter, the process would have eroded the installed sensor, requiring a replacement.

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[3] *Stellite* is a trademark of the Deloro Stellite Company.

The initial plant response to increase thermowell life was simply to rotate the installed thermowell 180 degrees. Although this effectively doubled the lifespan of the installed thermowells, it acquiesced to expensive repetitive replacement and exposed the plant to difficulty sourcing quick replacements for a part requiring a specialty coating.

However, the acceptance of thermowell erosion caused an even more significant expense to the operating plant. These thermowell-thermocouple installations were being used for control purposes. The control system tuning included a response time factor for the installed sensor. Although tuning was appropriate at installation, as the thermowell wall eroded, the response time of its installed sensor changed significantly. This change caused the control system to overreact, wasting significant energy resources in response to the control indication.

The solution to this problem was to use a solid ceramic with a metallic support structure, as shown in the second thermowell from the top. Because the ceramic being exposed to the flow of coal dust was a solid, it did not have the imperfections existing in a coating. The result was dramatic. Protection tubes manufactured in this manner, such as the bottom one shown in the figure, have lasted for six years and more without failure at significantly less cost than predecessor thermowells in the same installation, which rarely lasted six months.

Thermowells with coatings such as Stellite or other hard facings are unequivocally outside of the scope of a 19.3 TW analysis. Accordingly, operators must be cognizant of the likely basis for an anticipated failure. In this instance, the appropriate design for success is not one that falls within the 19.3 TW standard. In this instance, the better design required characteristics that placed it outside of the scope of 19.3 TW [10].

Erosion-Related Compromise of a Pipe Wall with Thermowell Installation

Figure 5-8
Boiler feed lines removed because of flow-accelerated corrosion

These boiler feed lines (see Figure 5-8) downstream of a high-pressure feedwater heater were removed due to flow-accelerated corrosion (FAC) of the pipe in areas localized to the root of the installed thermowells (see Figure 5-9). The existence of the couplings on the outside of the pipe wall indicates that these thermowells were most likely not full penetration welded into the pipe wall.

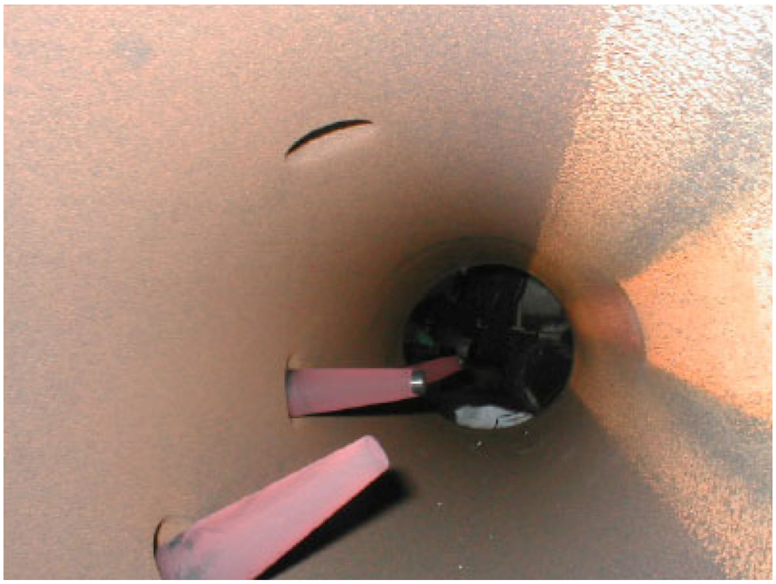

Figure 5-9
Internal view of boiler feed tubes showing advanced FAC localized to the placement of thermowells

As a result of this corrosion, wall thickness was reduced from 1.3 in. (33.02 mm) to 0.9 in. (22.86 mm) [11]. The thermowells were manufactured from F22. The pipe wall material is unknown but appears to be of ferrous material. FAC is not known to occur in stainless steel piping.

In a new installation, inclusion of a minimum chromium content in piping materials above 200°F but below 500°F effectively mitigates FAC. In this case, localized high-velocity areas around the thermowell root due to the crevice between the pipe wall and the thermowell shank would contribute to the effect of the FAC. The chemical composition of the pipe wall and water itself would also have an impact.

Corrosion-Related Failure of a Resistance Temperature Detector—Thermowell Assembly

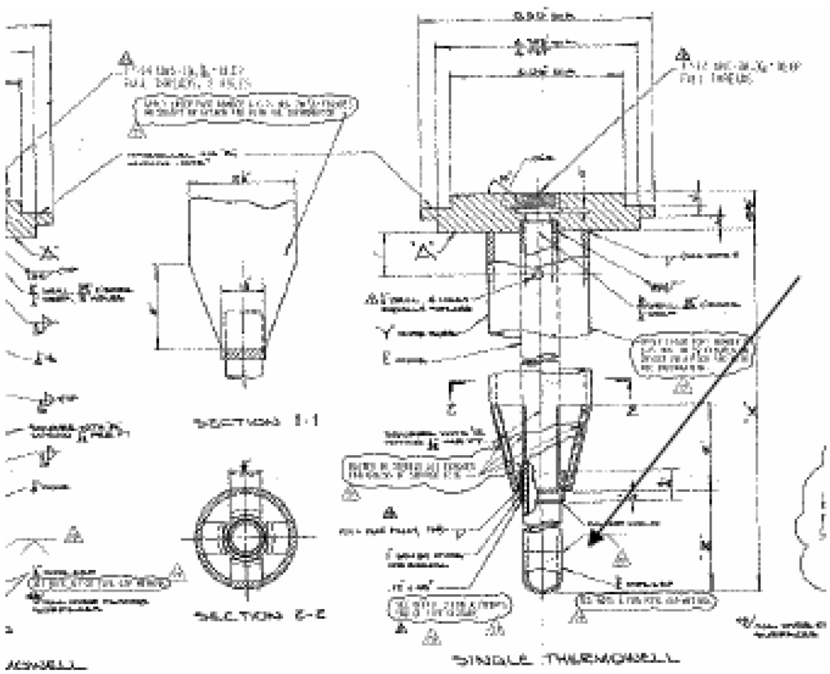

Figure 5-10
Protection tube for a resistance temperature detector

Failure of the depicted protection tube (see Figure 5-10) was identified after 14 months of immersion in a nuclear low-activity waste evaporator when testing of the installed sensor indicated a low resistance to ground. Data from the distributed control system indicated that over this time the resistance temperature detector (RTD) protection tube assembly had been exposed to temperatures exceeding 100°C (212°F) for approximately 3,440 hours (less than one-half year). Because the preceding protection tube in this location had failed within 18 months due to penetration, the cause of failure of this thermowell was initially presumed to be penetration.

Surprisingly, when the protection tube was pressure-tested to 50 psig (446.06 kPa), no leak was detected. However, the RTD remained fixed in the protection tube and could not be removed, moisture was noted on the RTD wires, and the RTD connectors showed signs of oxidation. Following decontamination, an examination of the thermowell revealed that the end cap, although manufactured from 304L SS like the 0.5-in. (12.7-mm) Schedule 40 304L pipe to which it was welded, maintained a different microstructure that permitted preferential corrosion of the tip (see Figure 5-11).

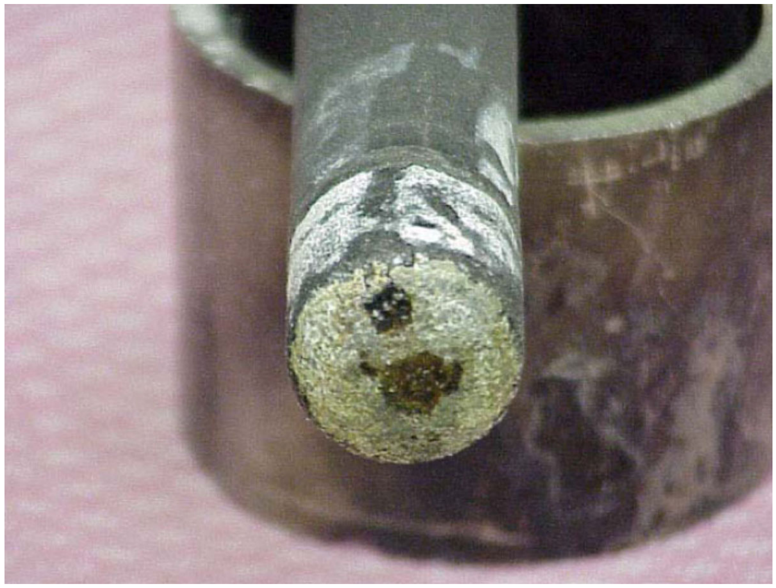

Figure 5-11
Corrosion to the tip welded to the end of the protection tube

Corrosion of the tip quickly migrated into the temperature sensor, resulting in RTD failure. In this case, greater longevity could likely be obtained by selection of materials less susceptible to corrosion. Multiple references exist to assist engineers with anticipating the likely suitability of a particular material in a process environment [13].

As shown in Section 4 of this report on the ASME thermowell standard, where corrosion and erosion rates are predictable, evaluation against the 19.3 TW standard is possible [14].

Corrosion-Related Failure of Thermowells in a Nuclear Power Plant in India

A batch of 316L stainless steel thermowells were procured by a nuclear power plant for installation in 612 heavy water coolant lines entering and exiting the core of a nuclear power plant. The wells were pressure tested at the nuclear power plant before installation using a flexible hose and a soapy solution. The purchase order called for the wells to be pressure tested by the manufacturer as well, but this was apparently not performed. Approximately 20% of the thermowells failed this inspection and were found to be leaking at the tip.

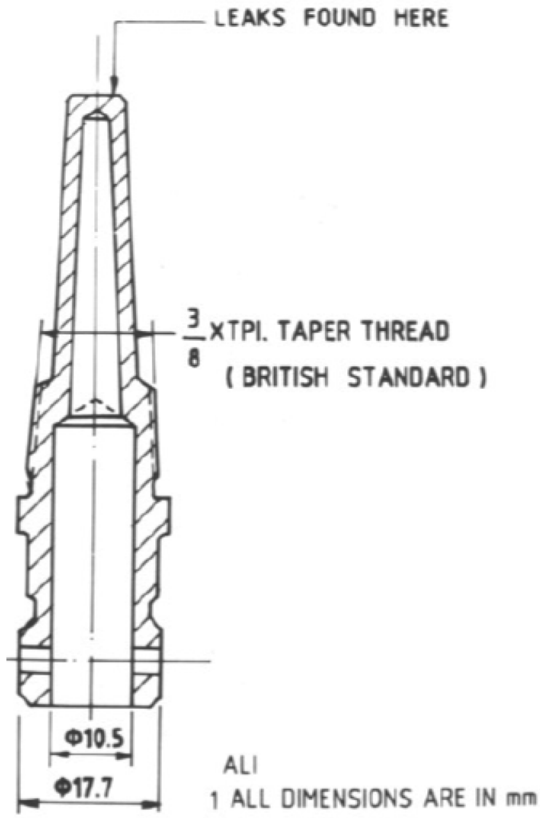

Figure 5-12
Schematic showing thermowell design and location of pin-hole leaks

Although the tips looked solid to the naked eye, a scanning electron microscope examination of the failed thermowells revealed through-holes present at the tip and longitudinally oriented inclusions (see Figure 5-12 and Figure 5-13). Inspectors characterized the internal surfaces of the thermowells as having the appearance of a cracked wooden surface because of inclusion removal (see Figure 5-13).

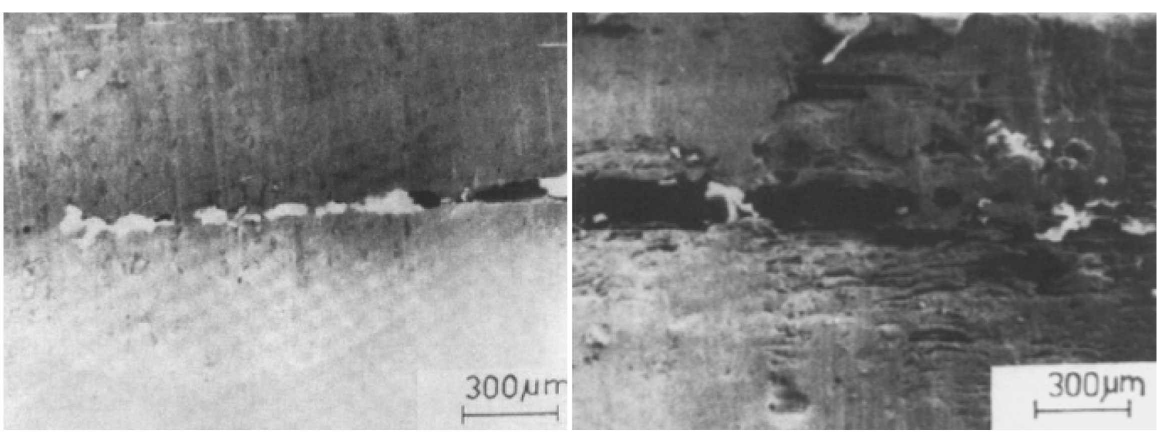

Figure 5-13
Scanning electron microscopic images showing longitudinal inclusions and a rough inside surface of failed thermowells

An electron dispersive X-ray analysis revealed that the inclusions consisted primarily of calcium oxide with small amounts of chromium and iron oxides. Assessment of the likely sources of these inclusions was the result of entrapped slag in the material at the time that the metal was manufactured. When the calcium oxide came into contact with water during the inspection process, it dissolved, leaving holes in the thermowell tip. Preventive action adopted in response to this investigation was to require that the UT for the material take place before well fabrication. Additionally, the requirement for pressure testing was reiterated to the manufacturer [15].

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6

EVALUATING EFFECT OF THERMOWELL DESIGN ON MEASUREMENT ACCURACY AND RESPONSIVENESS

As discussed in previous sections, field reports of thermowell failures have caused many thermowell designs to grow more conservatively—meaning shorter and thicker. The achievement gained due to design improvement is greater process integrity. But for every gain there is a risk. The risk in this instance is the possibility of an adverse impact on the temperature measurement accuracy or speed of response. The trick is in quantifying the degree of error or amount of lag introduced as a result of this dynamic.

Various mathematical formulas have been generated in the attempt to solve this problem. For the benefit of those so inclined, this section does provide formulas for those interested in achieving a mathematical approximation. However, those formulas yield approximations only. Moreover, this is aimed to assist the engineer and end user. Many items that are interesting variables to the process system designer (varying levels of heat transfer of the process fluid or gas by changing the process fluid or gas, varying heat transfer of the materials of construction by changing the thermowell material, varying the velocity of the process fluid or gas) are to the instrumentation and controls of practitioner immutable facts of life not subject to variance. These are included for discussion to illustrate without exhaustively categorizing some of the many variables that can impact a measurement accuracy or response lag. Numerous practical recommendations that do not require mathematical solutions are also presented.

Characteristics Improving Accuracy

Installation errors in temperature measurement commonly result from conduction error (stem loss), radiative exchange error, kinetic energy dissipation, and internal heating [1].

The metal body of a thermowell, the metal sheath of the installed temperature sensor, and the wires inside that temperature sensor all serve as excellent conductors of heat. Where heat is conducted radially (from the outer radius of the well to the sensor installed inside of the thermowell), this quality improves the accuracy of the temperature measurement and speed of response [1]. In some cases, users have attempted to incorporate a thermal paste or heat transfer fluid into the bore of the well to accelerate heat transfer between the thermowell and installed probe. Unfortunately, this strategy often backfires because the heat transfer fluid can lose its thermal conductivity as it cooks over time, causing the installed sensor to perform more poorly and can even cause the sensor to become stuck in the thermowell requiring removal and replacement of both items [2].

A more reliable means to improve radial conduction is to decrease the OD of the thermowell, which shortens the heat transfer path from the process to the installed sensor [1].

Just as heat is conducted radially through the thermowell to the installed sensor, it is also conducted axially toward the typically cooler temperature of the thermowell body that is outside of the process. In this case, the heat transfer becomes a source of error often referred to as *conduction error* or *stem loss*. As heat flows up the body of the thermowell, the sensor tip is cooled, in some cases preventing it from reaching thermal equilibrium with the process being measured. The impact of this error can generally be reduced by increasing the immersion length of the thermowell into the process and insulating the back end of the process.

At least one source indicates that as a general rule, 5 diameters plus the length of the sensing element is sufficient for most industrial applications because it introduces no more than 1% error (see Figure 6-1). For 0.01% accuracy, 10 diameters plus the length of the sensor is recommended. Every 5 diameters of immersion reduces the effect by an additional two orders of magnitude [3].

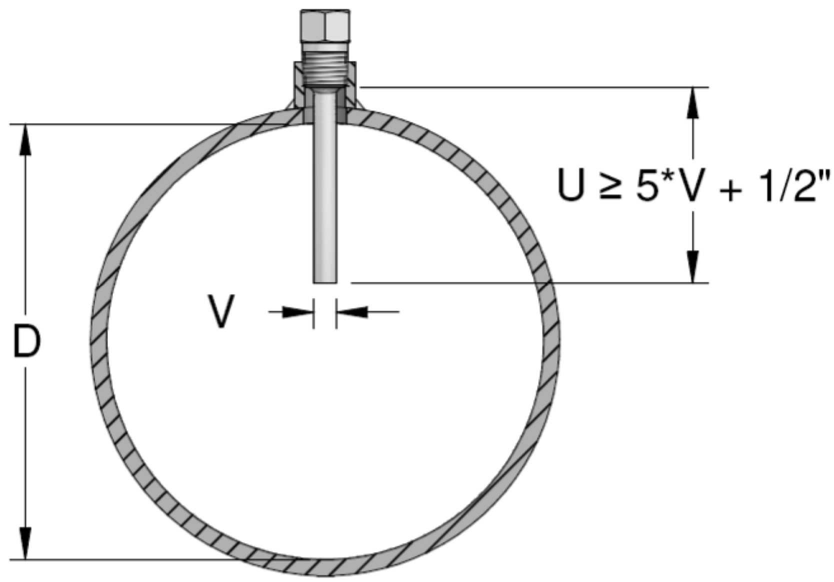

Figure 6-1
Thermowell U exceeding its width V by a factor of 5 plus the length of its sensing element (0.5 in. [12.7 mm]) to reduce the installation error to approximately 1%

This analysis is sensitive to the characteristics of the process fluid being measured. Accurate measurement of air will require a longer immersion length than measurement of a liquid [4]. Table 6-1 shows some recommendations for thermowell insertion lengths established by various ASME PTCs [5-9].

Table 6-1
ASME PTC recommendations for thermowell insertion lengths

Code	Minimum Immersion Requirement
PTC 6, Steam Turbines	3 in. (76.2 mm) or not less than one-fourth the pipe ID.
PTC 12.1, Feedwater Heaters	No stated requirement.
PTC 12.2, Condensing Apparatus	Cooling water—where well mixed, 6 in. (152.40 mm) into flow but no longer than one-half pipe diameter. Where flow cannot be proven mixed, traverse is required.
PTC 14, Evaporator Apparatus	3 in. (76.2 mm) or not less than one-fourth the pipe diameter. Lines over 12 in. (304.80 mm) require multiple sensors.
PTC 12.3, Deaerators	3 in. (76.2 mm) or more into the fluid space.

Finally, where it is possible to extend or retract the length of the immersion into the process, the practitioner can eliminate conduction error by taking readings at progressively longer immersion depths and allowing the temperature indication to reach equilibrium (see Figure 6-2). As soon as a depth has been achieved at which the temperature ceases to rise, conduction error has been eliminated.

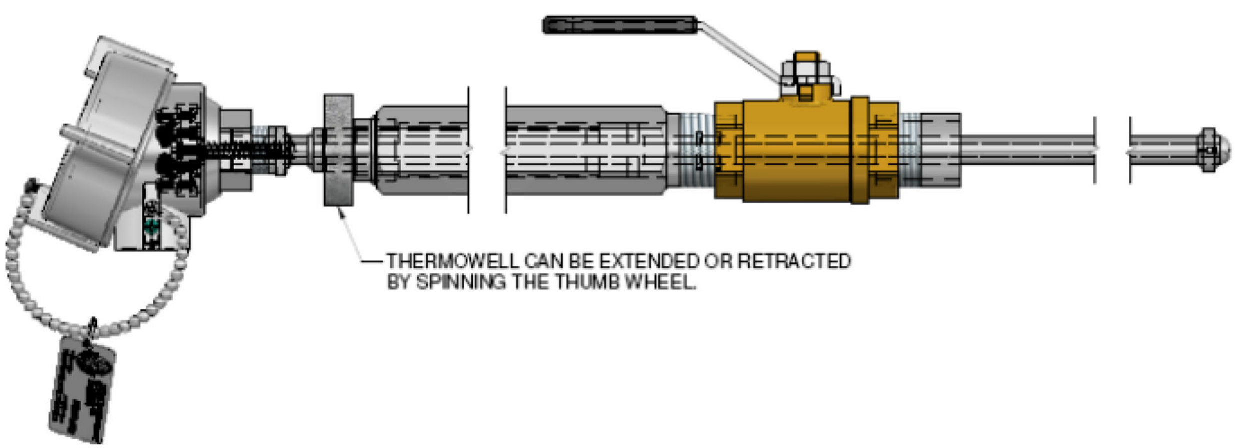

Figure 6-2
Protection tube with an installed sensor capable of being extended or retracted into a process

Radiative exchange error occurs when a sensor is exposed to an object that is hotter or colder than the process being measured. To the extent that the sensor can absorb heat from or transfers heat to this object at a greater rate than the process media, an error can occur. Again, a smaller diameter is an advantage for accurate temperature measurement in this instance because the smaller size is an advantage for heat transfer from the process to the sensor rather than over the radiant source. Other means of reducing this potential for error include shielding the thermowell from the source of radiation, locating the thermowell where it cannot see the heat source, or locating the thermowell in a higher-velocity section of the process because higher velocities are an advantage for heat transfer from the process to the installed sensor [1].

Kinetic energy dissipation occurs as the passage of the fluid around the thermowell shank heats the thermowell and in turn heats the installed sensor. This has little impact on practical applications because it becomes significant at very high velocities only, on the order of Mach 1 or greater. Even in such instances, the thermowell serves to reduce the impact of this phenomenon on the installed sensor [1].

Conduction Error

Here we consider the case of a thermowell immersed in a process fluid whose temperature is higher than that of the enclosing walls; the reverse may be considered with appropriate changes to algebraic signs.

The thermowell receives heat from the process fluid and enclosing walls by convection and radiation and loses it to same, and to the outside world, by conduction and radiation. For a differential well cross-section of thickness *dx*, this heat balance is given by the following:

$$dq_c + dq_r = \frac{dq_k}{dx} dx \qquad \text{Eq. 6-1}$$

where the subscripts c, r, and k correspond to convection, radiation, and conduction, respectively.

Conduction error is due to the imperfect transfer of heat to the well-sensor system, by convection and radiation, and to heat loss through the thermowell root, by conduction. In principle, reductions in conduction error are achieved by increasing thermal contact between the process fluid and the temperature sensor or by decreasing heat flow through the body of the thermowell or both. However, design changes that tend to reduce conduction error—such as increasing the length of the well or its bore—also tend to cut against thermowell safety. This section presents several ways to improve measurement accuracy without unduly compromising well integrity. But first expressions for dq_c, dq_r, and dq_k are given, as well as a procedure for calculating conduction error.

Convection. Convective heat transfer to the well is described by Newton's cooling equation, as follows:

$$dq_c = h_c dA_c (T_{adi} - T_x) \qquad \text{Eq. 6-2}$$

where *hc* is the convective heat-transfer coefficient of the well, *dAc* is the cross-sectional area of the well, *Tadi* is the adiabatic temperature of the fluid, and *Tx* is the temperature of the well. The convective heat-transfer coefficient *hc* describes more or less how readily heat is transferred to the well. The *hc* can be approximated as a function of the Nusselt number and refined through correction curves to account for variations in relevant thermodynamic state properties [10]. Low values of *hc* militate against accurate temperature measurement. Note also, the adiabatic temperature of the fluid is used in lieu of the static temperature to approximate more closely the fluid temperature that the sensing element *feels*.

Radiation. The Stefan-Boltzmann equation can be modified to describe the emission and absorption of radiation by the well. In its basic form, the equation is written as follows:

$$dq_r = \sigma \cdot dA_r \cdot T^4 \qquad \text{Eq. 6-3}$$

where σ is the Stefan-Boltzmann constant, dA_r is the surface area of the radiating body (in this case, the well), and *T* is its absolute temperature.

Absorption. The well absorbs heat radiation from the fluid and enclosing walls pursuant to Equation 6-3, subject to the following constraints:

- The radiant contribution from the enclosing walls is multiplied by a factor $(1 - \alpha)\cdot \epsilon_x$, on the assumption that the fluid absorbs a fraction α of the radiation emitted by the walls and that the remainder of the radiation is absorbed by the well in proportion to the well's emissivity ϵ_x. The enclosing walls are assumed black.
- The radiant contribution from the fluid is multiplied by a factor $(\frac{\epsilon_x+1}{2}) \cdot \epsilon_f$. The first term accounts for the incomplete absorption of the radiation incident on the well's surface and the second for the gray-body characteristics of the fluid.

Emission. The well emits radiation to the process fluid and to the enclosing walls according to slightly modified versions of Equation 6-3. It is assumed that the radiation emitted by the well—specifically, that portion which does not get reabsorbed as a consequence of reflections between the well and the process fluid—is absorbed by the fluid in proportion to the absorptivity of the fluid α and by the enclosing walls in proportion to $(1 - \alpha)$.

Emissions to the process fluid are described by the following:

$$dq_{r,(x\to f)} = \alpha \cdot \sigma(\frac{\epsilon_x+1}{2})dA_r T_x^4 \qquad \text{Eq. 6-4}$$

where the ϵ_x in the term $(\frac{\epsilon_x+1}{2})$ accounts for the gray-body characteristics of the well and the remainder of the parenthetical for radiant reflections between the well and fluid.

Emissions to the enclosing walls are described by the following:

$$dq_{r,(x\to w)} = (1-\alpha) \cdot \epsilon_x \sigma dA_r T_x^4 \qquad \text{Eq. 6-5}$$

where ϵ_x again accounts for the gray-body characteristics of the well.

Net radiation. An equation for the net radiant heat transfer to the well (the dq_r of Equation 6-1) falls immediately from the previous arguments. According to the same, lower-well emissivities and higher-fluid emissivities tend to reduce measurement errors.

Conduction. Heat flows by conduction through the body of the thermowell, from the tip toward the thermowell root and beyond, which can prevent the installed sensor from reaching the fluid temperature. Temperature measurement errors are a direct consequence.

This phenomenon is described by Fourier's conduction equation, as follows:

$$q_k = -kA_k \frac{dT_x}{dx} \qquad \text{Eq. 6-6}$$

where *k* is the thermal conductivity of the well, A_k is the well's annular cross-sectional area at a distance *x* from the thermowell tip, and T_x is the well's temperature at *x*. It follows from Equation 6-6 that a reduction in *k* or A_k would reduce conduction inside the well, and conduction error as a result. Note that conduction through the sensor wires need not be considered on the assumption that $(kA)_{well} \gg (kA)_{sensor}$.

Conduction error calculation. A temperature profile for the well can be constructed by dividing the well into a finite number of cross sections and, for each of the cross sections, equating heat flow in with heat flow out, pursuant to Equation 6-1. The resulting equations form the spine of an algorithm that tracks heat flow, and therefore temperature, from one well cross section to the next. A solution to the algorithm is obtained as follows.

An initial guess is made as to the temperature of the first well cross section, at the thermowell tip. Upon iteration, a temperature for the cross section at the thermowell root is obtained. The root temperature is then compared to the wall temperature *Tw*, and the initial guess is adjusted accordingly. This process is repeated for the new guess and as necessary thereafter. A unique temperature profile for the well can be obtained cheaply through any of a number of iterative schemes; Newton's method is one [7].

Results. Trend curves are shown in Figures 6-3 through 6-6 as a means of providing the reader with an understanding of the effect of each of several variables on temperature measurement error. In three of the graphs, the y-axis is labeled *Ttip – Tw / Tadi – Tw*, where it is assumed that *Ttip* would equal *Tadi* in the absence of measurement error. Therefore, larger values for *Ttip – Tw / Tadi – Tw* should be regarded as an indication of more accurate temperature measurements. Figure 6-3 shows a small benefit in decreasing the thermal conductivity of the well, attainable by a careful choice of well material. Figure 6-4 shows a larger benefit in ensuring that the convective heat-transfer coefficient is not too small. Figure 6-5 shows the benefit of bringing the wall temperature closer to the fluid temperature, usually done by insulating the pipe. Figure 6-6 shows the interplay between fluid and well emissivities, in particular, the detrimental effect of immersing a high-emissivity thermowell in a low- or even moderate-emissivity process.

As an example, steam flows at a rate of 5.1 lbm/ft^2-s. To simplify the calculation it is assumed that the steam flows in an uninsulated pipe whose walls are held at 300°F (148.89°C). The steam has properties as follows: velocity = 67.5 ft/s, density = 0.0256 lbm/ft^3, specific heat = 0.4764 Btu/lbm-R, viscosity = 0.0000128 lbm/ft-s, emissivity = 0.35. The well immersion length = 8 in. (203.20 mm), root diameter = 1.5 in. (38.10 mm), tip diameter = 0.875 in. (22.225 mm), bore diameter = 0.26 in. (6.604 mm), k = 15 Btu/h-ft-R, and ϵ_{well} = 0.97. If the temperature at the well tip is 606.7°F (319.28°C), what is the fluid temperature? **T_{adi} = 651.1°F (343.94°C).**

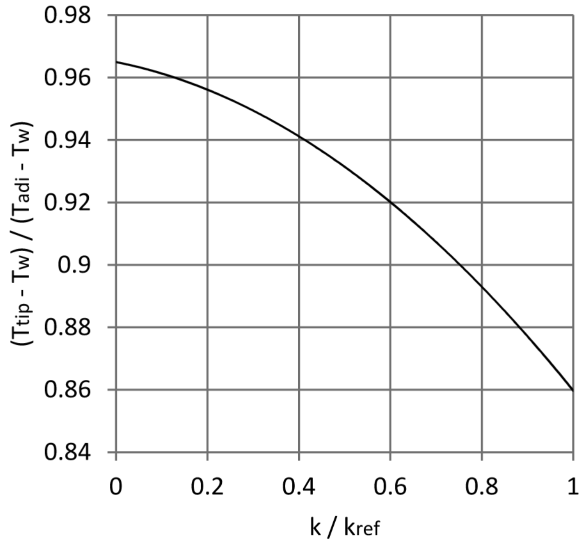

Figure 6-3
Effect of thermowell conductivity on conduction error (Choosing a thermowell material with low k limits heat flow toward the root and consequently the conduction error.)

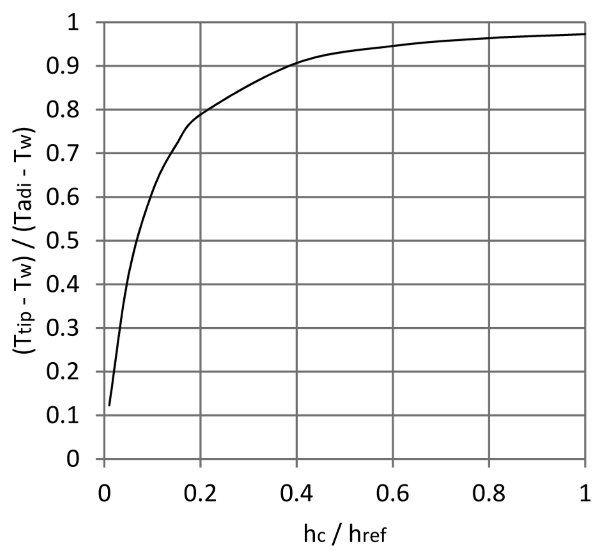

Figure 6-4
Effect of the film heat coefficient on conduction error (Choosing a thermowell material with a large hc puts the sensing element in close thermal contact with the fluid, boosting measurement accuracy.)

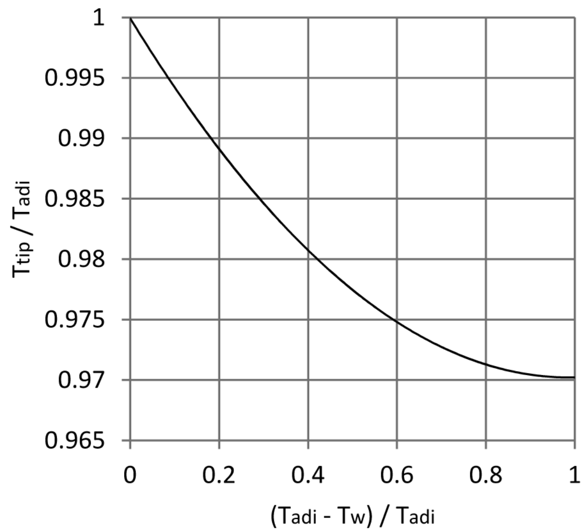

Figure 6-5
Effect of wall temperature on conduction error (Insulating the pipe wall near the thermowell is an effective means of decreasing conduction error.)

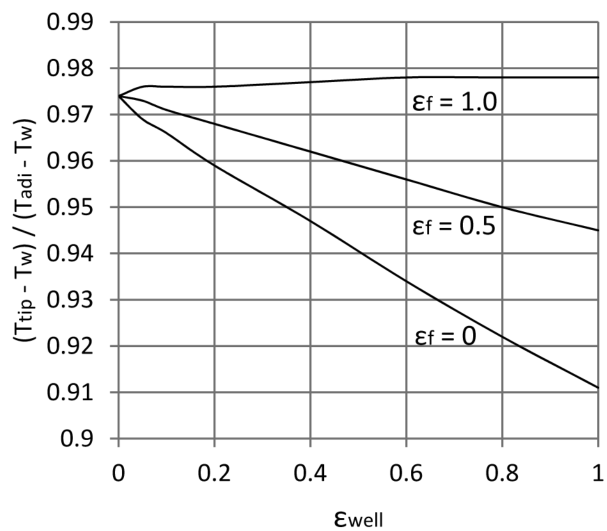

Figure 6-6
Effect of fluid emissivity on conduction error (High-emissivity thermowells can be used in high-emissivity fluids such as water without appreciable loss of measurement fidelity.)

Therefore, for this installation, the measured value of the fluid temperature is off by 44.4°F (6.89°C). In practice, such an installation would rarely (if ever) be left uninsulated. Now, assume fluid temperature to ±5°F (±2.78°C) is required. Table 6-2 shows how changing various characteristics of the thermowell installation would impact the relative accuracy of the temperature measurement.

Table 6-2
Changes to thermowell installation capable of improving sensor measurement accuracy

	Initial Value	New Value	Error °F (°C)	Comment
Thermowell diameter	1.5 in. (38.10 mm)	0.875 in. (22.23 mm)	39.6 (22)	Smaller root diameters correspond to larger values of hc.
Thermowell emissivity	0.97	0.57	30.8 (17)	When Єfluid is low, a low-emissivity well material should always be chosen.
Thermowell conductivity	15 Btu/h-ft-R	10 Btu/h-ft-R	42.0 (23.3)	For kwell < ~20, changes to kwell have only a small effect on conduction error.
Pipe-wall temperature	300°F (148.89°C)	625°F (329.44°C)	4.9 (2.7)	Insulating the pipe with 1 in. (25.4 mm) of magnesia is an effective way to increase the wall temperature and obtain an accurate temperature measurement.

Response Time

Response time is adversely impacted by adding mass to the material surrounding the sensing element, which delays the time period within which the sensor will reach thermal equilibrium with the process into which it is installed.

As with conduction error, the changes that improve measurement response times tend to encroach on well safety. The smaller the thermowell diameter and the greater the velocity of the process media, the more rapidly the installed sensor will reach thermal equilibrium with the process fluid. This section discusses the factors that influence measurement response in the context of first- and second-order response time and one- and two-dimensional time constant calculations.

First-order response. For a one-dimensional temperature sensor in an environment of which the temperature is evolving in time, the heat transfer rate of the system can be expressed in terms of Newton's law of cooling and Black's heat capacity equation, as follows:

$$hA \cdot (T_e - T) = Mc \cdot {dT}/{dt} \qquad \textbf{Eq. 6-7}$$

where h is the film coefficient, A is the sensor surface area, Te is the environment temperature at time t, T is the sensor temperature at time t, M is the sensor mass, and c is the sensor heat capacity. Equation 6-7 assumes that heat transfer to the sensor occurs by convection only, that the thermal resistance of the system resides exclusively in the convective heat transfer film around the sensor, and that the thermal capacity of the system resides exclusively in the sensor itself.

Equation 6-7 can be rearranged as $\frac{dt}{\rho Vc/hA} = \frac{dT}{T_e - T}$ (Equation 6-8), where the M in Equation 6-7 has been replaced by $\rho \cdot V$. The denominator of the left-hand side is defined hereafter as the ideal time constant, as follows:

$$\boldsymbol{\tau = \rho Vc/hA} \qquad \text{Eq. 6-8}$$

pursuant to the insight that τ is the thermal capacitance of the sensor (ρVc) multiplied by the thermal resistance of the film ($1/hA$), in direct analogy to the time constant of an electric circuit. Similarly, more realistic estimates of response time can be obtained by mapping the well-sensor system to more complex electric circuits; see the section on second-order response.

Solving Equation 6-8 for $Te - T$ yields an equation for the sensor temperature T at time t, as follows:

$$\boldsymbol{T_e - T = (T_e - T_1) \cdot e^{-t/\tau}} \qquad \text{Eq. 6-9}$$

where boundary conditions that correspond to a step change in the environmental temperature were assumed.

Plugging $t = \tau$ into Equation 6-9 gives a working definition for τ, as follows:

$$\boldsymbol{T_e - T = {}^{1}/_{e} \cdot (T_e - T_1)} \qquad \text{Eq. 6-10}$$

with τ simply the time at which 63.2% of the initial temperature difference $(T_e - T_1)$ has been eliminated.

Second-order response. The second-order response considers separately the convective heat-transfer film, the thermowell, the temperature sensor, and the air gap between the thermowell and temperature sensor, where the first-order response considered the first two factors only. The second-order response can be quantified by appeal to the following equivalence(see Figures 6-7 and 6-8).

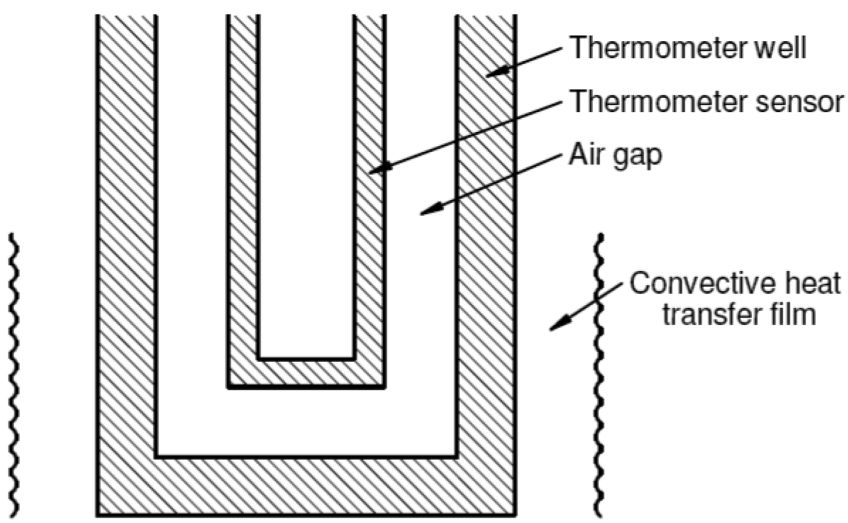

Figure 6-7
Simplification of sensor-thermowell installation used to inform the response time

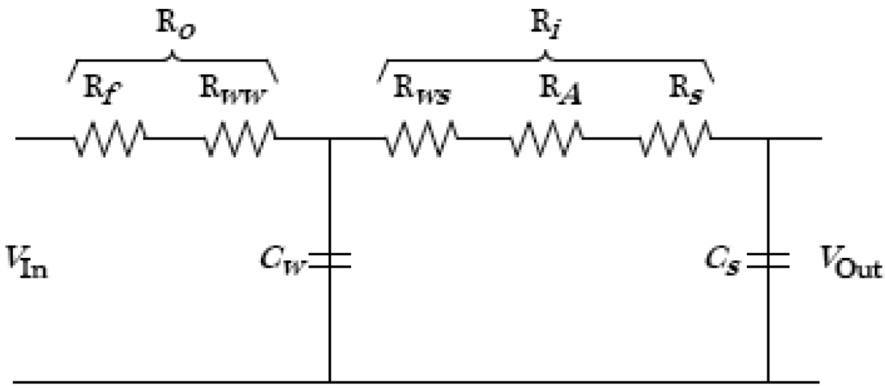

Figure 6-8
Second-order response

Specifically, an equation of the form of Equation 6-11 can be derived for the sensor temperature T at a time t after a step change in temperature ΔT, as follows:

$$T = \Delta T \cdot [1 - (\frac{r_1}{r_1 - r_2}) \cdot e^{-r_2 t} + -(\frac{r_2}{r_1 - r_2}) \cdot e^{-r_1 t}] \quad \textbf{Eq. 6-11}$$

where r_1 and r_2 are reciprocals of the time constants τ_1 and τ_2. In most cases $r_1 \gg r_2$, and a single τ equal to τ_2, compassing the 63.2% definition of the time constant, suffices to describe the system [11].

The time constant. The ideal time constant given by Equation 6-8 should be used in certain circumstances only. In particular, it should be avoided in the following, where the Biot number:

$$Bi = {hD_o}/{2k} \quad \textbf{Eq. 6-12}$$

(physically, the ratio of the film resistance to the well resistance) is greater than 0.2, because in such cases the ideal approximation yields values for the time constant that are much too low. In these cases, replacing the film coefficient *h* in the ideal time constant with an effective film coefficient *heff* improves the accuracy of the time constant substantially because *heff* accounts for the well resistance in addition to the film resistance at the cost of only a small amount of additional information about the well. Explicitly, as follows:

$$h_{eff} = \frac{1}{(1/h) + R_w \cdot A_w} \quad \textbf{Eq. 6-13}$$

where R_w is the well thermal resistance, A_w is the well surface area, and $R_w \cdot A_w = \frac{\ln (D_o/D_i) \cdot D_o}{2k}$ (20).

Alternatively, a two-dimensional approximation of the time constant, accounting for heat transfer in the radial *and* axial directions, provides a similar but more pronounced benefit; it may be obtained at low informational cost through the Biot and Fourier numbers, *Bi* and *Fo*. Expressions for *Fo* at the 63.2% response (that is, for $t = \tau$) are shown in Equation 6-14 and Equation 6-15. Equation 6-16 defines *Fo* in terms of *t*. $\tau_{two-dim}$ falls directly from Equations 6-14 through 6-16.

$$\log Fo = -.124 - .63(\log Bi) + .231(\log Bi)^2 \text{ for } 0.1 \le Bi \le 4.0 \quad \textbf{Eq. 6-14}$$

$$Fo = \frac{0.5}{Bi} \text{ for } 0.001 \leq Bi < 0.1 \qquad \textbf{Eq. 6-15}$$

$$Fo = \frac{2\alpha t}{d_o^2} = \frac{2kt}{\rho c d_o^2} \qquad \textbf{Eq. 6-16}$$

In general, $\tau_{ideal} \leq \tau_{two-dim} \leq \tau_{one-dim}$, such that the spread of the three values increases roughly with the Biot number. The ideal time constant is the shortest because it fails to account for well resistance, and the one-dimensional time constant is the longest because it accounts for well resistance but not axial conduction; the two-dimensional time constant is the most accurate because it is also the most realistic, accounting for well resistance and axial conduction.

As an example, neglecting higher-order effects, the response time is determined by the variables in the ideal time constant. Higher values of h and A, and lower values of ρ, V, and c, correspond to shorter response times.

A well immersion length = 6 in. (152.40 mm), outer diameter = 1.5 in. (38.10 mm), bore diameter = 0.26 in. (6.60 mm), thermal conductivity = 19.2 Btu/h-ft-R, density = 502 lbm/ft^3, and specific heat = 0.135 Btu/lbm-R. The thermal conductance of the film is 1200 Btu/h-ft^2-R. At time t = 0, the well is immersed in a process fluid held at 279.2°F (137.3°C). The well's temperature was 100°F (37.78°C) just before immersion. Give values for the ideal, one-dimensional, and two-dimensional time constants, and for the time at which 99% of the initial temperature difference will have been erased.

> 6.16 s, 48.35 s, 19.05 s (The ideal time constant is invalid because Bi = 3.91.)
>
> t_{99} = 87.73 s

Now, assume $\tau_{two-dim}$ ≤10s is required. Table 6-3 shows several changes that could be made to the installation in an effort to meet this requirement.

Table 6-3
Impact of thermowell installation modifications and the relative impact on the response time

	Initial Value	**New Value**	$\tau_{two-dim}$	t_{99}
Well density	502 lbm/ft^3	400 lbm/ft^3	15.18	69.9
Specific heat of well	0.135 Btu/lbm-R	0.100 Btu/lbm-R	14.11	65.0
Thermal conductance of film	1200 Btu/h-ft^2-R	1600 Btu/h-ft^2-R	17.34	79.8
Outer diameter	1.5 in. (38.10 mm)	1 in. (25.4 mm)	9.33	43.0

Other considerations. Several factors not addressed can impact the time constant significantly, including the Mach number, the size of the temperature change, radiation, axial conduction, turbulence, and installation details.

Mach numbers below 0.4 have no appreciable effect on the time constant, and the effect of larger Mach numbers can be minimized by designing a well specific to the temperature and pressure of the fluid.

Axial conduction from the measuring junction to the support probe along bare thermocouple wires can increase the time constant. Equation 6-17 gives an estimate of the effect:

$$\tau_{k,c} = \tau_c\left(1 + \frac{\pi^2 \tau_c \alpha}{4L^2}\right) \qquad \textbf{Eq. 6-17}$$

where τ_c, which contemplates convection alone, refers to any of the previous three time constants, α refers to the thermal diffusivity of the wires, and L to the distance from the measuring junction to the support probe. An equation similar to Equation 6-17, accounting for radiation effects, may be useful in cases where the support probe is held at a constant temperature [12].

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7

THERMOWELL INSTALLATION RECOMMENDATIONS

The power generation industry has standardized on typical practices for thermowell installation methods, including placement, accessories, as well as attachment configurations.

General Installation Practices

Thermowells are located in accordance with the equipment design requirements associated with where specific temperature measurements are required. This stems primarily from the need to have measurement points upstream or downstream of heat exchanger equipment, steam desuperheaters, boilers, or other equipment where temperature needs to be monitored. High performance equipment such as a desuperheater typically requires the temperature measurement to be a specific distance downstream from the spray nozzle, typically upward of 30 pipe diameters or 3 seconds of media travel time. This ensures proper mixing of the flowing fluid and the spray media before a temperature measurement. The specific placement requirements are usually dictated by the desuperheater manufacturer to assure optimal performance of its equipment.

For critical equipment, redundant thermowells are often installed to prevent a single-sensor failure from causing a shutdown. Where redundant thermowells are used, they are generally placed at least 12 in. (304.80 mm) apart (or 1 pipe diameter, whichever is larger). Where this is not possible, they can be offset by 45 degrees around the circumference of the piping. This prevents one thermowell from blocking the other and causing a shadowing effect that could affect the downstream well.

Thermowells are arranged typically in order of importance, with those used for control or continuous remote monitoring purposes being furthest upstream, followed by thermowells used for local gauges and then thermowells used for testing.

Thermowells are furnished either with lagging extensions or extension nipples and unions. The selection is generally left to the designer. Both can extend the electrical connection out past the end of the thermowell and allow for the head and terminal block to be located sufficiently away from the piping, insulation, and lagging. Lagging extensions consist of added length to the thermowell itself and can be helpful for gauges or for welded thermowells, where additional length is required for thick-walled piping. Extension nipples are typically less expensive and more convenient. They can be furnished with piping unions to allow removal of the head and terminal block without the danger of unthreading the thermowell itself while a process is on-line. Unions also enable the removal of a sensor from a thermowell without having to rotate an attached enclosure. This can be especially useful when the enclosure is physically attached to the sensor on one end and to a conduit on the other. Nipples and unions also have less direct contact with the thermowell itself, and therefore reduce thermal conduction errors (heat flow away from the sensor) when compared with lagging extensions. In either case, when the piping is insulated, it is important that the well itself be covered with insulation. This also helps reduce conduction errors.

Thermowell bores are selected by the designer and typically come in a standard size of either 0.25 in. (6.35 mm) or 0.375 in. (9.525 mm). The typical practice in power generation is to use 0.25-in. (6.35-mm) bores for RTDs and thermocouples, and 0.375-in. (9.525-mm) bores for test thermowells and gauges. The 0.375-in. (9.525-mm) bores are used for test wells because they are easier to clean. Test thermowells are also often specified with a plug and chain so that the thermowell bore remains clean while it is out of use.

Thermowell tip thicknesses are generally standardized at either 0.1875 in. (4.7625 mm) or more commonly, 0.25 in. (6.35 mm). The tip thickness is the primary governing factor for a thermowell's ability to withstand pressure and is specifically evaluated by PTC 19.3 TW. It should be noted that 0.25 in. (6.35 mm) is suitable for nearly all power generation process operating and design conditions.

Thermowell Attachment Methods

Power generation services generally use the most traditional types of thermowell attachment methods. In general order of preference, those methods include the following:

- **Threaded connections**. Uses tapered pipe threads and threaded o-lets or pipe couplings welded on the surface of the piping.
- **Flanged connections**. Uses flat-faced or raised-face configurations attached to flanged nozzles on the piping.
- **Welded connections**. Uses full-penetration welds into the pipe wall.
- **Socket-weld connections**. Uses socket-welded o-lets on the surface of the piping.

Other attachment methods are available, such as Van Stone or sanitary service. However, these are not typically used for power generation services. Also available are installations where thermowells are threaded directly into the pipe wall with no boss or coupling. This practice is generally avoided due to the same issues that typically occur with RT plugs. Failures from this practice have been reported in the industry.

Selection of a particular installation method is based on the piping configuration/construction and the most economical method for the installer.

Threaded Installations

Threaded installations are most common and a low potential for installation problems. They can be used for low- and high-temperature applications and allow for relatively easy removal and replacement of the thermowell if required. They are used for steam, water, or chemical service in line sizes up to around 20 in. (508 mm) or 24 in. (609.6 mm). Thermowell connection sizes range from 0.5 in. (12.7 mm) NPT, 0.75 in. (19.05 mm) NPT, 1 in. (25.4 mm) NPT, and 1.5 in. (38.10 mm) NPT, depending on the designer or owner's preference. Note that thermowells use a general purpose tapered pipe thread (unlike RT plugs). Consequently, the tapered thread constitutes both a pressure boundary and overall seal. The tapered thread requires a sealant to completely eliminate leaks and prevent thread galling during removal. The thermowell material is usually 316 stainless steel, either forged or bar stock. The wells are typically installed in the field, after the piping has been erected. Figure 7-1 shows a common threaded thermowell installation.

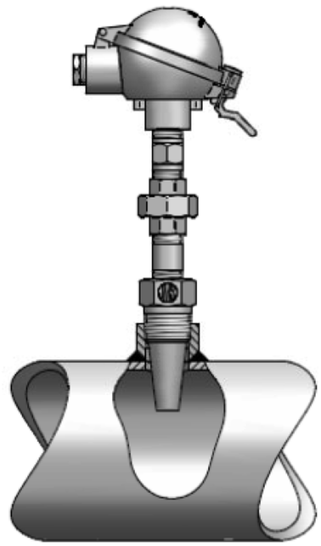

Figure 7-1
Threaded thermocouple assembly in piping of 2.5 in. (63.50 mm) and larger in vessels

For process connection sizes, the best practice is to standardize on a series of configurations to minimize size combinations. This reduces the chances of a thermowell being installed in the wrong location. For low-temperature services (typically below 450°F [232.22°C]), the threaded joint uses pipe dope or Teflon tape as a sealant and thread lubricant. At intermediate temperatures (below 925 ft [281.94 m]), high-temperature, graphite-based sealants or tapes are used to seal the threads.

At and above 925°F (496.11°C) (or for pressures at or above 1500 psi [10,443.46 kPa]), seal welding is required by ASME B31.1. Thermowells are subject to vibration-related forces as discussed earlier. The threaded joint is not generally designed to remain fully engaged under flow-induced vibration. Consequently, the threads can back out over time, eventually resulting in leakage paths. The seal weld is specifically required to prevent the threads from backing out and causing leakage. The seal weld is not a pressure retaining weld. It instead just provides restraint to the pressure boundary provided by the threaded joint. The seal weld on a thermowell is typically smaller than that used for an RT plug. Most commonly, high pressure/temperature piping for power generation services use alloy piping such as F22 or F91 chrome/molybdenum steel. Because seal welding is required in these applications, the thermowell must be constructed from a compatible forged material. This ensures that the thermal expansion coefficients between the materials match and that no dissimilar metal welding procedures are required.

Generally, in main steam and hot reheat lines, welded connections are recommended. Oxidation in the threaded joints of threaded thermowells has been shown to reduce the thread engagement and therefore the thermowell retainment. This damage will eventually lead to failure of the seal weld.

Where seal welding is required, typically no tape or pipe thread compound is applied. This is due to the likelihood that the thread compound will vaporize and cause inclusions or voids within the seal weld. These weld irregularities would lead to cracks and eventual failure of the joint.

The threaded thermowell uses a boss or o-let welded on to the surface of the piping. This works well for piping 2 in. (50.80 mm) and larger. Historically, thermowells were sometimes threaded directly in the piping. This proved problematic, particularly for high-temperature applications where creep mechanisms caused distortion of the threads and ultimate failure (as described in Section 5 of this report). Threading of thermowells directly into piping is not recommended.

For smaller piping (less than 2 in. [50.80 mm] nominal), thermowells can be installed in oversized piping tees or elbows. Tees can be used where the well is installed either perpendicular to the piping or parallel to the piping, where the tee is used as an elbow. Figure 7-2 shows an illustration of this arrangement.

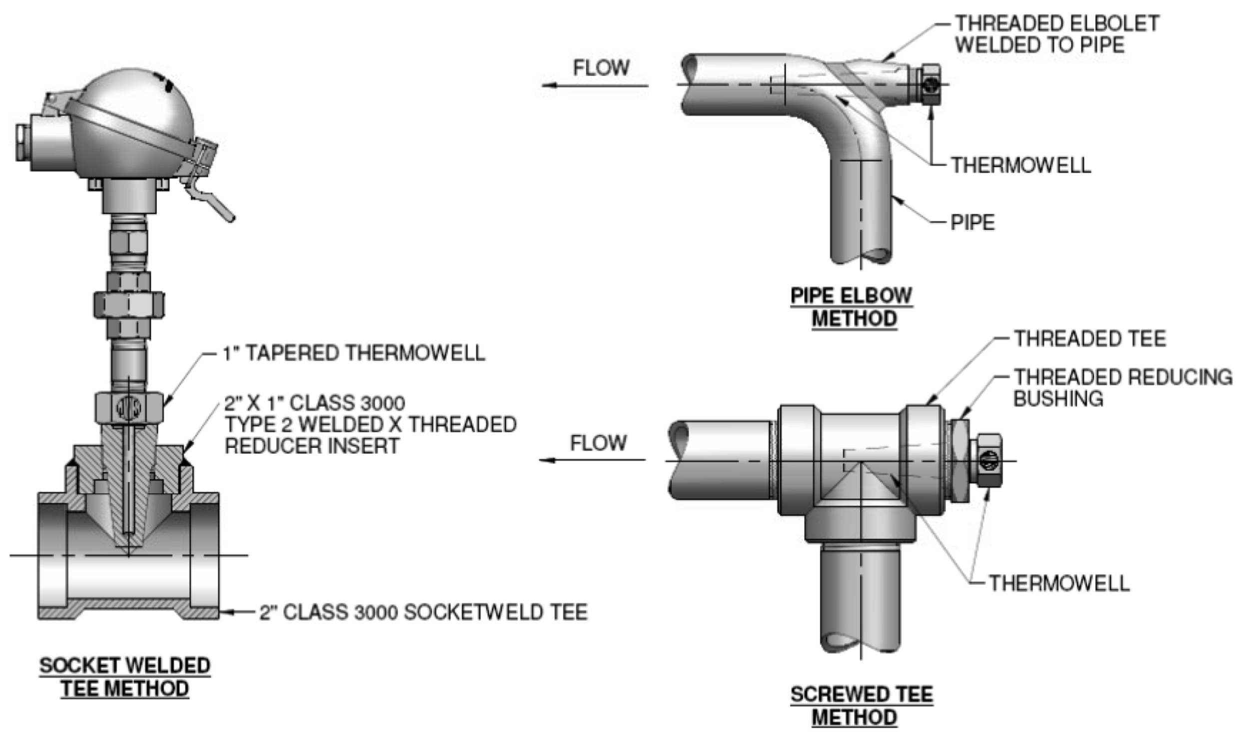

Figure 7-2
Threaded thermocouple assemblies in piping of 2 in. (50.80 mm) and smaller

Installation of a threaded well requires a minimum number of engaged threads to maintain a pressure tight joint, as indicated in Table 7-1.

Table 7-1
Thread engagement requirements and characteristics

NPT	Minimum Threads[a]	No. of Threads for Hand-Tight Engagement [b]	Total No. Effective Threads	Threads[c]
0.5 in. (12.7 mm)	6	4.48	7.47	14 in. (355.6 mm)
0.75 in. (19 mm)	6	4.75	7.63	14 in. (355.6 mm)
1 in. (25.4 mm)	7	4.6	7.85	11.5 in. (292 mm)
1.25 in. (31.75 mm)	7	4.83	8.12	11.5 in. (292 mm)
1.5 in. (38.1 mm)	7	4.83	8.32	11.5 in. (292 mm)
2 in. (50.8 mm)	8	5.01	8.69	11.5 in. (292 mm)

Notes:

(a) Minimum threads of engagement per ASME B31.1, Section 104.3, paragraph B.4.2.2.

(b) Number of threads to reach hand-tight per ASME B1.20.1.

(c) Crane per *Machinery Handbook* (25th ed.).

For threaded wells, the area within the pipe wall is not exposed to process flow. Consequently, the well must extend sufficiently into the piping to clear the pipe wall and any fitting. This can add 1 in. (25.4 mm) to 1.5 in. (38.10 mm) for light-duty service (thin-walled pipes), and upward of 3 in. (76.2 mm) to 4 in. (101.6 mm) for severe service applications. For steam lines to turbines, the extra length typically results in a well that will not survive the vibration forces during high-velocity, steam cleanout operations associated with installation and commissioning. These forces are often two or three times normal operation and can result in quick failure of the thermowell. Consequently, for new plant service (or new piping installations), threaded wells on steam turbine supply lines must typically be removed before steam cleanout/steam blow.

Table 7-2
Typical threaded thermowell applications for coal-fired units

Service	Typical Line Size	Well Connection Size	Well Major Diameter	Well Minor Diameter
Closed cooling water	16 in. (main cooling water header)	0.75 in. or 1 in. NPT	0.875 in. or 1.0625 in.	0.625 in.
Condensate	18 in.	1 in. NPT	1.0625 in.	0.625 in.
Feedwater	20 in.	1.5 in. NPT with seal weld	1.625 in.	1 in.
Steam line drip legs	8 in.	1.5 in. NPT with seal weld	1.625 in.	1 in.

1 in. = 25.4 mm

Flanged Installations

Flanged thermowells are also common but typically used for larger line sizes exceeding 24 in. (609.60 mm). Flanged thermowells are also used for tanks where flanged nozzles are common. The larger line sizes associated with flanged connections are usually for high-flow water lines such as circulating water, open-cycle cooling water, or river makeup water. Quite often, these lines are not steel but instead fiber-reinforced polymer, chlorinated polyvinyl chloride, lined polyvinyl chloride, concrete, or other nonmetallic material. The smaller-threaded process connections are not easily compatible with the pipe fittings. The flange connection is also much more durable and robust than a similar threaded connection. It will withstand the wear/tear associated with shipping, handling, and installing large pipe spools. Smaller-threaded connections (couplings or o-lets) are more susceptible to damage during handling and installation of the pipe.

Flange sizes are normally 1.5 in. (38.1 mm) or 2 in. (50.8 mm), with 2 in. (50.8 mm) being the most common. The wells are installed in the field, after the piping has been erected. Figure 7-3 shows a typical flanged thermowell installation.

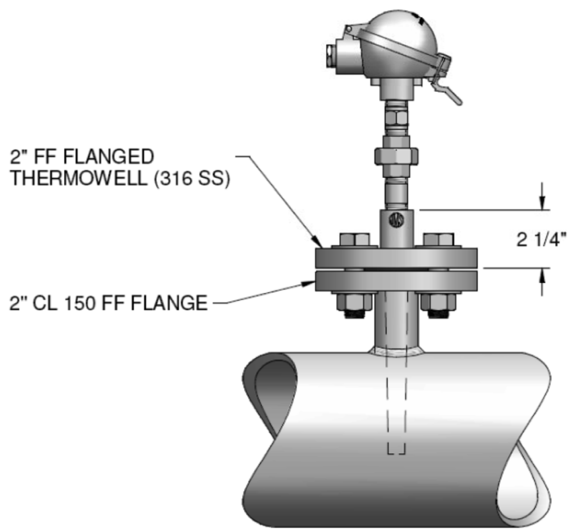

Figure 7-3
Thermocouple assembly in piping of 3.5 in. (88.9 mm) and larger in vessels

Flanged thermowells can be either flat-faced or raised-face, based on what is provided on the connection to the piping or equipment. Flat-faced flanges are used for concrete or nonmetallic materials to prevent snapping off the mating flange during installation.

Flanged thermowells for power generation service are usually in relatively low-pressure and low-temperature environments. Consequently, 316 stainless steel is most common for well construction. It provides good corrosion resistance and strength. The flanged thermowell is a weldment consisting of a standard off-the-shelf blind flange with a hole and a machined thermowell welded in place. The attachment weld can be either a partial- or full-penetration weld, with full-penetration welds preferred to provide additional strength.

With a flanged connection, no welding, thread compound, or other considerations are required for the thermowell attachment. Gaskets are required that are similar to those used for other flanged joints in the piping system.

When compared to the other services, the well-length insertion is longer for flanged applications than for other installation methods (even for similarly sized pipe). This is due to the offset from the nozzle to the pipe wall and can often add 4 in. (101.6 mm) to 7 in. (177.8 mm) of additional length.

For longer applications, some care is required to ensure that the well will be strong enough to withstand the forces and vibration from flowing fluid. There have been many recent failures of flanged thermowells in circulating water service due to high-fluid velocities. Flow just downstream of elbows can have upward of twice the velocity of the average line velocity. So a good practice is to ensure that thermowells are 3 diameters or more downstream of elbows/bends.

Table 7-3
Typical flanged thermowell applications for coal- or combined-cycle units

Service	Typical Line Size	Well Connection Size	Well Major Diameter	Well Minor Diameter
Circulating water	78 in. (1981.2 mm)	2 in. (50.8 mm) FF Flanged	1.75 in. (44.5 mm)	1.125 in. (28.6 mm)
Demineralized water storage tank	—	2 in. (50.8 mm) RF Flanged	1.75 in. (44.5 mm)	1.125 in. (28. 6 mm)

Welded Installations

Welded installations consist of two styles: socket welded and full-penetration welded. In both cases, no mechanical joint is used. The pressure-retaining and pressure-sealing duty of the joint is through the welded connection.

Socket-Welded Applications

Socket-welded installations are similar to threaded installations. However, instead of a tapered thread, the well is attached with a socket-welded boss or coupling. Figure 7-4 shows typical socket-welded thermowell installations. A simple fillet weld is made between the well and the boss/coupling to provide full strength and sealing. The well installation is robust but not easily removed or replaced. Socket-welded wells can be used on a variety of applications for both water and steam. However, they are predominantly used for steam applications on shop-fabricated piping sections associated with boilers. They are convenient when the piping system itself is welded and when there are other concurrent welding operations included in the pipe fabrication process. Process connection sizes for welded thermowells are quite similar to threaded installations. Stainless steel can be used for socket-welded thermowells. However, because most of the piping is carbon or alloy steel, matched material wells are more often used to avoid differential stresses and dissimilar metal-welding procedures. Following the weld process, nondestructive examination is required. For services over 750°F (398.89°C), dye penetrant or magnetic particle tests are required by ASME B31.1, Section 136.4. For services at or under 750°F (398.89°C), visual examination is required.

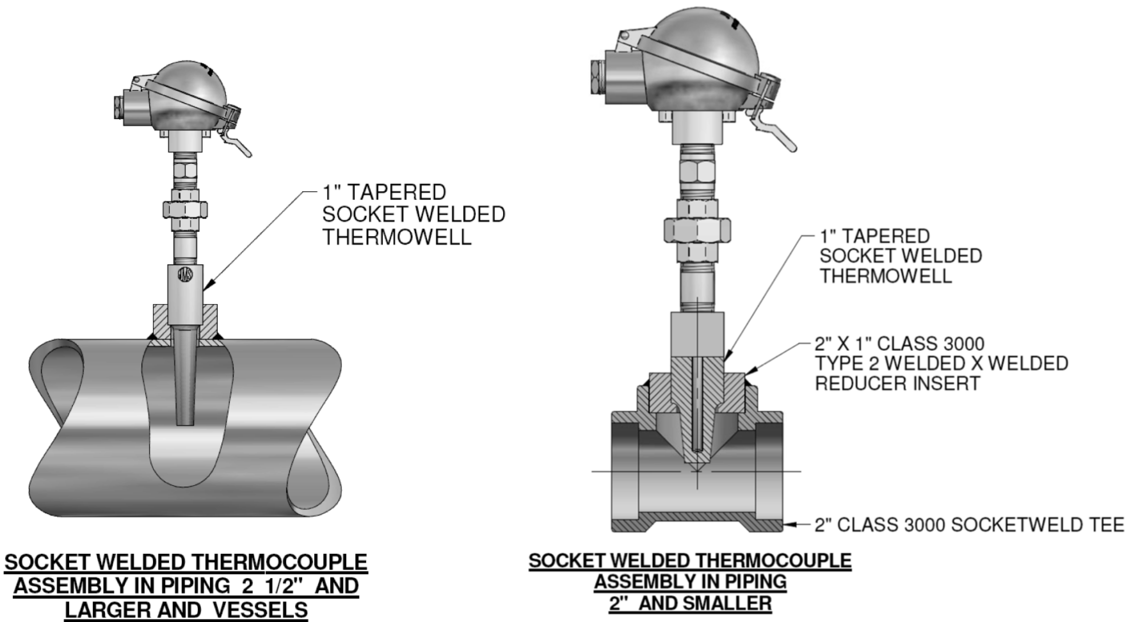

Figure 7-4
Socket-welded thermocouple assembly

For steam line cleanout on new power plant services, the socket-weld thermowell cannot be removed and therefore must be designed to withstand the vibration forces associated with the high-steam velocities. This can limit the insertion depth when compared to a full-penetration weld design.

Full-Penetration Welded Applications

Full-penetration weld thermowells consist of thermowells welded directly into process piping. For power generation applications, they are used almost exclusively for steam lines. Figure 7-5 shows a typical full-penetration weld application. The weld extends through the complete thickness of the pipe wall. This means that the firm support of the well starts at the inside wall of the pipe, allowing a maximum length of the well to be exposed to the process fluid. Full-pen welded wells are suitable for steam blow/steam cleanout applications. To match thermal expansion and avoid dissimilar metal-weld procedures, the thermowells are constructed from materials equivalent to the piping, typically forgings such as F91 or F22.

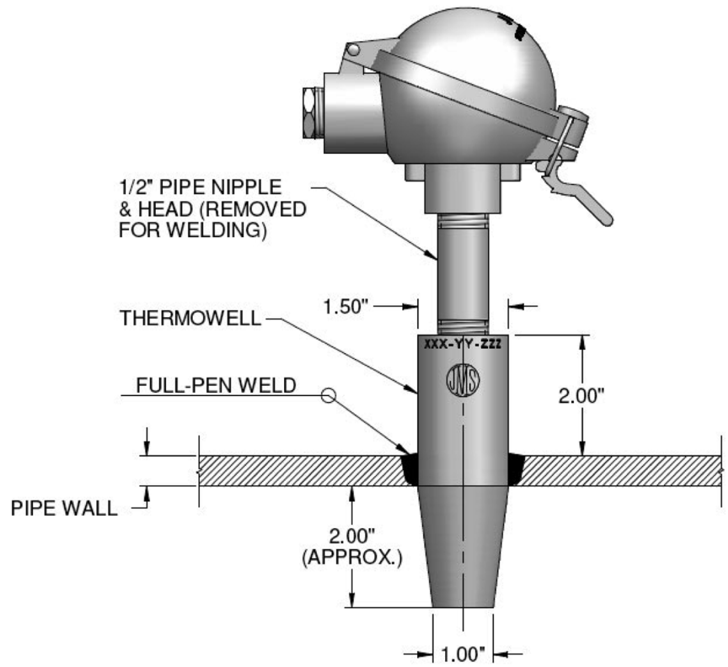

Figure 7-5
Welded thermowell assemblies

The full-penetration welded thermowells are installed at a pipe fabrication shop, where the welding procedures can be tightly monitored and controlled. The weld can be costly. However, the cost is offset by the design's ability to remain in the line during steam cleanout.

For a 1.5-in. (38.10-mm) welded thermowell on a main steam service, the penetration in the piping can be upward of 10 in. (254 mm) in diameter. Care must be taken during assembly to ensure that the well insertion is correct before making final weld passes.

The welding is typically accomplished using a gas-tungsten, arc-welding process. Because it is usually on alloy piping, preheating and post-heating are typically required to ensure proper weld-stress relieving. Nondestructive examination will also be required following the weld to inspect for surface or internal defects. Typically, magnetic particle or dye penetrant tests are required for services at or above 350°F (176.67°C) per ASME B31.1, Section 136.4. For services at or under 350°F (176.67°C), visual examination is required.

Table 7-4
Typical welded installations for power plants

Service	Typical Line Size	Well Connection Size	Well Major Diameter	Well Minor Diameter
Main steam	20 in. (508 mm)	1.5 in. (38.1 mm) welded	1.5 in. (38.1 mm)	1 in. (25.4 mm)
Hot reheat steam	30 in. (762 mm)	1.5 in. (38.1 mm) welded	1.5 in. (38.1 mm)	1 in. (25.4 mm)

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8
RT PLUG DESIGN AND INSTALLATION GUIDE

RT Plug Installation Error and Material Selection

RT is frequently performed on large-bore, high-energy piping to inspect for internal volumetric defects in welds. The operation involves the insertion of an X-ray point source (J-tube) through a small penetration in the pipe wall with fittings using machined threads. As soon as the testing is completed and the source removed, the penetration in the pipe is closed off using a threaded solid metallic plug. The plug is screwed into the pipe and then seal-welded. The threads comprise the pressure-retaining portion of the joint, not the seal weld.

RT plugs are similar to thermowells in that both are attached and inserted into the piping system wall without branch piping. Both often use a threaded connection. Both can be inserted and/or threaded into the pipe wall without integrally reinforced branch fittings (coupling or o-lets). Both can use threads because the mechanical piping joint with a seal weld to close off any leakage paths. Thermowells differ from RT plugs in that they extend into the piping flow stream and are subject to velocity-induced vibration stresses. More commonly in modern construction, thermowells are not threaded directly into piping. Instead they are threaded into integrally reinforced branch fittings that are welded onto the pipe-wall surface. Seal welding, when necessary, is performed between the thermowell and the branch fitting.

Historical/Past Practices

RT plugs have a variety of configurations and attachment variations. Historically, the plugs have been simply pieces of steel bar with machine threads. The machined threads are required due to the RT source attachment fittings. Tapered pipe threads are not common because they are not typically compatible with the test equipment. After the plug is screwed in, it is seal welded to eliminate any leakage path and to assure that the threads stay tight and engaged to maintain a pressure boundary. The threads are the pressure-retaining component, not the seal weld. Modern plug designs and installation practices are typically based on the requirements of the PFI Standard ES-16 for access holes, bosses, and plugs for radiographic inspection of pipe welds.

The RT plug includes a straight nonthreaded portion that extends through the pipe wall to the ID. The upper portion protrudes outside of the pipe and serves as a point for a wrench as well as a surface to seal weld against. Plug sizes range from 1 in. (25.4 mm) to 2 in (50.8 mm). The plugs are either attached directly into the pipe OD or on occasion attached to cover plates welded over pipe openings.

In the past, plug materials were sometimes forged or bar stainless steel to inhibit corrosion and provide high-temperature strength. In other cases, the plug material might match the pipe material.

Rather than a machined cylinder, the plug configuration also could use a cap or U arrangement with the U portion either away from the piping or toward the piping (see Figure 8-1).

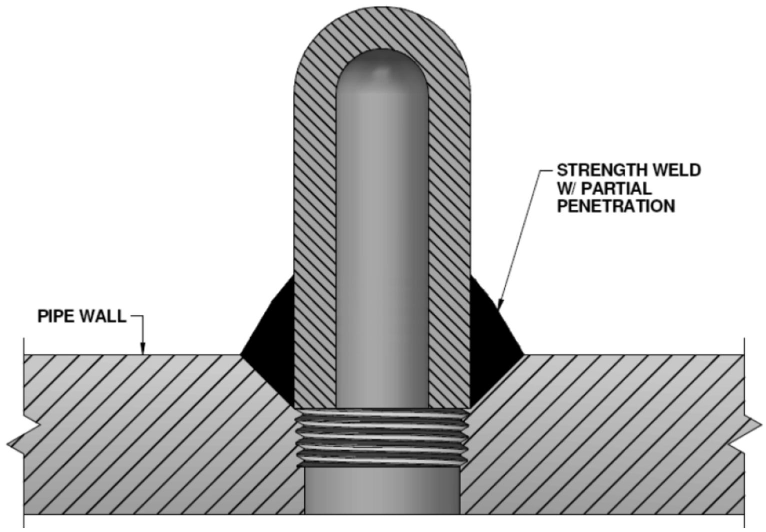

Figure 8-1
Cap-style RT plug

Case Histories

There are numerous case histories of failed RT plugs that have been documented over the years at both fossil and nuclear power facilities. Although there are many reported failures, the failures manifest as steam or water leaks discovered during plant operation. There are few, if any, cases of blowouts where plugs are ejected from the piping.

A typical RT plug failure report would be where a roving operator notices water dripping from insulation/lagging on a steam or high-energy feedwater line. A subsequent inspection reveals a crack around an RT plug seal weld. The area is cordoned off, and the leak is repaired at the next convenient outage. As soon as the plant is off-line, further inspections reveal additional damage/cracking at other RT-plug locations. Some typical cases are listed in Table 8-1.

Table 8-1
Typical RT-plug failures

Type of Plant, Year of Event	Failure Description
Muskogee, unit 3, gas-fired, 1984	Leakage occurring on main steam line from insulation. Investigation revealed cracked seal weld around test plug. Additional cracked seal welds discovered later.
Shawville, unit 2, coal-unit, 1989	During planned inspection, seal-weld cracks found on numerous RT plugs on main steam piping. 23 included cracks 360 around the perimeter of the plug.
Big Cajun, units 1 and 2, coal-unit, 1993	Cracks on RT-plug seal welds discovered in the radiant superheater cross-over piping during a condition assessment inspection.
Mihama Power Station, unit 3 nuclear unit, early 2000s	Cracks around RT-plug seal weld on feedwater line during plant operation.
Entergy nuclear unit, 2009	Cracks around RT-plug seal weld on feedwater line during plant operation.

Figure 8-2
Typical RT-plug weld failures

The leaks/cracks are most commonly associated with a phenomenon known as *creep swelling*, where the pipe deforms radially as it is exposed to high pressures and temperatures. The swelling leads to deformation of the threads and ultimately disengagement of the threads so that the seal weld becomes a pressure-retaining weld. The seal welds are not inherently designed for pressure-retaining capability and ultimately begin to crack.

The typical failures include a few contributing factors such as where the plug material is not compatible with the pipe material; where the attachment threads are insufficient; or, in some cases, where erosion mechanisms wear away the plug.

The most common error has typically been where stainless steel plugs were installed in carbon or alloy steel piping. The stainless steel has a higher rate of thermal expansion than the piping, which results in stress that can fatigue the threads and damage the seal weld. This is typically solved by replacing stainless-steel plugs with plugs fabricated from similar material matching the pipe. For example, in the case of P91 alloy pipe, the plugs would need to be fabricated using F91 alloy.

Contributing factors also include insufficiently sized seal welds. As described earlier, the creep-swelling phenomena can lead to failure of the threads and result in the seal weld becoming a pressure/strength weld. This issue is typically solved by grinding off the seal weld and replacing it with a larger strength weld.

Another mode of failure results from the actual plug hole not being drilled completely perpendicular to the OD of the pipe wall. As soon as the plug is installed and tightened down, the mating surfaces between the OD of the pipe wall and the underneath portion of the plug are not completely flat against each other. This causes an inherent stress riser that can ultimately produce a crack and leak path for steam.

A less commonly seen contributor is erosion from the flowing media or from solid particles entrained in the flowing media. This mechanism is more commonly associated with the cap-style designs, where a hollow section is formed inside of the RT bore hole in the pipe wall. Fluid vortices and particles impinge on the internal radius of the bore hole and erode the plug material. If the plug includes threads, the threads can also be damaged. The typical solution is to use either the inverted plug design or go back to a more traditional solid plug with matched material and a strength weld to restrain the threads.

RT-Plug Design and Installation Recommendations

Based on industry experience, several common practices have evolved for the design of RT plugs. These are based on industry standards, primarily those provided by PFI ES-16, along with recommendations from numerous boiler manufacturers. The current best practice is to use a solid metallic plug fabricated from a material that is metallurgically compatible with the pipe. Typically, this material will be forged, although bar-stock materials are also acceptable. The material must be listed by B31.1 or ASME BPVC as suitable for power generation service. This arrangement is shown in Figure 8-3. The plugs include straight machine threads. The plug body extends to the inside wall of the pipe to prevent erosion from flowing vortices when the pipe system is in service.

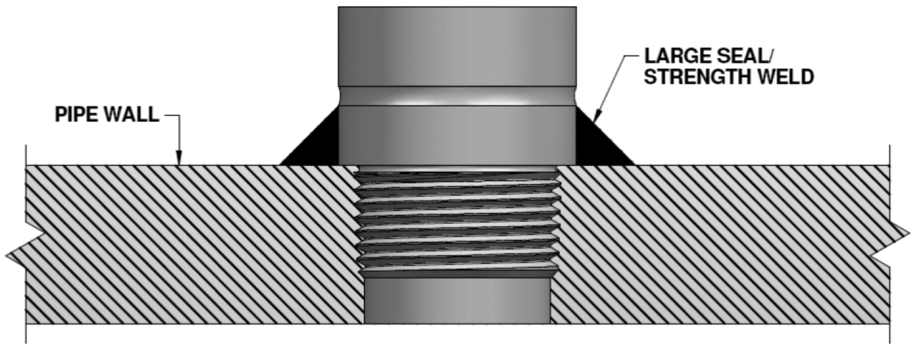

Figure 8-3
PFI-style RT plug

A variation of the plug style shown in Figure 8-3 is shown in Figure 8-4. The plug construction is very similar. However, the bore inside of the pipe has been machined to create a bevel inside the wall of the pipe. This allows for a partially penetrating weld that requires no threads to maintain a pressure boundary. This installation is generally more expensive. However, it eliminates any possibility of failures/leaks due to an improper seal weld.

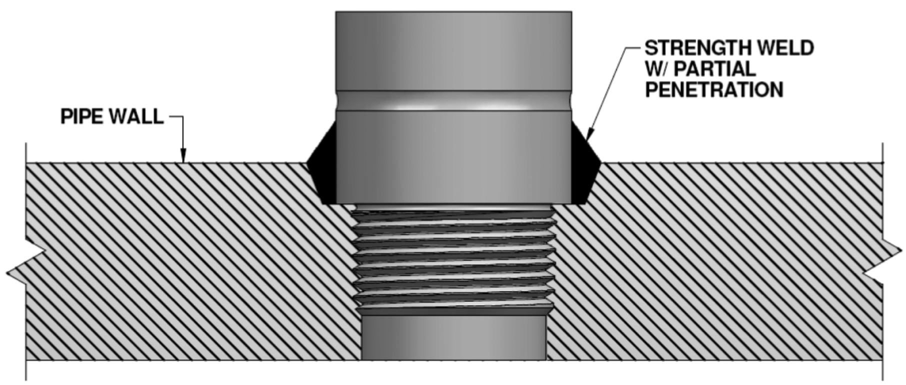

Figure 8-4
Alternate PFI-style RT plug

Alternative styles are also used and sometimes recommended by the boiler suppliers. One boiler supplier in particular uses an inverted cap-style of plug that is threaded into the pipe. The cap is made of a similar material to the pipe, and (by the design) accommodates some swelling of the pipe material during thermal cycling. This arrangement is shown in Figure 8-5.

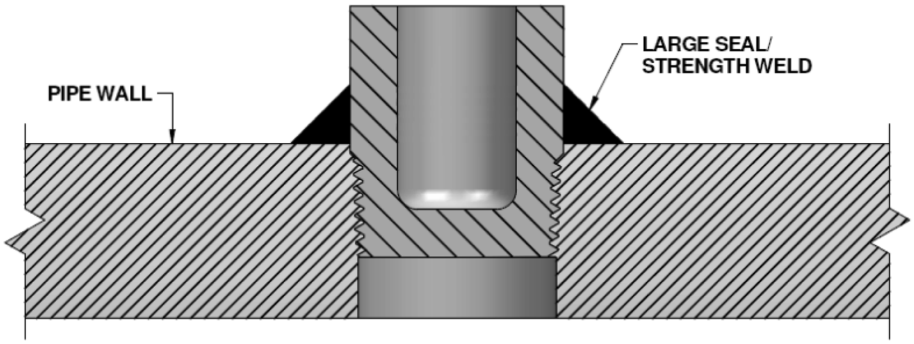

Figure 8-5
Inverted-cap-style RT plug

The seal welding that is performed for either design is in reality a strength weld with a 0.375 in. (9.525 mm) minimum fillet weld using two or more passes to ensure that each weld pass start-and-stop locations are adequately fused and melted together. Upon completion and clean up, the welds are examined using either a die-penetrant or magnetic particle nondestructive examination technique.

Following installation, a random sampling of the RT plugs should be inspected annually to look for possible plug degradation or cracking in the seal welds. Where possible, the threaded holes should be checked for any swelling. Where systemic problems are found, additional plugs subject to similar operating conditions should be inspected.

Any issues that are found should be resolved by installing new similar material plugs and rewelding. Where existing plugs do not follow the criteria described previously, new plugs should be installed in accordance with the previous recommendations and installation procedures.

Future Considerations for RT Inspections

It should be noted that the UT method is rapidly overtaking radiographic methods for high-energy piping system inspections. The UT method is slightly less expensive, there are no radioactive X-ray sources required, and the results are equivalent or superior to RT methods. No penetrations into the piping are required, so no plugs, welding, or additional post-weld heat treatment is required. The timing required for UT inspection is significantly lower because no evacuation or quarantined areas are required. UT methods have been evaluated to save approximately $460 per test.

The ASME Codes such as B31.1 Power Piping and portions of BPVC, Section 1, were revised several years ago to allow the use of UT in identical applications to those that previously used RT methods. Going forward, the preference would be to avoid RT plugs all together in favor of UT methods.

References

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A

DIMENSIONAL REQUIREMENTS AND MANUFACTURING TOLERANCES FOR THERMOWELLS UNDER 19.3 TW

Table A-1
Dimensional limits for straight and tapered thermowells

Description	Symbol	Minimum	Maximum
Unsupported length	U	2.5 in. (63.5 mm)	24 in. (609.6 mm)
Bore diameter	D	0.125 in. (3.175 mm)	0.825 in. (20.955 mm)
Tip diameter	B	0.36 in. (9.14 mm))	1.83 in. (46.48 mm)
Taper ratio	B/Q	0.58 in. (14.73 mm)	1 in. (25.4 mm)
Bore ratio	d/B	0.16 in. (4.06 mm)	0.71 in. (18.03 mm)
Aspect ratio	U/B	2 in. (50.8 mm)	—
Minimum wall thickness	(B-d)/2	0.12 in. (3.05 mm)	—

Notes:

(1) Thermowells of length less than the minimum specified require design methods outside of the scope of the standard.

(2) Equations are valid for longer thermowells; however, only single-piece, drilled bar-stock shanks are covered by the standard.

Table A-2
Dimensional limits for step-shank wells

Description	Symbol	Minimum	Maximum
Unsupported length	U	5 in. (127 mm)	24 in. (609.6 mm)
Bore diameter	D	0.24 in. (6.10 mm)	0.265 in. (6.731 mm)
Step diameter ratio for B= 0.5 in. (12.7 mm)	B/Q	0.5 in. (12.7 mm)	0.8 in. (20.3 mm)
Step diameter ratio for B= 0.875 in. (22.225 mm)	B/Q	0.583 in. (14.808 mm)	0.875 in. (22.225 mm)
Length ratio	Ls/U	0	0.6 in. (15.2 mm)
Minimum wall thickness	(B-d)/2	0.12 in. (3.05 mm)	—
Allowable dimensions (Note 1)			
Tip diameter	B	0.5 in. (12.7 mm)	0.875 in. (22.225 mm)

Note:

(1) Methods apply for other tip diameters but correlation for natural frequency is supplied for only 0.5-in. (12.7-mm) and 0.875-in. (22.225-mm) tip ODs.

Table A-3
Manufacturing tolerances for 19.3 TW thermowells

Unsupported length (U)	±1%	
Step length (Ls)	±1%	
Root diameter (Q)	±3%	
Tip diameter (B)	±3%	
Bore diameter (d)	Best of ±3% or (+0.005 in. [0.127 mm]/-0.003 in. [-0.076 mm])	
Surface finish	16-32 µin. Ra (0.41-0.81 µm Ra)	
Out of round (OD)	-0.005 in. (-0.127 mm) Total indicator reading	
Concentricity (bore to OD)	±10% of Minimum wall thickness	

B

CHANGES OF NOTE TO THE ASME 19.3 THERMOWELL STANDARD

Table B-1
Revisions to the ASME 19.3 thermowell standard

	19.3	**19.3 TW-2010**
Velocity range	<300 fps.	Not limited.
Shank style	Tapered.	Tapered, straight, and stepped.
Elbow installations	Not stated.	Tip pointed away from the flow permitted. Tip into the flow requires calculation of Strouhal and Bending moment using CFD or experimental assessment.
Installation shielding	Not stated.	Included as a small factor reducing the impact of stress on the well.
Life cycle	Unstated.	10^11 cycles.
Welds along the shank	Unstated.	Prohibited unless used to attach flange to stem.
Coatings and velocity collar	Unstated.	Stated that these are outside of scope.
Erosion and corrosion	Unstated.	Calculation considering these factors provided.
Manufacturing tolerances	Unstated.	Provided.
Process connections	Not mentioned.	Applicable to flanged, weld-in, socket weld, and threaded. Ball joints, spherical union,s and packing glands not permissible.
Calculation of natural frequency	Based on well length, modulus of elasticity, and well material density.	Considers the same factors as in 19.3 but also considers mass of installed sensor, mass of process fluid, bore size, well mass, well diameter, well shape, and manner of installation.
Calculation of wake frequency	Strouhal number times velocity divided by tip diameter where Strouhal number always equals 0.22.	Strouhal number tailored to process where viscosity is known, 0.22 is offered as a default value where viscosity is unknown.

Table B-1 (continued)
Revisions to the ASME 19.3 thermowell standard

	19.3	19.3 TW-2010
Calculation of wake-frequency limit	<80% of natural frequency. No consideration of in-line resonance phenomenon. No adjustment for process fluid density.	<40% of installed natural frequency (f_n^c) for general case. <80% of f_n^c for low density gas (N_{Sc}>2.5 & *Re* <100,000). Either <40% f_n^c, **or** between >60% f_n^c and <80% f_n^c during steady-state operation if well design passes cyclic-stress test at in-line resonance. Designer should beware and proceed with extreme caution when applying this limit and consider full range of steady-state fluid velocity. Even when test is met, sensor damage can still occur and unanticipated reductions in velocity or immersion length can lead to well failure. **No limit** where fluid velocity is <2.1 ft/s and specific thermowell design and process compatibility requirements are met.
Assessment of stress	Assessed steady-state stress.	Steady-state stress and dynamic stress assessed independently of each other. Both bending modes and shear evaluated. Stresses evaluated against static and fatigue limits.
Pressure	Tip and shank pressure based on BPVC.	Same. Adds that ASME B16.5 should be considered to establish working pressure ratings for flanged thermowells.
Fillet radius	Not mentioned.	An important consideration, especially for flanged thermowell designs.
In-line resonance	Not considered.	Important consideration due to field reports of failure.
Dimensional requirements	Outdated due to use of beaded sensors in thermowells.	Well defined and updated. Thermowells should be checked against dimensional requirements of standard for conformance. Thermowells that do not meet dimensional requirements are outside the scope of 19.3 TW.

C
CERTIFICATE OF VALIDATION

Thank you very much for your interest in [illegible] SwiftyCalc thermowell software. We appreciate the opportunity to work with [illegible] and should you have further questions or if I can be of further assistance, please do not hesitate to let me know.

<u>Certificate of Validation Quality Statement</u>

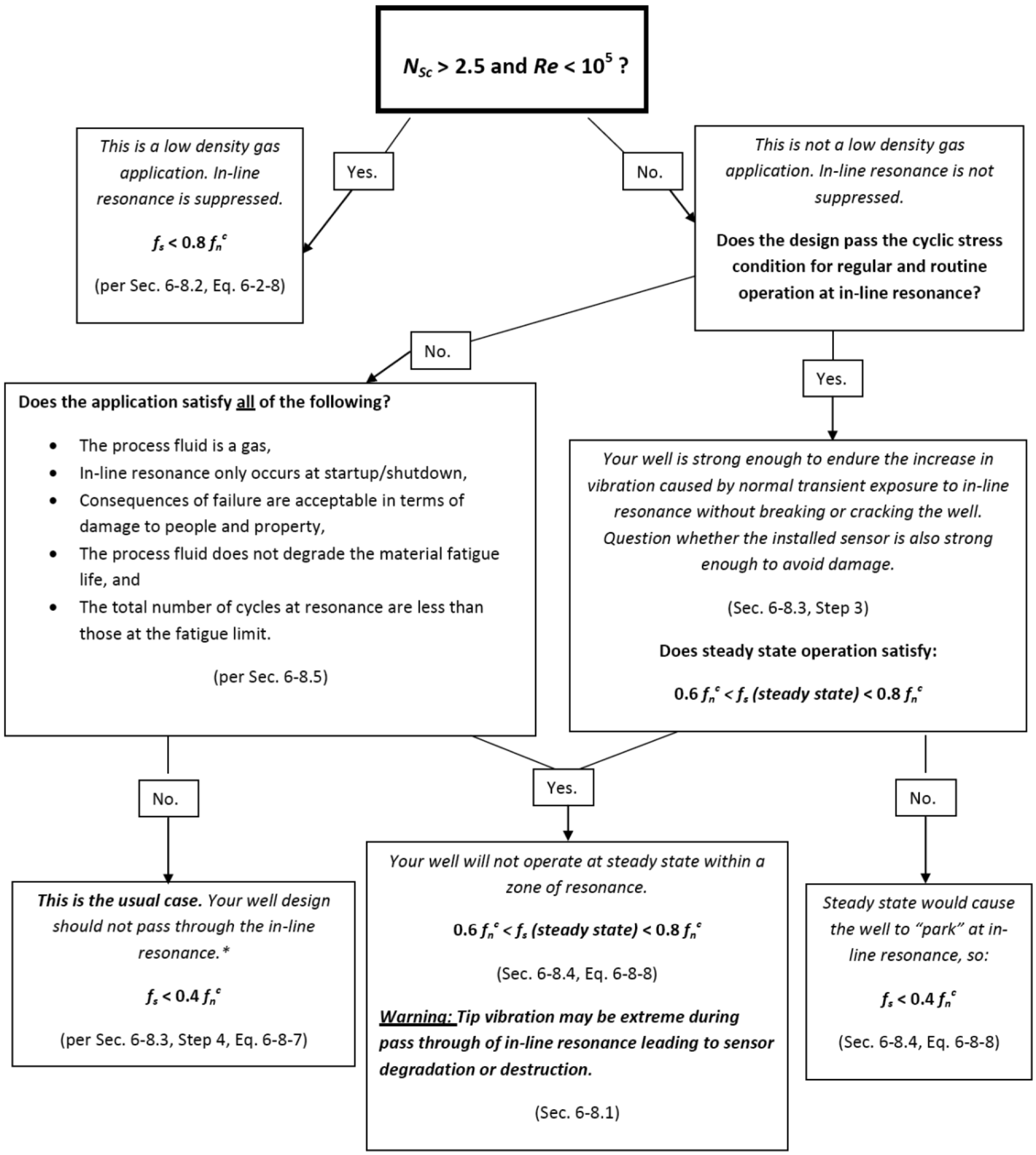
[illegible] certifies that SwiftyCalc v. 2.1 has been validated by means of hand comparison of the attached calculation report to the example 8-1 and 8-2 contained in ASME/ANSI PTC 19.3TW-2010. Thermowells standard as indicated in the enclosed.

[illegible] is an ISO 9001:2008 registered company, UL File No.: 10001132QM08. As future changes and improvements are made to SwiftyCalc v 2.1, those changes will be documented by increasing the number of the revision sequentially which shall be validated accordingly. Copies of the current validation report can be obtained by request to [illegible] or from the [illegible] website [illegible]

D

ESTABLISHING WAKE-FREQUENCY LIMIT FLOW CHART

What Wake Frequency (f_s) Limit Applies?



E

CYCLIC-STRESS TEST EXAMPLES

SwiftyCalc™ Thermowell Design Report (ASME PTC 19.3-TW 2010)

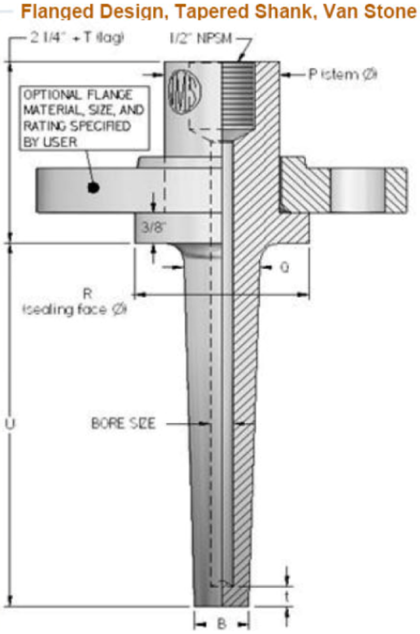
Report Information - v2.1

Customer:	JMS Southeast, Inc.	Date/Time:	10/15/2012 9:04:40 AM (EST)
Tag Number(s):	38.71 fps pass per cyclic stress -- EPRI App. E	Reference #:	4324B44A54A24F8

Thermowell Configuration

Process Conn. | Shank:	Flanged | Tapered
Thermowell Material:	316 SS
Plug/Chain:	No
Internal Conn.:	1/2" NPSM
Flange Size | Rating:	2" | 300 lb.
Flange Facing:	Van Stone
Flange Material:	316 SS
Bore Size:	0.26"
Insertion Depth (U):	14"
Shielded Length (L_0):	4 1/4"
Lag Extension (T):	No Lag
Root Diameter (Q) | Fillet:	1 1/8" | 3/16"
Tip Dia. (B) | Thickness (t):	7/8" | 1/4"

Flanged Design, Tapered Shank, Van Stone Facing



Process Operating Conditions

Process Fluid:	Other: Hydrocarbon gas
Max Temperature (T) / Pressure (P):	215.01 °F / 306.03 psig
Fluid Velocity (v):	38.71 ft/s
Fluid Viscosity:	0.01 cP
Fluid Density:	1.34 lb/ft^3

Thermowell Material Properties

Density (ρ):	0.29 lb/in^3
Elastic Modulus, $E(T)$:	2.751e+7 psi
Allowable Stress (S) / Fatigue Limit (S_f):	17044.83 psi / 13600 psi

Stresses

Peak Oscillating Stress (Root):	324.43 psi
Von Mises Stress (Root):	185.717 psi

Vibration

Inline Freq. Limit (Pass Cyclic Stress):	67.76 Hz
Transverse Freq. Limit (Controlling):	135.53 Hz
Installed Natural Freq.:	169.41 Hz
Wake Frequency:	116.79 Hz

Pressure

Pressure Rating:	610.99 psig
Process Pressure:	306.03 psig

Thermowell Rating

	Status	Value	Limit
Oscillating Stress	Pass	324.43 psi	13220.32 psi
Steady-State Stress	Pass	185.72 psi	25567.25 psi
Pressure	Pass	306.03 psig	610.99 psig
Frequency	Pass	116.79 Hz	135.53 Hz
Dimensional Limit	Pass	--	--

Theoretical Maximums

Max Insertion Depth: 10 1/2"

This configuration passes the PTC 19.3TW-2010 but is not recommended. Reductions in velocity or unsupported length may cause this well to fail.

Figure E-1
Thermowell passes a cyclic-stress test at 38.71 ft/s (11.80 m/s) with a warning

SwiftyCalc™ Thermowell Design Report (ASME PTC 19.3-TW 2010)

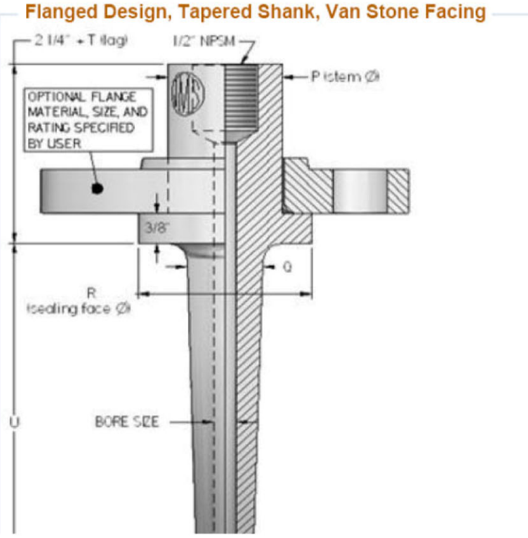
Report Information - v2.1

Customer:	JMS Southeast, Inc.	Date/Time:	10/15/2012 9:04:40 AM (EST)
Tag Number(s):	45 fps fail -- EPRI App. E	Reference #:	1B099D7239B2462

Thermowell Configuration

Process Conn. | Shank:	Flanged | Tapered
Thermowell Material:	316 SS
Plug/Chain:	No
Internal Conn.:	1/2" NPSM
Flange Size | Rating:	2" | 300 lb.
Flange Facing:	Van Stone
Flange Material:	316 SS
Bore Size:	0.26"
Insertion Depth (U):	14"
Shielded Length (L_0):	4 1/4"
Lag Extension (T):	No Lag
Root Diameter (Q) | Fillet:	1 1/8" | 3/16"
Tip Dia. (B) | Thickness (t):	7/8" | 1/4"

Flanged Design, Tapered Shank, Van Stone Facing



Process Operating Conditions

Process Fluid:	Other: Hydrocarbon gas
Max Temperature (T) / Pressure (P):	215.01 °F / 306.03 psig
Fluid Velocity (v):	45 ft/s
Fluid Viscosity:	0.01 cP
Fluid Density:	1.34 lb/ft^3

Thermowell Material Properties

Density (ρ):	0.29 lb/in^3
Elastic Modulus, $E(T)$:	2.751e+7 psi
Allowable Stress (S) / Fatigue Limit (S_f):	17044.83 psi / 13600 psi

Stresses

Peak Oscillating Stress (Root):	642.227 psi
Von Mises Stress (Root):	249.499 psi

Vibration

Inline Freq. Limit (Controlling):	67.76 Hz
Transverse Freq. Limit:	135.53 Hz
Installed Natural Freq.:	169.41 Hz
Wake Frequency:	135.77 Hz

Pressure

Pressure Rating:	610.99 psig
Process Pressure:	306.03 psig

Thermowell Rating

	Status	Value	Limit
Oscillating Stress	Pass	642.23 psi	13220.32 psi
Steady-State Stress	Pass	249.50 psi	25567.25 psi
Pressure	Pass	306.03 psig	610.99 psig
Frequency	Fail	135.77 Hz	67.76 Hz
Dimensional Limit	Pass	--	--

Theoretical Maximums

Max Insertion Depth:	9.8"

Figure E-2
Same thermowell and conditions as Figure E-1 fails 19.3 TW at a higher velocity of 45 ft/s (13.72 m/s)

SwiftyCalc™ Thermowell Design Report (ASME PTC 19.3-TW 2010)

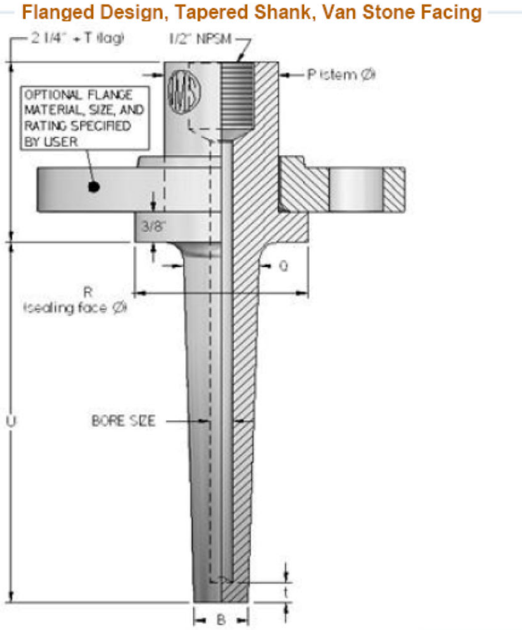
Report Information - v2.1

Customer:	JMS Southeast, Inc.	Date/Time:	10/15/2012 9:06:56 AM (EST)
Tag Number(s):	34 fps fail -- EPRI App. E	Reference #:	C9B0BC280BA6460

Thermowell Configuration

Process Conn. | Shank:	Flanged | Tapered
Thermowell Material:	316 SS
Plug/Chain:	No
Internal Conn.:	1/2" NPSM
Flange Size | Rating:	2" | 300 lb.
Flange Facing:	Van Stone
Flange Material:	316 SS
Bore Size:	0.26"
Insertion Depth (U):	14"
Shielded Length (L_0):	4 1/4"
Lag Extension (T):	No Lag
Root Diameter (Q) | Fillet:	1 1/8" | 3/16"
Tip Dia. (B) | Thickness (t):	7/8" | 1/4"

Flanged Design, Tapered Shank, Van Stone Facing



Process Operating Conditions

Process Fluid:	Other: Hydrocarbon gas
Max Temperature (T) / Pressure (P):	215.01 °F / 306.03 psig
Fluid Velocity (v):	34 ft/s
Fluid Viscosity:	0.01 cP
Fluid Density:	1.34 lb/ft^3

Thermowell Material Properties

Density (ρ):	0.29 lb/in^3
Elastic Modulus, $E(T)$:	2.751e+7 psi
Allowable Stress (S) / Fatigue Limit (S_f):	17044.83 psi / 13600 psi

Stresses

Peak Oscillating Stress (Root):	201.409 psi
Von Mises Stress (Root):	144.531 psi

Vibration

Inline Freq. Limit (Controlling):	67.76 Hz
Transverse Freq. Limit:	135.53 Hz
Installed Natural Freq.:	169.41 Hz
Wake Frequency:	98.42 Hz

Pressure

Pressure Rating:	610.99 psig
Process Pressure:	306.03 psig

Thermowell Rating

	Status	Value	Limit
Oscillating Stress	Pass	201.41 psi	13220.32 psi
Steady-State Stress	Pass	144.53 psi	25567.25 psi
Pressure	Pass	306.03 psig	610.99 psig
Frequency	Fail	98.42 Hz	67.76 Hz
Dimensional Limit	Pass	--	--

Theoretical Maximums

Max Insertion Depth:	11 1/2"

Figure E-3
Same thermowell as Figure E-1 and Figure E-2 fail at lower velocity of 34 ft/s (10.36 m/s)

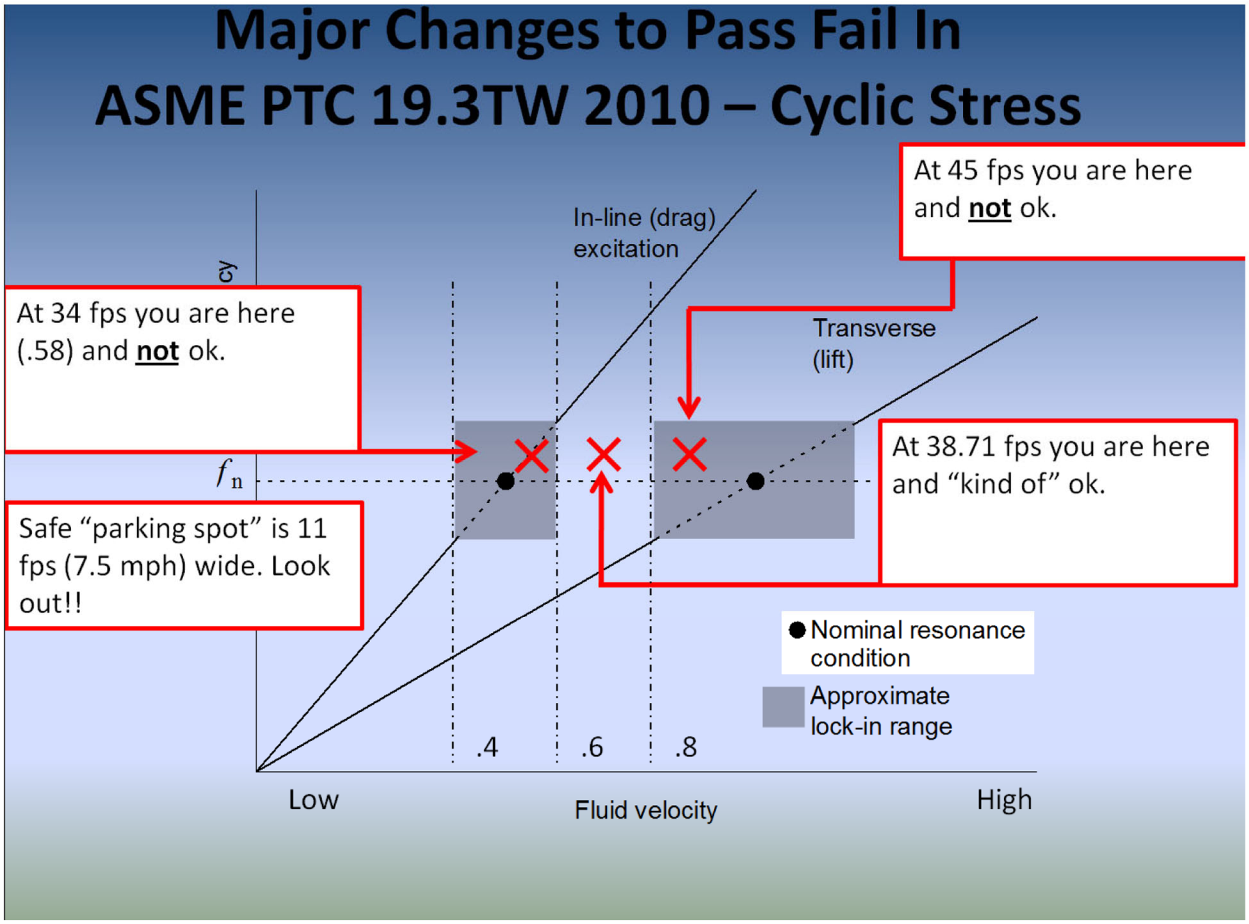


Figure E-4
Layout showing the predicted relationship to resonance zones at 34 ft/s (10.36 m/s), 38.71 ft/s (11.80 m/s), and 45 ft/s (13.72 m/s)

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