# Heat Recovery Steam Generators

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FIRST EDITION, JANUARY 1995

**American Petroleum Institute**
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**Manufacturing, Distribution and Marketing Department**

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# Heat Recovery Steam Generators

## SECTION 1—GENERAL

### 1.1 Scope

This publication provides guidelines for the selection or evaluation of heat recovery steam generator (HRSG) systems. Details of related equipment designs are considered only where they interact with the HRSG system design. This publication does not provide rules for design, but indicates areas that need attention and offers information and description of HRSG types available to the designer or user to aid in the selection of the appropriate HRSG system.

The HRSG systems discussed are those currently in industry use. A general description of each HRSG system begins Sections 2 through 5. Selection of an HRSG system for description does not imply that other systems are not available nor recommended. Many individual features described in these guidelines will be applicable to any type of HRSG system.

Appendices A, B, and C refer to Sections 1 through 6.

### 1.2 Referenced Publications

**1.2.1** The editions of the following standards, codes, and specifications that are in effect at the time of publication of this publication shall, to the extent specified herein, form a part of this publication.

ABMA[1]

*Recommended Boiler Water Limits and Associated Steam Purity*

ANSI[2]/ASME

PTC 4.4 *Gas Turbine Heat Recovery Steam Generators Performance Test Code*

ASME[3]

*Boiler and Pressure Vessel Code,* Section I, "Power Boilers" and Section VIII, Division 1, "Pressure Vessels."

ASTM[4]

*Standards for Tubes, Sampling, and Testing*

TEMA[5]

*Standards of the Tubular Exchanger Manufacturers Association* (seventh edition)

[1]American Boiler Manufacturers Association, 950 North Glebe Road, Arlington, Virginia 22203.
[2]American National Standards Institute, 11 West 42nd St., 13th Floor, New York, New York 10036-8002.
[3]American Society of Mechanical Engineers, 345 East 47th Street, New York, New York 10017-2392.
[4]American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103-1187.
[5]Tubular Exchanger Manufacturers Association, 25 North Broadway, Tarrytown, New York 10591-3201.

**1.2.2** In addition, this publication draws upon the work presented in the following publications:

*Steam: Its Generation and Use,* Babcock & Wilcox Company, New Orleans, Louisiana.

*Combustion Engineering—A Reference Book on Fuel Burning and Steam Generation,* Combustion Engineering Co., Inc., Stamford, Connecticut.

A. Bar-Cohen, Z. Ruder, and P. Griffith, "Circumferential Wall Temperature Variations in Horizontal Boiler Tubes," *International Journal of Multiphase Flow,* Vol. 9, No. 1, Massachusetts Institute of Technology, 1983.

B.Y. Taitel and A.E. Dukler, "A Model for Predicting Flow Regimen Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," *AICHE Journal,* Vol. 22, No. 1, University of Houston, January 1976.

### 1.3 Definition of Terms

**1.3.1** *Heat recovery steam generator (HRSG)*—A system in which steam is generated and may be superheated or water heated by the transfer of heat from gaseous products of combustion or other hot process fluids.

**1.3.2** *Firetube HRSG*—A shell and tube heat exchanger in which steam is generated on the shell side by heat transferred from hot fluid flowing through the tubes.

**1.3.3** *Heat pipe HRSG*—A compact heat exchanger consisting of a pressure vessel and a bundle of heat pipes. The heat pipes extract heat from a hot fluid and transport it into a pressure vessel where steam is generated.

**1.3.4** *Vertical shell and tube watertube HRSG*—A shell and tube heat exchanger in which steam is generated in the tubes by heat transferred from a hot fluid on the shell side.

**1.3.5** *Watertube low pressure casing HRSG*—A multiple tube circuit heat exchanger within a gas-containing casing in which steam is generated inside the tubes by heat transferred from a hot gas flowing over the tubes.

**1.3.6** *Watertube pipe coil HRSG in a pressure vessel*—A tube or pipe coil circuit within a pressure vessel in which steam is generated inside the tubes by heat transferred from a high temperature fluid or fluidized solids surrounding the tube circuits.

# SECTION 2—FIRETUBE HEAT RECOVERY STEAM GENERATORS

## 2.1 General

A firetube HRSG produces steam from boiler feedwater in contact with the outside tube surface, while cooling a hot fluid which passes through the tubes. The hot fluid is often a high temperature gas resulting from combustion or other chemical reaction. Moderate temperature gases, liquids, and slurries are also used.

High temperature severe service firetube HRSGs are supplied with boiler water in substantial excess of that vaporized. Natural (thermosiphon) or forced (pumped) circulation systems are employed. Boiler feedwater is introduced to an overhead steam drum, which provides for water storage and steam-water separation in addition to the static head driving force for natural circulation systems.

Less severe service lower temperature firetube HRSGs are often once-through (nonrecirculating) kettle boilers. Figures 1 and 2 illustrate horizontal and vertical units involving natural circulation from an overhead drum. Figure 3 is a kettle steam generator.

## 2.2 Application

### 2.2.1 HIGH TEMPERATURE/HIGH FLUX UNITS

Firetube HRSGs with high temperature process fluids (exceeding 900°F) resulting in high boiling flux rates (in excess of 30,000 Btu per hour per square foot) are considered severe service applications. Gas temperatures exceeding 2000°F and flux rates to 100,000 Btu per hour per square foot can be accommodated in firetube HRSGs. Mechanical features as described in 2.6.1 are required for these severe services.

The following process applications are typical of those which often make use of severe service firetube HRSGs:

a. Steam reformer effluent (hydrogen, methanol, ammonia plants).
b. Ethylene plant furnace effluent.
c. Fluid catalytic cracker flue gas.
d. Sulfur plant reaction furnace effluent.
e. Coal gasifier effluent.
f. Sulfuric and nitric acid reaction gases.

Typical steam-side operating pressures range from as low as 150 pounds per square inch for fluid catalytic cracker and sulfur plant applications to as high as 1800 pounds per square inch for ammonia and ethylene facilities.

### 2.2.2 MODERATE TEMPERATURE/LOW FLUX UNITS

Firetube HRSGs, which handle hot fluid temperatures not exceeding 900°F with flux rates of 30,000 Btu per hour per square foot and below, have a wide range of process applications. Any hot fluid stream with a temperature sufficiently above the steam saturation temperature can be utilized. Typical process applications include:

a. Fluid catalytic cracking unit slurries.
b. Miscellaneous refinery hot oil and vapor streams.
c. Sulfur recovery condensers.

Steam-side operating pressures range from 50 pounds per square inch to 600 pounds per square inch.

## 2.3 System Consideration

### 2.3.1 PROCESS FLUID

The thermal-hydraulic performance and mechanical construction of the equipment to a large degree are dependent on specific characteristics of the hot process fluid. Each process fluid has unique aspects which must be accounted for in the firetube boiler design to ensure reliable operation. For example, process fluid hydrogen content may significantly increase flux.

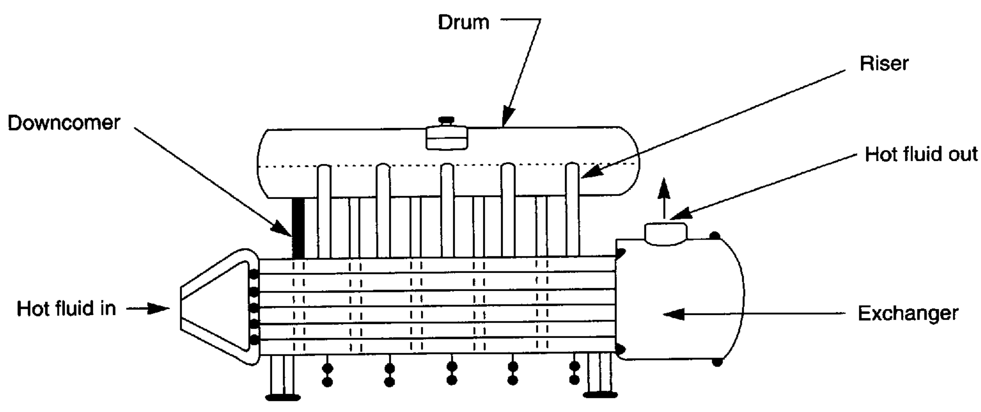



Figure 1—Horizontal Firetube with External Drum HRSG

#### 2.3.1.1 Fouling

Fouling of the tube inside surface in firetube HRSGs is largely a function of the specific process fluid. It is also dependent on velocity, residence time, tube size and orientation, and wall temperature.

Examples of specific concerns include:

a. Ethylene furnace effluent quench coolers are subject to coke deposition due to continuation of the cracking process at elevated temperature. Therefore, high gas velocities resulting in minimum residence time at temperature are used.
b. Hydrogen plant steam/hydrocarbon reformer effluent heat recovery boilers are subject to silica fouling when improper refractories are used in the upstream secondary reformer (for ammonia facilities), transfer lines, or boiler inlet channels.
c. Fluid catalytic cracking slurry steam generators are generally designed for a velocity of 5 to 7 feet per second to avoid settling out the solid constituents.
d. Fluid catalytic cracking flue gas HRSGs tend to foul with catalyst deposits.

#### 2.3.1.2 Velocity

The fluid velocity inside the tubes must meet certain minimum criteria for the specific processes as noted under 2.3.1.1. There are also maximum velocity limitations with respect to the erosive nature of particulate bearing streams. In most cases, however, the velocity is set by maximum pressure drop or by maximum allowable heat flux limits which must be considered in design.

#### 2.3.1.3 Pressure Drop

Pressure losses across the tube side of a firetube HRSG are limited by overall system considerations. For instance, the performance of an olefins plant cracking furnace is penalized by excessive backpressure imposed by downstream firetube quench coolers. Sulfur recovery condensers are normally designed for pressure losses of 1 pound per square inch or less, due to the low operating pressure level.

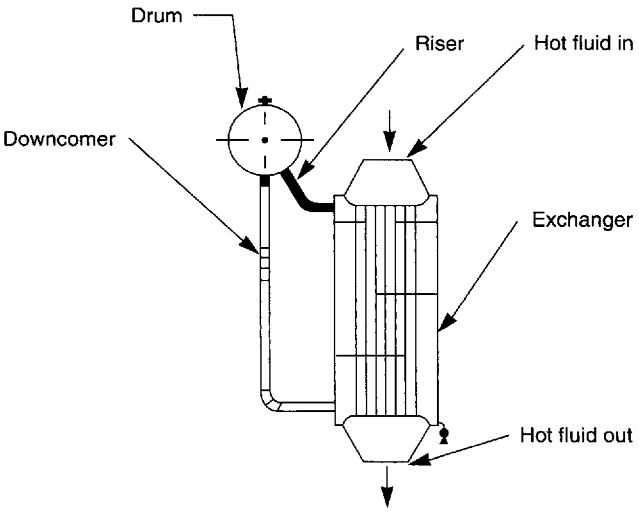



Figure 2—Vertical Firetube with External Drum HRSG

#### 2.3.1.4 Temperature Approach

The degree to which the hot process fluid is required to approach the steam saturation temperature strongly affects the HRSG size. The *approach* is defined as the difference between the gas outlet temperature and the saturated steam temperature. As the design approach is reduced, the surface area requirement increases. HRSGs with large approaches tend to use larger diameter or shorter tubes than those with close approaches.

#### 2.3.1.5 Outlet Temperature Control

Certain process applications require close control of the process fluid outlet temperature. For instance, secondary reformer effluent in an ammonia plant enters a CO to $CO_2$ shift reactor after being cooled by the firetube HRSG. Overcooling by the HRSG adversely affects the shift reaction catalyst. For this reason such firetube HRSGs incorporate a hot gas bypass system, which may be either internal or external. Refer to 2.6.1.11 for further construction details.

The amount of gas bypassed is a function of turndown, extent of fouling, and the design temperature approach. The equipment tends to overcool the process fluid when run at reduced throughput and when clean. HRSGs with large design approaches tend to overcool due to the large thermal driving force at the outlet end. Such units require large bypass systems for temperature control to handle significant bypass fractions.

#### 2.3.1.6 Gas Dew Point

Hot gas streams which may reach the dew point of one of the gas constituents require special attention. Condensation can occur on cold surfaces, such as the tubes and refractory lined walls, even though the bulk gas temperature may be above the dew point. If bulk gas cooling below the dew point occurs, as in sulfur recovery boilers, provision must be made to ensure condensate removal.

### 2.3.2 BOILER FEEDWATER/STEAM

Appendices A and B provide general information with regard to the boiler feedwater/steam system. Additional considerations unique to firetube equipment are covered in 2.3.2.1 and 2.3.2.2.

#### 2.3.2.1 Heat Flux

Maximum allowable heat flux rates for firetube HRSGs are a function of equipment construction details, steam pressure, recirculation rates, and water quality. Specific construction features which affect flux limits include:

a. Tube quantity, diameter and pitch; in general, flux limits are lower for increasing tube quantity or decreasing pitch to diameter ratio.
b. Quantity, size, and location of risers and downcomers.
c. Clearance between bundle and shell.

Actual flux rates for comparison with design limits are based on clean tube surface at the tube inlet where the process fluid is the hottest. Firetube HRSG design should account for increased hot process fluid heat transfer coefficients due to tube entrance effects.

#### 2.3.2.2 Boiler Water Circulation

Critical service high temperature firetube HRSGs are furnished with elevated steam drums, from which boiler water is supplied with substantial excess recirculation rates. Systems may be either natural (most common) or forced circulation.

Low flux HRSGs may also be furnished with an external drum. However, such HRSG equipment more commonly makes use of an expanded shell side compartment with the tube bundle submerged in the boiler water volume. Liquid disengagement occurs above the established liquid level within the expanded shell. Such a unit is commonly referred to as a kettle boiler. Natural circulation patterns occur within the kettle shell. A water-steam mixture rises through the tube bundle; the vapor rises through the steam/water interface to the steam space above; and the boiler water recirculates back down each side of the bundle to the bottom of the shell. The kettle HRSG shell serves the purposes of a steam drum in a conventional boiler system. It differs from a conventional drum in that the HRSG heating surface is self contained, connections are altered, and steam/water internal flow patterns are different. Saturated steam generated in kettle HRSGs is normally used for process or heating purposes. For such cases the requirements for purity and quality (see Appendix A) are not high. Therefore, separation is commonly achieved by deflector plates or dry pipes. Refer to 2.6.2.4 for additional shell details.

## 2.4 Advantages of Firetube Over Watertube HRSGs

### 2.4.1 EASE OF CLEANING

Tubes containing fouling prone hot process streams such as olefins plant cracking furnace effluent, coal gasifier overhead, and fluid catalytic cracking flue gas are easier to clean in firetube HRSGs.

### 2.4.2 RESIDENCE TIME

Firetube HRSGs have lower process fluid volume and residence time for services where time at temperature is a factor.

### 2.4.3 HIGH PRESSURE OR HIGH TEMPERATURE PROCESS FLUIDS OR SPECIAL METALLURGY REQUIREMENTS

High pressure process fluids contained on the tube side may minimize HRSG weight. This is particularly beneficial when alloy materials are used. For example, ammonia converter effluent can reach 5000 pounds per square inch and requires alloy or clad materials. For this case a firetube HRSG may be preferred.

### 2.4.4 VIBRATION

Firetube HRSGs are less susceptible to damaging flow-induced tube vibration or acoustic vibration when cooling large volumetric flow rate gas streams.

### 2.4.5 REFRACTORY LINING

Elevated temperature gas which requires insulating refractory to avoid overheating pressure bearing components is often best handled in firetube equipment. This is particularly true for pressurized gas streams, which cannot be handled in rectangular duct enclosures. Refractory lining in firetube

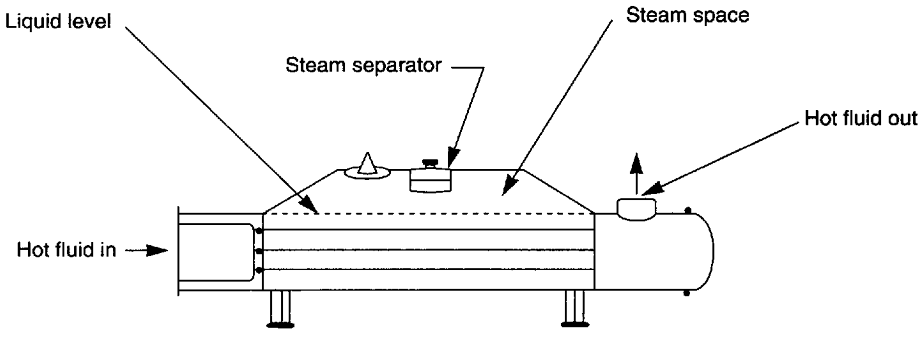



Figure 3—Kettle HRSG

HRSGs is generally required only in the inlet channel compartment. In comparison, shell and tube watertube HRSGs require more extensive refractory linings, which must be engineered to accommodate bundle insertion and removal.

#### 2.4.6 LOW THROUGHPUT ATMOSPHERIC PRESSURE FLUE GASES

Firetube HRSGs are better suited for incinerators and other combustion systems producing relatively low flow rates of flue gas.

#### 2.4.7 COMPACT DESIGN

Firetube HRSGs normally require less plot space due to compact design.

Horizontal firetube HRSGs with an external steam drum can have the drum mounted on the shell. The drum is supported by the interconnecting risers and downcomers, thereby eliminating costs associated with independent support.

### 2.5 Disadvantages of Firetube Relative to Watertube HRSGs

#### 2.5.1 HIGH THROUGHPUT ATMOSPHERIC PRESSURE FLUE GASES

Firetube HRSGs are not well suited for handling large flow volumes of near atmospheric pressure gases. Streams such as gas turbine exhaust require large cross-sectional flow area as provided by watertube coils installed in rectangular duct enclosures.

#### 2.5.2 LOWER HEAT TRANSFER COEFFICIENTS

Heat transfer coefficients for flow inside tubes are generally lower than for flow across the tube banks. For this reason firetube HRSGs tend to require more bare tube surface than watertube HRSGs.

The use of extended surface (fins) against a low pressure process gas can be an effective means of reducing size. This option is often utilized in watertube HRSGs, but is generally considered impractical for firetube designs.

#### 2.5.3 HIGH PRESSURE STEAM APPLICATIONS

For cases involving high pressure steam, typically 1500 pounds per square inch and above, firetube HRSGs require heavy wall shell cylinders and tubes. This is particularly true for high capacity systems. For this reason firetube HRSGs in high pressure steam systems weigh more than their watertube counterparts.

#### 2.5.4 HOT TUBESHEET CONSTRUCTION

The hot tubesheet design of firetube HRSGs, particularly its attachment to the shell and the tubes, may be complex. The severity of service relates to the coexistence of multiple conditions, such as:

a. High inlet gas temperature.
b. High pressure on the steam side.
c. Loading imposed by the tubes due to axial differential thermal growth relative to the shell.
d. Potential erosive effects of particulate bearing gases.
e. Potential for corrosive attack from the process and steam sides.

The tubesheet is commonly made of Cr-Mo ferritic steels which require special attention during fabrication and testing. Many firetube HRSGs require a thermal and stress analysis to prove the construction acceptable for all anticipated operating conditions.

### 2.6 Mechanical Description

#### 2.6.1 HIGH TEMPERATURE/HIGH FLUX UNITS

##### 2.6.1.1 Refractory Lined Inlet Channel

Inlet channels of high temperature units are internally refractory lined to insulate the pressure components. A number of refractory systems are available, including dual and monolithic layers, cast and gunned, or with and without internal liners. Various types of refractory anchoring systems are also used. Metallic needles may be considered to further reinforce the castable.

The selection of refractory materials and their application method must be compatible with the process service conditions. The design must account for concerns such as:

a. Insulating capability, including effect of hydrogen content on the refractory thermal conductivity.
b. Chemical compatibility with the process fluid.
c. Gas dew point relative to cold face temperature.
d. Erosion resistance against particulate bearing streams.
e. Potential for coking under metallic liners.

##### 2.6.1.2 Channels

Several channel construction options exist. The gas connections may be in-line axial or installed radially on a straight channel section. Access into the channel compartment is generally through a manway in large diameter units, or through a full access cover in small units.

##### 2.6.1.3 Tubesheets

The single most distinguishing feature of high temperature firetube HRSGs is the thin tubesheet construction. Conventional shell and tube exchangers operating at moderate temperatures incorporate tubesheets designed according to the requirements of TEMA. Typical tubesheet thicknesses in such units range from 2 inches to 6 inches or more. Use of

TEMA tubesheets in high temperature high flux (severe service) firetube HRSGs is not recommended because the tubesheet metal temperature gradient would be excessive and high stresses would result.

The thin tubesheet design is based on the use of the tubes as stays to provide the necessary support for the tubesheets. Tubesheet thicknesses typically range from $^5/_8$ inch to $1^1/_2$ inches. Flat portions of the tubesheets without tubes must be supported by supplementary stays.

Sufficient cooling of the tubesheet depends on efficient heat transfer at the tubesheet backface by shell side vaporization of water and high local circulation rate. This offsets the heat input from the gas through the front face and, more importantly, the area created by all the tube hole perforations. The steady state tubesheet temperature is dependent on the tube pitch to diameter ratio and the tubesheet thickness.

Tubesheet temperature can be further minimized by limiting heat flow to the tubesheet with the use of insulated ferrules inserted in each tube inlet. The ferrules project 3 inches to 4 inches from the tubesheet face. The space between the ferrules is packed with refractory, which secures the ferrules and insulates the tubesheet face. Ferrules are either a high temperature resistant metallic or ceramic material, wrapped with an insulating paper for a lightly snug fit in the tube bore. Overcompression of the insulation will reduce its effectiveness. Figures 4 and 5 show details of one style each of a metallic and ceramic ferrule. Other configurations have been used.

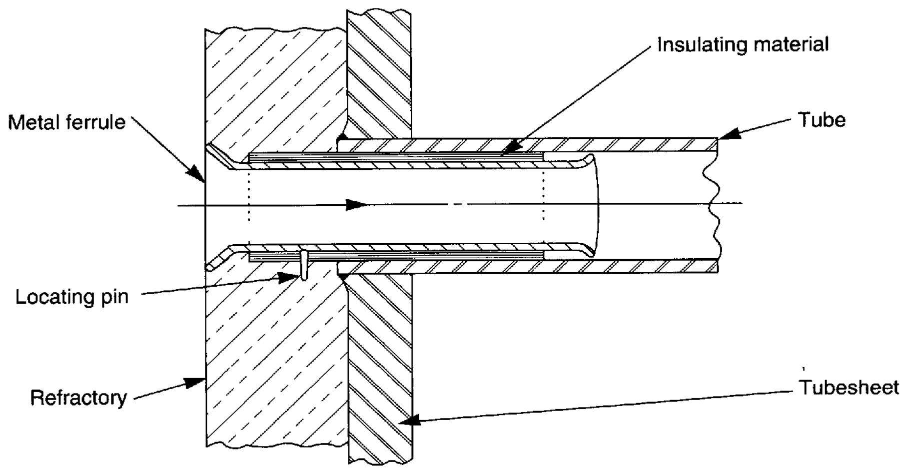



Figure 4—Insulated Metal Ferrule

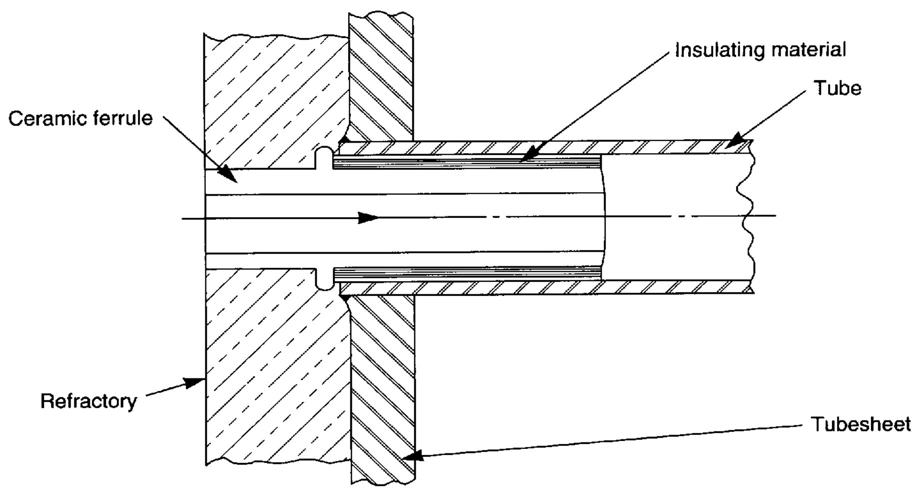



Figure 5—Insulated Ceramic Ferrule

#### 2.6.1.4 Tube-to-Tubesheet Joints

The tube-to-tubesheet joints must provide a positive seal between the process fluid and the water-steam mixture under all operating conditions and the resulting pressure and thermal loads. The joints must also withstand transient and cyclic conditions.

Tube-to-tubesheet joints in severe service applications are typically strength welded using one of the following configurations:

a. Front (tubeside) face weld: The tubesheet may be J-groove beveled (see Figure 6A) or the tube may be projected from the flat face, then welded with a multiple pass fillet (see Figure 6B). Additionally, each tube is pressure expanded through the thickness of the tubesheet except near the weld. Such joints may be used in elevated gas temperature applications generating steam at pressures to approximately 1000 pounds per square inch.
b. Full depth weld: A deep J-groove with minimum thickness backside land is welded out with multiple passes as shown in Figure 7. If the land is consumed and fused, the tube and tubesheet become integral through the full tubesheet thickness. Full depth welded joints are often specified for high temperature gases generating steam at pressures above 1000 pounds per square inch.
c. Back (shell side) face weld: This type of joint is often called an internal bore weld. The welding is performed by reaching through the tubesheet tube hole. It has been applied to a wide range of firetube HRSG operating conditions, including high pressure steam systems. A particular characteristic of this joint is that its integrity is clearly verifiable by radiographic examination.

A distinct advantage of the full depth and internal bore joints is their lack of a crevice between the tubesheet and tube outer surface. A crevice, if present, is subject to accumulation of boiler water impurities. In high temperature service the insulating effect of a buildup of such material can result in crevice corrosion and mechanical failure of the joint.

#### 2.6.1.5 Tubesheet Peripheral Knuckle

A thin tubesheet is generally attached to the shell with a peripheral knuckle between the flat (tubed) portion and the point of attachment to the outer shell (see Figure 8). The knuckle provides this critical joint with necessary flexibility to absorb the axial differential movement between tubes and shell caused by operating temperatures and pressures. Proper design of the knuckle is essential for reliable operation of a firetube boiler.

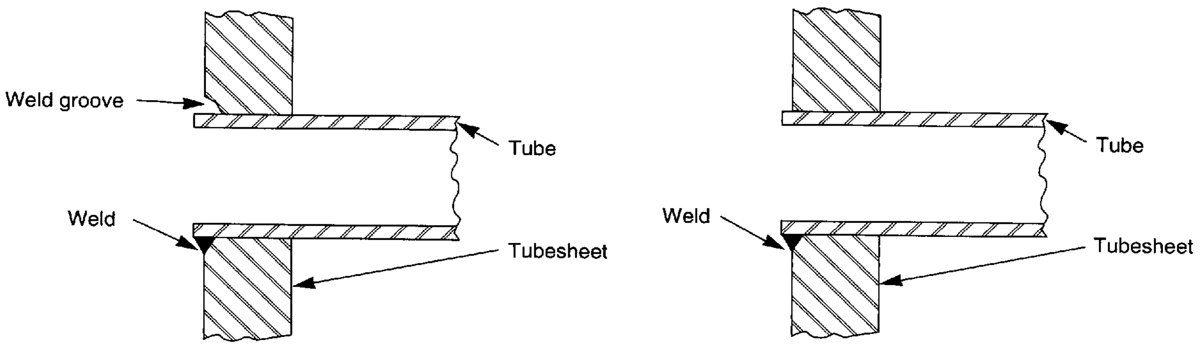
The most severe cases are those involving elevated temperature gases with high heat transfer rates and with high steam side pressure. Such conditions impose considerable loads on the knuckles. An example of a severe service application would be reformer effluent in a hydrogen plant used to produce 1500 pounds per square inch steam. Examples of less severe services include fluid catalytic cracking flue gas and sulfur recovery plant tail gas where condensers generate steam at 600 pounds per square inch and below.

#### 2.6.1.6 Channel-Tubesheet-Shell Interconnection

Numerous configurations are available for the interconnection of the thin tubesheet with the HRSG shell and the gas inlet channel. Figures 8A through 8H illustrate a number of these. Selection depends on factors such as:

a. Extent of tube versus shell differential thermal growth.
b. Steam pressure.
c. Process gas pressure.
d. Materials of construction.
e. Vertical versus horizontal HRSG orientation.

Joints shown in Figures 8A and 8B are used for mild services only, due to the fillet weld attachment and accompanying crevice. Figures 8C through 8F all have butt




J-GROOVE BEVELED TUBESHEET

MULTIPLE PASS FILLET

Figure 6—Conventional Strength Weld

welded attachment to the shell. The flanged construction of Figure 8F permits channel removal. Figure 8G is used for high pressure steam service and Figure 8H is well-suited for vertically installed units.

#### 2.6.1.7 Tubesheet Without Peripheral Knuckle Configuration

A proprietary firetube HRSG design utilizes a stiffened thin tubesheet which eliminates the peripheral knuckle. Rather than relieving the tube axial loads with flexible knuckles, the loads are transmitted directly to the HRSG shell through a stiffening system which backs up the thin tubesheet. This design may permit the use of longer tubes. The differential movement absorbed by the knuckles of a conventional firetube HRSG tubesheet is proportional to the tube length. For such HRSGs a length limit exists, beyond which the knuckles would be incapable of accepting the imposed loads within stress limits of the material.

#### 2.6.1.8 Dual Compartment Firetube HRSGs

The length limitation described in 2.6.1.7 is of significant concern primarily with high temperature, high flux, high steam pressure equipment. For such cases the option exists to use dual compartment construction. Two firetube HRSGs, each with conventional knuckled tubesheets, are installed in series, as shown by Figure 9.

The two compartments may be served by a common steam drum. Advantages of this configuration include:

a. Reduces differential growth between shell and tubes within each compartment.
b. Permits optimization of heat transfer surface through utilization of different tube diameters and lengths in each compartment, thereby reducing the total surface required.
c. Permits locating the internal bypass system in the second compartment, thereby subjecting the control components to less severe temperature conditions.

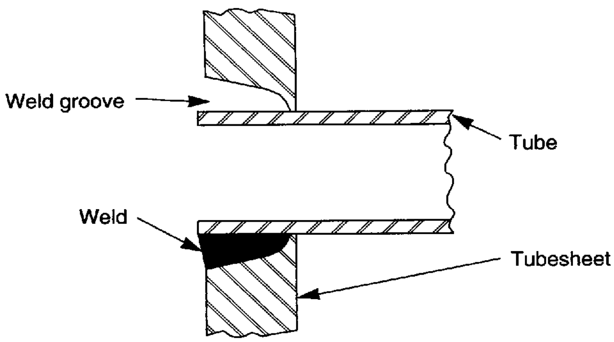



Figure 7—Full Depth Strength Weld

#### 2.6.1.9 Tubes

Typical tube diameters in high temperature firetube HRSGs range from 1.25 inches to 4 inches. Use of relatively large tubes permits the following:

a. Low pressure drop application typical of low pressure process gas streams such as tail gas of sulfur recovery plants.
b. Thermal design at lower heat fluxes.
c. Installation of tube inlet ferrules without over-restricting the flow area available at each tube entrance.
d. Limits the potential for plugging tubes in services prone to fouling.

The minimum tube wall thickness is governed by applicable code rules. Except for cases involving very high process gas pressures, the steam pressure which acts externally generally controls the minimum tube thickness.

#### 2.6.1.10 Tube Arrangement and Spacing

Tubes are normally arranged on a triangular pattern, although square layouts may also be used.

The selection of tube pitch should address the following concerns:

a. The maximum allowed heat flux is a function of the tube pitch to diameter ratio. Decreasing the pitch to diameter ratio reduces the allowable design flux.
b. The tubesheet metal temperature is also dependent on the tube pitch. Decreasing the pitch increases the metal temperature.
c. A minimum tubesheet ligament width between adjacent tubes is required for welded tube ends to physically accommodate the tubesheet J-groove weld preparations. This is particularly significant for full depth welded joints.

#### 2.6.1.11 Multiple Tube Passes

Most high temperature process firetube HRSGs are of single tube pass construction. However, multiple pass tubes may be considered for processes involving near atmospheric pressure gases used to generate low pressure steam. The low heat transfer coefficients characteristically associated with such gases result in tube metal temperatures which very closely approach the steam saturation temperature. Therefore, the metal temperature difference and differential thermal growth of tubes of different passes are minimal. Hot pass tubes are typically larger diameter than subsequent passes in order to optimize heat transfer within pressure drop constraints. Figure 10 illustrates a two tube pass high temperature firetube steam generator.

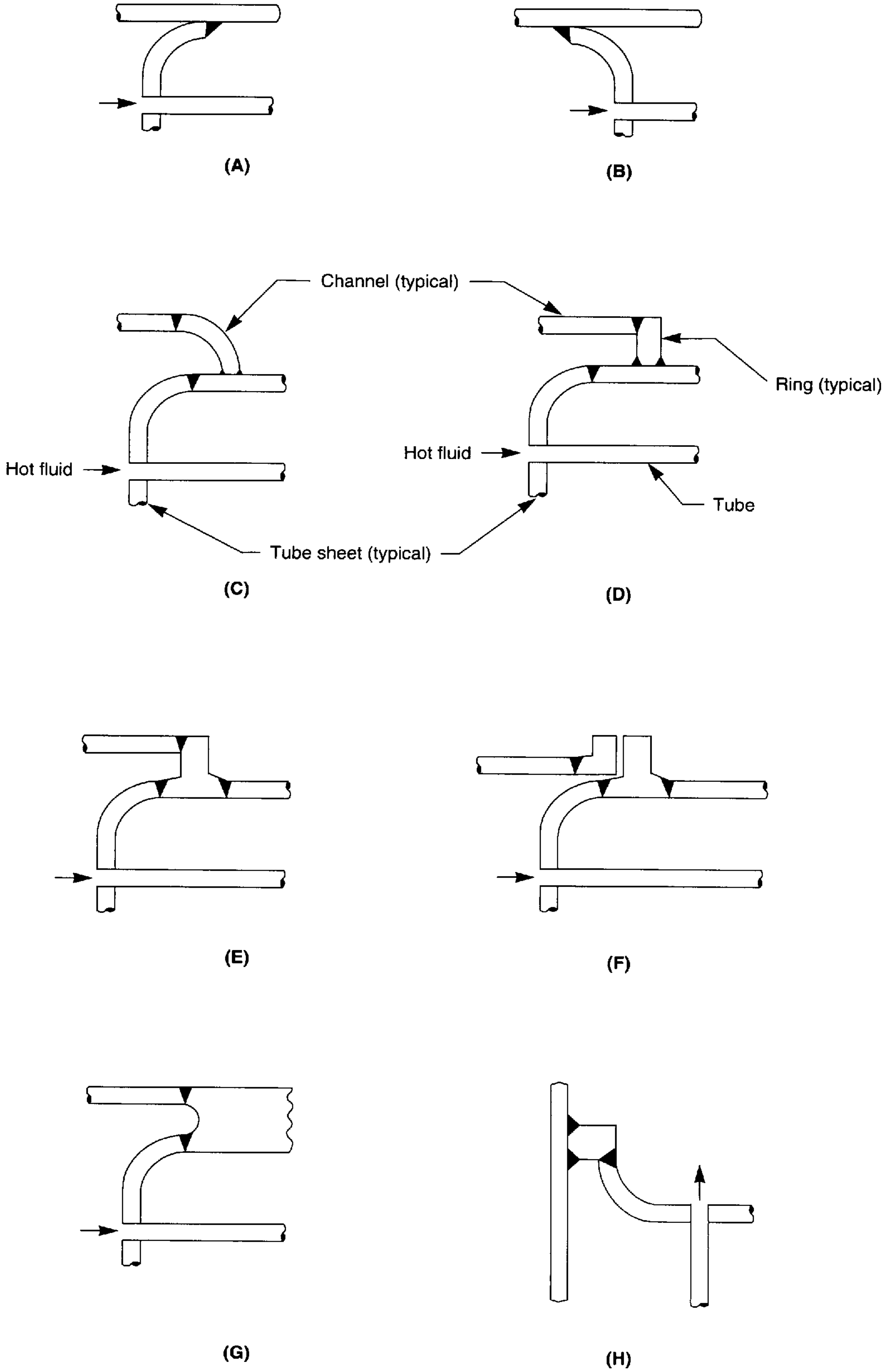



Figure 8—Channel-Tubesheet-Shell Interconnection

#### 2.6.1.12 Gas Bypass Systems

Gas bypass systems for boiler outlet temperature control may be external or internal to the boiler. Internal bypasses are commonly used because they take advantage of cooling the bypass pipe with boiler water. The pipe may be internally insulated to ensure that the metal temperature is maintained close to the water temperature. In high steam pressure applications the pipe may be attached to a transition knuckle in each tubesheet to absorb axial loads. The pipe is located in the center of the tube layout to provide for axisymmetric distribution of loads.

An automatically controlled valve is furnished at the outlet end of the gas bypass pipe. To reduce the size of the pipe and valve and to increase the flow control range, a plate with adjustable dampers may be installed in the outlet channel. By setting the dampers to a more closed position, the additional pressure drop imparted to the main gas stream encourages flow through the bypass. The outlet channel should be refractory lined or provided with internals to preclude the possibility of impingement of hot bypass gas on the channel wall. A typical internal bypass system is shown in Figure 11. Other systems are available.

#### 2.6.1.13 Risers and Downcomers

Adequate quantity, size, and proper location of risers and downcomers are essential for reliable operation of high temperature, high flux firetube HRSGs. Setting the steam drum elevation, sizing the interconnecting circulation piping, and positioning the connections are an integral part of the design.

Riser and downcomer design and connection positioning depend on boiler orientation. Horizontal firetube HRSGs are usually furnished with multiple risers and downcomers. Connections are positioned to serve zones of equal steam generating capacity. For single pass boilers the connections tend to be more closely spaced at the hot end. At least one

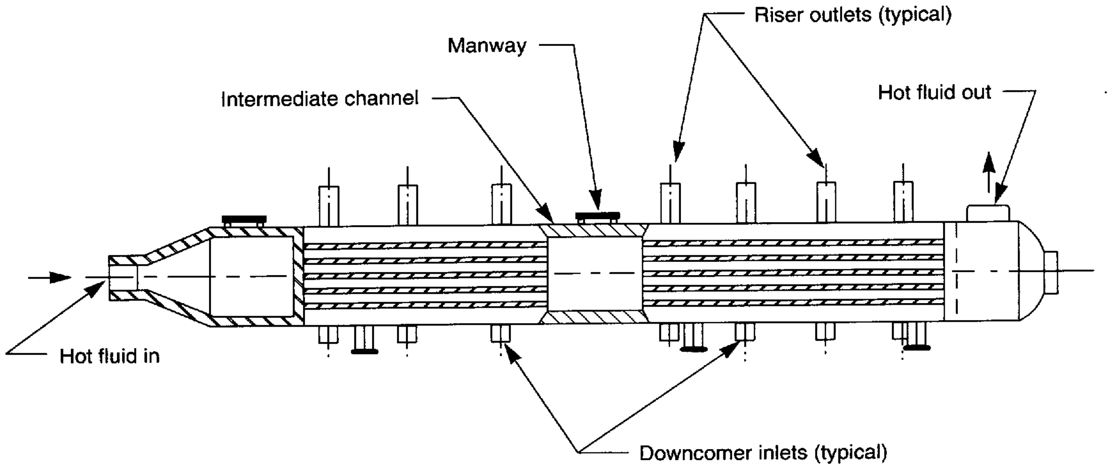



Figure 9—Dual Compartment Firetube HRSG

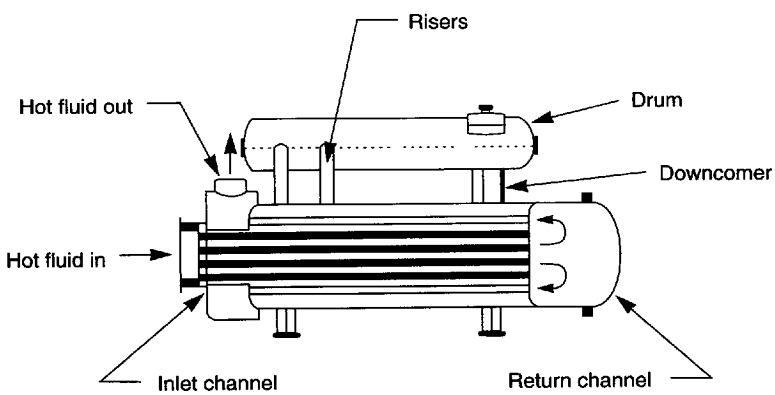



Figure 10—Two Tube Pass Firetube HRSG

riser and downcomer pair should be located as close as possible to the hot tubesheet.

Vertical units have one or more downcomer connections located at the bottom of the boiler shell. Of greater significance, however, is the construction at the top which must ensure ample and continuous wetting of the entire shell side face of the tubesheet. The following construction options may be considered to help avoid vapor blanketing beneath the upper tubesheet:

a. Multiple riser connections installed around the full circumference as high on the shell as possible.
b. Reverse knuckle tubesheets to permit further elevation of the riser connections relative to the tubesheet. Refer to Figure 8H.
c. Special baffling under the tubesheet to direct water across the back face of the tubesheet.
d. Special formed or machined upper tubesheet with a slight taper from the center upward to the periphery.
e. Installation of the entire boiler slightly canted from true vertical so that the tubesheet slopes slightly upward toward the risers which are located on that side.

### 2.6.2 KETTLE STEAM GENERATORS

Kettle steam generators are horizontally installed units with an enlarged shell side boiling compartment diameter relative to the tube bundle. The bundle penetrates through either a port opening in a conventional head, or the small end of an eccentric conical transition. The latter design is more common.

#### 2.6.2.1 Tube Bundle Construction

Tube bundles may be removable or fixed. Removable bundles offer certain advantages. The bundle may be removed for inspection, cleaning, repair, or replacement. Also, removable bundles avoid the differential axial thermal expansion stress which occurs in fixed tubesheet designs.

Removable bundles may be of either U-tube or floating head construction. For fluids prone to fouling or erosive process fluids that may require mechanical cleaning or inspection, the floating head type is preferred.

#### 2.6.2.2 Tube Size, Arrangement, and Number of Passes

Typical tube diameters are $^3/_4$ inch and 1 inch, although larger sizes are considered for highly prone to fouling or viscous process fluids such as in sulfur condensers. Tubes are arranged on either a square or triangular pattern. The square arrangement is used if cleaning of the outside tube surface is anticipated, as could be the case for generating low pressure steam from poor quality boiler water. In such cases $^1/_4$ inch minimum width cleaning lanes are maintained between tubes. Otherwise, a pitch to diameter ratio of 1.25 is normally used, unless heat flux considerations require a more extended spacing.

Multiple tube passes may be used for all bundle types described in 2.6.2.1, except for cases with extremely long hot fluid cooling ranges which may experience severe thermal stress. Single pass tubes are basically limited to fixed tubesheet construction.

#### 2.6.2.3 Channel Construction

The selection depends primarily on the anticipated frequency of opening the unit for inspection or cleaning. If frequent access is required, a channel with bolted cover plate is desirable. Channels may be any of the TEMA designated types.

#### 2.6.2.4 Shell Construction for De-Entrainment

A degree of disengagement of liquid is achieved in the steam space above the liquid level. The effectiveness of this volume is a function of the free height available. A typical minimum height is 20 inches in steam generating equipment. Units which produce very low pressure steam or operate at relatively high flux tend to need additional height. Simple dry pipe devices are sometimes used to enhance separation.

A properly sized kettle shell produces steam of adequate quality or purity for most process and heating applications. Higher purity steam may be achieved by the installation of separators in the vapor space above the liquid level, within a

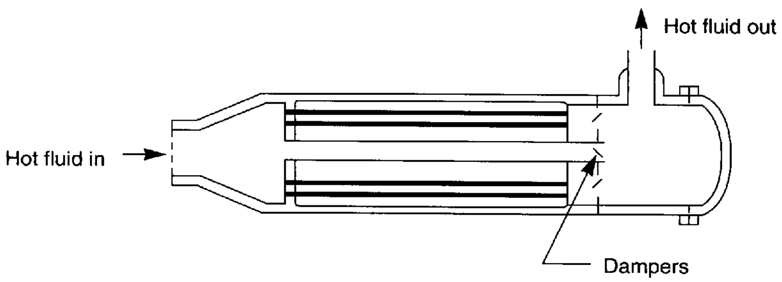



Figure 11—Internal Bypass System with Valve and Damper

dome welded to the top of the kettle, or in the exit vapor line. Types of separators include:

a. Wire mesh pads.
b. Chevrons.
c. Cyclones.
d. Combinations of Items a, b, and c.

Refer to Appendix A for further information.

### 2.6.3 OTHER TYPES OF FIRETUBE HRSGS

There are many other types of firetube HRSGs designed for a variety of services. They may be further classified as follows:

a. Proprietary designs developed for specific process applications.
b. Boilers designed with TEMA tubesheets and external drums. The boilers may be installed in the horizontal or vertical position.
c. Partially tubed horizontally installed boilers as shown in Figure 12. Tubes omitted from the top portion of the tubesheets provide the steam space for internal disengagement. The channel diameter is larger and the shell diameter is smaller than those of kettle HRSGs. Tubesheets may be TEMA, or stayed thin.

### 2.6.4 CODE CONSIDERATIONS

Firetube HRSGs are designed in accordance with either ASME *Boiler and Pressure Vessel Code,* Section I or Section VIII, Division 1.

Heavy tubesheet firetube HRSGs are normally designed to TEMA requirements. ABMA guidelines are commonly followed for boiler feedwater treatment, allowable concentration of boiler water dissolved solids, blowdown, and steam purity.

### 2.6.5 CONSTRUCTION MATERIALS

Materials selected for use in firetube HRSGs must be compatible with the process fluid, the boiler water, and steam with which they will come into contact. The materials must also exhibit mechanical properties consistent with the design requirements of the equipment.

#### 2.6.5.1 Corrosion Resistance

Each process fluid from which heat is being recovered has its own composition and may therefore have its own unique requirements for construction materials. An important factor in materials selection is often resistance to hydrogen attack, because many high temperature process gas streams have significant hydrogen content. The specification of materials must also account for the possibility of gas cooling below its dew point, and the corrosive acids which may be formed. Cold metal surfaces can cause local condensation, even though the bulk gas may be above the dew point.

Pressure components wetted by boiler water, including tubes and tubesheets, are normally fabricated from ferritic materials. Boiler shells are generally carbon steel. Materials subject to stress corrosion cracking, such as austenitic stainless steels, are normally avoided and are prohibited in the evaporator by ASME *Boiler and Pressure Vessel Code,* Section I.

The relative growth of the shell and tubes due to temperature changes is of considerable significance to firetube HRSG design. Materials with similar coefficients of thermal expansion are beneficial. This is another reason for avoiding the use of austenitic tubing.

## 2.7 Operations Description

Safe and reliable operation of firetube HRSGs depends on the development and use of good operating procedures, specific to the process and HRSG design.

### 2.7.1 PROCESS SIDE OPERATION

**2.7.1.1** New refractory lining may require a special heating sequence on start-up to effect proper dryout.

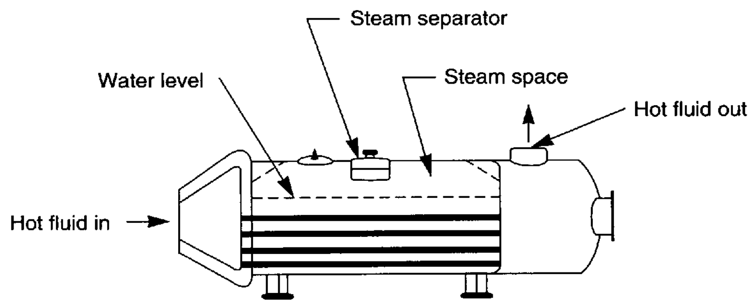



Figure 12—Partially Tubed Firetube HRSG

**2.7.1.2** Firetube HRSGs must not be subjected to hot gas flow unless the tube bundle is fully covered by boiler feedwater.

**2.7.1.3** The rate of temperature change during transients should be controlled to minimize the potential for thermal shock.

**2.7.1.4** All modes of operation should be evaluated during the design phase, particularly with regard to the ability of the boiler components to withstand the primary and secondary stresses during cyclic operation.

### 2.7.2 STEAM SIDE OPERATING CONCERNS

#### 2.7.2.1 Reliability of Boiler Feedwater Supply

Of primary importance to the successful operation of firetube HRSGs is the reliable supply of boiler water to the heat transfer surface. In the event of boiler feed water supply failure, the control system must shut off the hot stream flow to the HRSG. Refer to Appendix A for further information.

#### 2.7.2.2 Boiler Feedwater Treatment

Boiler feedwater chemical treatment must protect boiler components from water side corrosion. Improper treatment, or upsets, may cause premature failure. Water treatment specialists are normally consulted.

#### 2.7.2.3 Continuous Blowdown

Blowdown of boiler water must be used in conjunction with boiler feedwater treatment to ensure that boiler water impurities are maintained at or below recommended maximum concentration. Continuous surface blowdown may be accomplished through a perforated collector pipe located just below the water-steam interface or a connection at the shell bottom. Continuous blowdown from kettle HRSGs should be extracted primarily from the end opposite the feedwater inlet where impurities would be most concentrated.

#### 2.7.2.4 Intermittent Blowdown

Intermittent blowdown acts to remove settled accumulations of boiler water solids. Connections are located at low points in the shell, particularly in the most stagnant regions. Blowdown valves are operated at prescribed intervals, depending on the effectiveness of boiler water treatment.

#### 2.7.2.5 Liquid Level in Kettles

There is no clearly defined water-steam interface inside the shell. Steam bubbles rise vigorously through the water from the heat transfer surfaces. A density difference exists between the two phase mixture in the boiler shell and the liquid in an external gage glass. To ensure submerged tubes, the water level is normally maintained at 2 inches to 4 inches above the top of the uppermost tube row.

# SECTION 3—VERTICAL SHELL/TUBE WATERTUBE HRSGs

## 3.1 General

**3.1.1** A vertical shell/tube watertube HRSG is a vertical tube-bundle heat exchanger where steam is generated inside tubes by a shell-side hot fluid.

**3.1.2** Floating head, U-tube, or bayonet and scabbard tube construction are types of vertical shell/tube watertube HRSGs. See 3.5. Figures 13 and 14 are typical floating head and bayonet/scabbard types of vertical shell/tube watertube HRSGs. Other configurations may be used.

**3.1.3** Hot fluid can enter the shell from either the top or the bottom. The shell is usually a one pass shell TEMA type E arrangement. The steam/water side is a one pass system through the tube bundle or a two pass system through the U-tube and bayonet/scabbard designs.

**3.1.4** The vertical shell/tube watertube HRSG can be either natural circulation (thermosiphon) or forced circulation (pumped). The U-tube arrangement is always forced circulation. For either flow arrangement, the two phase steam/water mixture is separated in a steam drum. The separated water is recirculated back to the tubes. Weight percent of steam generated ranges from about 5 percent to about 20 percent of the total water circulated. Refer to Appendices A and B for steam drum and circulation considerations.

## 3.2 Application

**3.2.1** Vertical shell/tube watertube HRSGs are typically used to generate steam from hydrocarbon gases or liquids, catalyst-laden flue gases, and viscous process fluids. Vertical shell/tube watertube HRSGs are generally suitable for either clean or fouling shell-side fluids. Highly fouling or very dirty fluids, however, may be better suited for tube-side designs since these types are more easily cleaned. To facilitate cleaning the shell-side of bundles in fouling or dirty service, use removable tube bundles with square or rotated square pitch and $\frac{1}{4}$ inch minimum cleaning lanes. Shell-side velocities above 1 foot per second are preferred to minimize fouling. To avoid laminar flow and low heat transfer coefficients, vertical shell/tube watertube HRSGs are used where the shell-side fluid viscosity exceeds 10 centipoise.

**3.2.2** Any pressure steam may be generated, but these HRSGs are particularly suitable for high steam pressures.

## 3.3 System Consideration

**3.3.1** For natural circulation, the steam drum must be higher than the top tube opening of any of the steam generating tubes.

**3.3.2** High purity water is particularly important for the long-term operation and reliability of bayonet/scabbard designs. Deposits in bayonet/scabbard designs might insulate the tips of the tubes causing overheating and failure. U-tubes are also sensitive to deposits because of difficulty in cleaning. See Table A-1 for boiler water quality and associated steam purity.

**3.3.3** Vertical shell/tube watertube HRSGs may weigh less than fire tube designs. Examples are designs where steam pressure is 1500 pounds per square inch or greater and the process hot stream is 600 pounds per square inch or lower. API Recommended Practice 521 requires that the low pressure side design be raised to two-thirds the high pressure side design pressure to protect against tube rupture.

As an alternative to designing the shell side for two-thirds the high pressure side design, the shell can be protected against overpressurization by a relief valve. The shell side design pressure can then be based on the process stream conditions. The lower design pressure results in lower shell weight.

**3.3.4** Special features are required in design or operation to protect the HRSG in event of water failure.

**3.3.5** The tube side of U-tube bundles are difficult to clean via rodding around the U-bends. The tubes are susceptible to

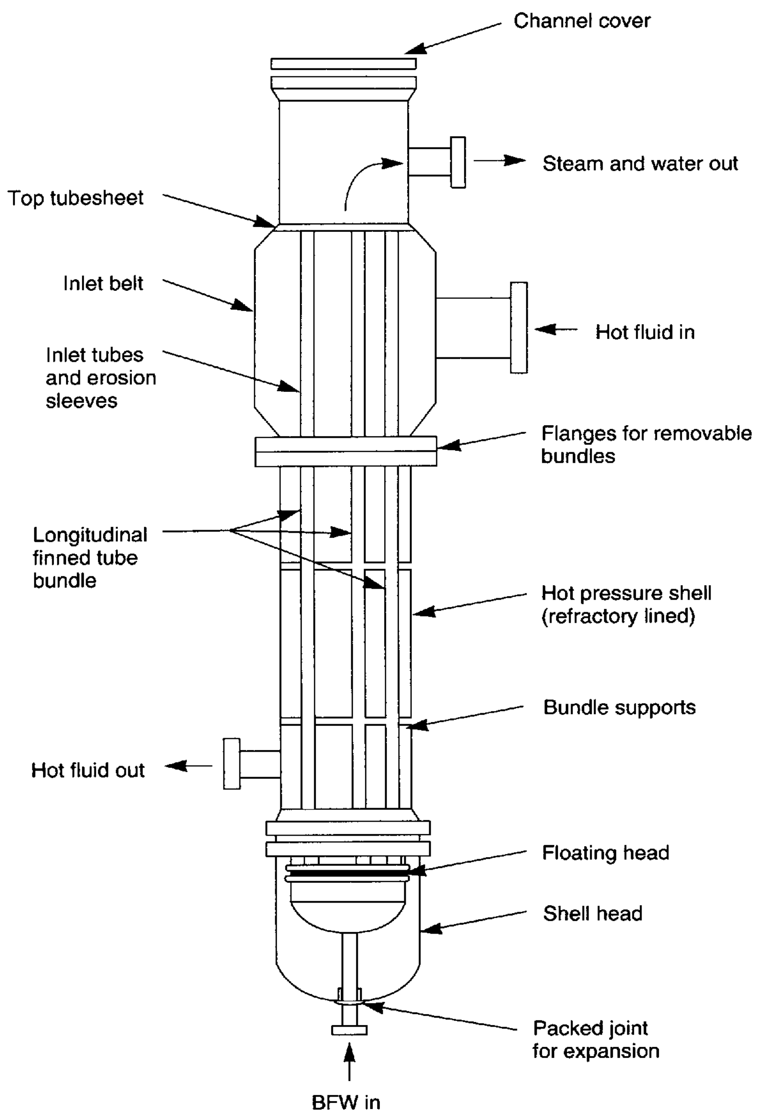



Figure 13—Vertical Watertube Floating Head HRSG

scale, deposits, and debris because of the small inside tube diameter and orientation of the tubes. Such debris may collect at the low point in the U-bend. Downcomer strainers may be installed to minimize tube plugging from large foreign objects.

Bayonet tube designs have a restrictive annulus between the tubes. This requires extra care in keeping debris out of the system which could block flow to a tube. A strainer is generally required in the water supply piping at the steam generator entrance in these cases.

## 3.4 Advantages of Vertical Shell/Tube Watertube Over Firetube HRSGs

**3.4.1** Vertical shell/tube watertube HRSGs can be designed for higher maximum heat flux than firetube HRSGs since flow distribution and steam generation are more uniform. See Table B-1 for heat flux comparison of watertube HRSGs versus firetube HRSGs.

**3.4.2** If multiple risers are required, they can each be arranged to have the same proportion of total flow. In high pressure systems, equal flow in each riser provides more uniform distribution to facilitate better performance of the steam drum.

**3.4.3** The tube bundle is free to expand so stresses from differential expansion between the tubes and shell are not large. This is particularly true of the bayonet tube design where each tube can expand independently without inducing tubesheet stresses from differential expansion between adjacent tubes.

**3.4.4** The vertical shell/tube watertube HRSG requires no refractory lining of the tube side channel or floating head

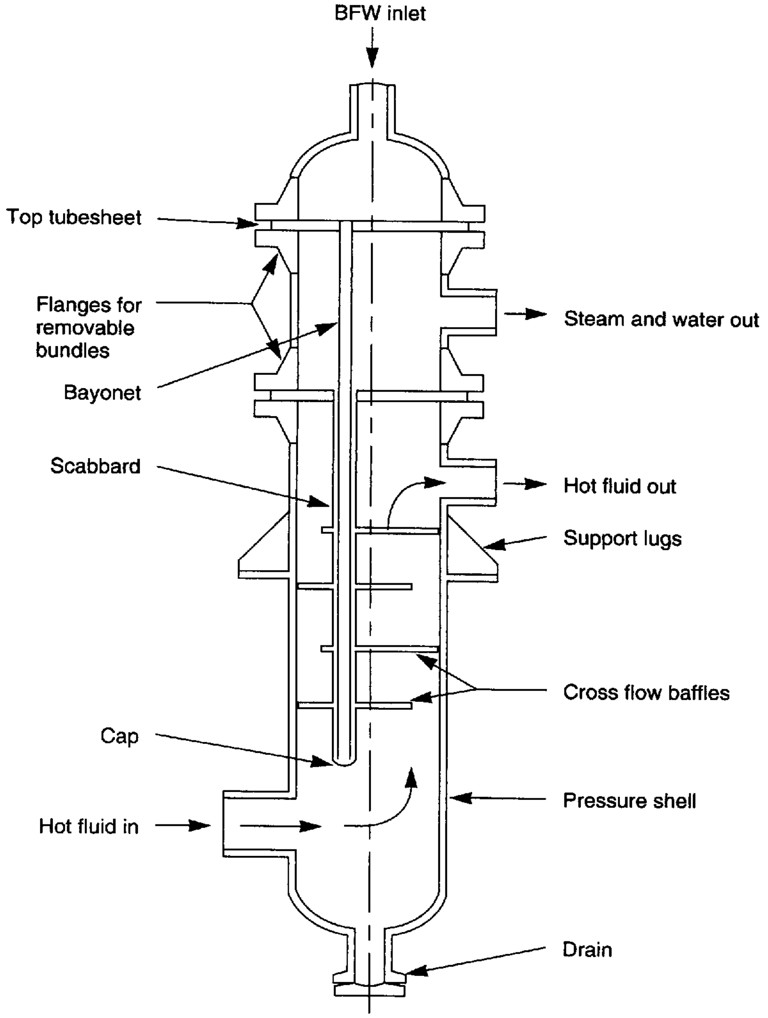



Figure 14—Bayonet Exchanger HRSG

tubesheet face. In the event of a single pass bare tube failure, no refractory has to be removed to repair the failed tube.

**3.4.5** If U-tube and bayonet tube designs have tubesheets at the outlet (cold end) of the shell, the tubesheets can be designed with lower alloy metallurgy than when located at the inlet or hot end of the shell.

**3.4.6** In the event of tube failure for bayonet tube units, the bayonet tube bundle and tubesheet can be removed to access the scabbard tube or tubes that failed.

**3.4.7** Spare tube bundles will enable quick turnaround since the damaged bundle can be quickly pulled and the spare bundle installed to allow the unit to be put back on stream.

## 3.5 Mechanical Description

### 3.5.1 FLOATING HEAD

The bottom tubesheet is a floating head configuration with a nozzle that passes from the floating head through the shell head to allow water to be fed from the bottom. The feed water is heated and becomes a two-phase mixture as it passes through the heated zone and enters the top channel. After one pass through the exchanger, the steam/water enters a steam drum. The hot fluid may be concurrent or countercurrent on the shell side. An expansion joint in the floating head inlet nozzle and the floating head are provided to compensate for thermal expansion between shell and tube.

### 3.5.2 FIXED TUBESHEET

The shell of the heat exchanger may contain an expansion joint to allow for differential thermal growth between the tubes and the shell.

### 3.5.3 U-TUBES

A U-tube vertical shell/tube watertube HRSG consists of a vertical shell with a channel at the top. Inside is a traditional U-tube bundle. Water enters the channel, flows down the inlet leg and up the outlet leg of the U-tube. The heating fluid flows up or down through the bundle shell side. The U-tube bundle is free to move in response to thermal growth and is not affected by the shell thermal growth.

### 3.5.4 BAYONET TUBES

The bayonet vertical shell/tube watertube HRSG employs a set of concentric tubes. The smaller diameter tube is called the bayonet, and the larger diameter tube is called the scabbard. The scabbard tube pattern may be a standard triangular or square pitch. Each scabbard tube is inserted through two tubesheet holes and attached. The end of the scabbard tube is capped.

The bayonet tube and tubesheet pattern are identical to the scabbard pattern. The bayonet tubes are attached to this tubesheet and are not capped.

The two bundles are assembled so that each bayonet is inserted into its corresponding scabbard. The tubesheets are separated axially by a channel spacer piece. Refer to Figure 14.

## 3.6 Operations Description

The boiler feed water enters the bayonet channel compartment, flows down through the bayonets, up the scabbard annulus to the lower channel compartment, and then out into a steam/water riser. The double channel bundle is inserted into a vertical flanged shell. The process heating stream enters the shell at the bottom below the ends of the scabbard bundle and flows up through the bundle, exiting the shell at the top just beneath the scabbard bundle tubesheets.

# SECTION 4—WATERTUBE COILS INSIDE PRESSURE VESSELS

## 4.1 General

**4.1.1** Watertube coils may be located either horizontally or vertically inside a vessel. The vessel contents are the heat source. Figure 15 shows a horizontal arrangement.

**4.1.2** The coils are supported inside the vessel at several parallel levels.

**4.1.3** The coils may be fabricated of either pipe or tubing.

## 4.2 Application

A typical example is a cat-cracker catalyst regenerator equipped with a fluidized bed of catalyst at 1300°F to 1400°F. This catalyst is a large source of heat to generate steam within the coil(s).

## 4.3 System Consideration

**4.3.1** Frequently the coils are designed with multiple tube side flow passes. In these cases, the cross-section flow area, the heat transfer surface area of each pass, and the water flow rate to each pass should be identical. Design inlet flow velocity in each pass should be in the range of 3 to 7 feet per second.

**4.3.2** The heat transfer parameters, such as transfer rate, circulation ratio, and specific flow rate, must be selected to ensure nucleate boiling.

**4.3.3** The design of the coils is quite critical. Conservative practice dictates careful choice of coil inside diameter, length, and heat flux to arrive at a satisfactory and operable system to avoid film boiling, vapor lock, or unstable flow conditions. During process upsets, such as cessation of bed fluidization or circulation, loss of steam generation may occur in one or more of the individual parallel passes. The system design shall consider this possibility.

**4.3.4** Forced circulation is recommended to ensure a fixed flow rate to each coil with a minimum circulation ratio of 5:1.

**4.3.5** An annular flow regime is desired. If annular flow cannot be achieved, special inserts may be installed to ensure wetted walls.

**4.3.6** The system shall be designed with the water side pressure always being greater than the shell side pressure.

**4.3.7** Applications may exist where flow measurement or control may be required on individual water side passes of multipass coils. Isolation of individual passes may be considered, although the loss of cooling may damage the coil.

## 4.4 Mechanical Description

The coil shall be designed to meet the requirements of the applicable ASME code. Thermal stresses and mechanical loads must be considered in designing the coils.

## 4.5 Operations Description

**4.5.1** Proper drum water treatment must be exercised to avoid having water side deposits. Such deposits would lead to high tube metal temperatures, loss of thermal efficiency, and ultimate tube failure. Water side deposits may also lead to possible pump failure. Where several parallel steam generation coils are required to make up a total steam rate, a careful choice of control valve location is necessary to ensure balanced flow. Since the heat transfer environment in which the steam generating coils are located is a severe service, orifices balance flow at the inlet of each parallel coil. Control valves must be provided there also to shut down specific coils in the event of a break or leak from the coil.

**4.5.2** Pressure relieving devices may be required on the vessel to protect the vessel in the event of coil failure.

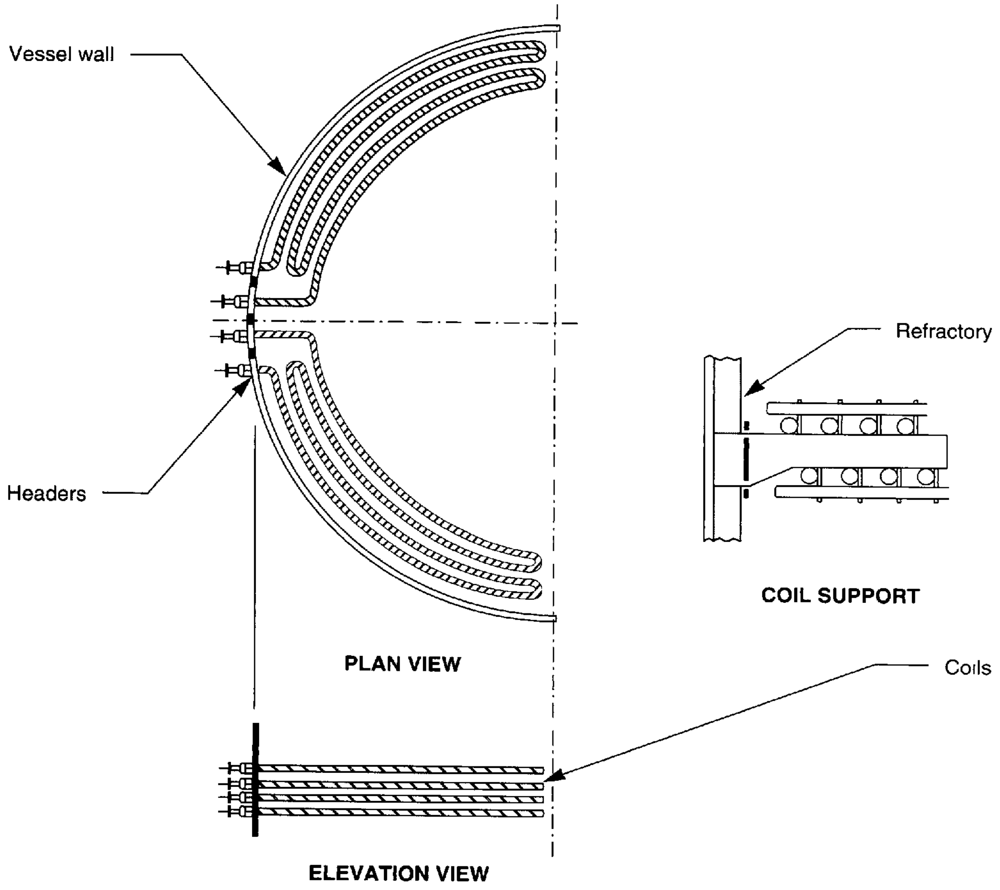



Figure 15—Pipe Coil HRSG Inside a Pressure Vessel

# SECTION 5—WATERTUBE LOW PRESSURE CASING HRSG

## 5.1 General

### 5.1.1 TYPICAL SYSTEM

The watertube low pressure casing HRSG generates steam inside a number of tube circuits that are heated by a hot gas stream flowing through an enclosure of insulated steel casing plate.

The gas normally flows across the tubes in a single pass from inlet to outlet. In certain cases, baffles or directional vanes may be used to direct the gas across the tubes creating additional gas passes.

Steam generating tubes are connected to drums or headers. The tubes may be arranged in one continuous circuit or may be manifolded at their inlet and outlet ends to form a number of parallel flow paths.

Steam drums may be either integral to the steam generating tube circuit or mounted remotely from the tubes.

Additional tube circuits may be used for preheating feedwater or superheating steam.

## 5.2 Application

The watertube low pressure casing HRSG is used to recover heat from low pressure exhaust or flue gases. Some common applications are:

a. Heat recovery from combustion turbine exhaust gas to produce steam for use in process(es), in enhanced oil recovery, and in cogeneration.
b. Heat recovery from fired heater flue gas to produce steam.
c. Heat recovery from fluid catalytic cracking regenerator flue gas to produce process steam.

The casing shall be designed with tight joints, preferably seal welded, to prevent gas leaks to the atmosphere. Some minor leakage may occur at casing penetrations where thermal growth must be accomodated. The watertube low pressure casing HRSG is not used in services where leaks of the exhaust or flue gas would not be permissible.

## 5.3 System Consideration

The watertube low pressure casing HRSG may generate steam at a single pressure level or multiple pressure levels. Generating at multiple pressure levels may increase the effectiveness of recovering the heat from the gas and will provide steam for various plant needs.

Combustion turbine HRSGs used in cogeneration or combined cycle power plants often generate steam at two or three pressure levels. Each pressure level may have its own economizer, evaporator, or superheater section.

Multiple pressure level combustion turbine HRSGs often produce high pressure steam for steam turbines, intermediate pressure steam for injection into combustion turbines for $NO_x$ control or induction into steam turbines, and low pressure steam for deaerators.

When steam requirements are greater than can be obtained with the heat available from a combustion turbine exhaust gas, supplementary firing can be used to increase the available heat.

If steam is required when the combustion turbine gas flow is curtailed, fresh-air firing (see 5.6.11) with ambient combustion air can be used to generate steam.

A gas bypass system can be provided to isolate the gas source from the HRSG. This will allow independent operation of the gas source or HRSG. A combustion turbine can be started with the gas bypassed to the atmosphere for rapid start-up. Modulating the gas can also reduce the thermal shock of start-up to the HRSG or control the HRSG steam output.

The gas may be slightly above or below atmospheric pressure. Combustion turbine exhaust static pressures are typically in the range of 8 inches to 16 inches $H_2O$ and the HRSG casing design pressure is typically 20 inches $H_2O$. Fired heater flue gas pressures are normally slightly below atmospheric pressure. Fluid catalytic cracking regenerator flue gas pressure may be 1 pound per square inch gauge or greater. The HRSG casing is normally limited to gas pressures of 5 pounds per square inch gauge or less due to the practical strength of the gas path enclosure casing.

For combustion turbine HRSGs, the gas pressure drop should be optimized considering the reduction in combustion turbine output with increased back pressure and the enhanced heat recovery with increased gas pressure drop in the HRSG.

Combustion turbine exhaust gas temperature may range from 750°F to 1100°F. When supplementary fired, the gas temperature entering the HRSG may be as high as 1800°F without water wall construction.

The gas temperature exiting the HRSG is normally in the range of 250°F to 500°F. The exit gas temperature depends on feedwater temperatures, steam requirements, and corrosion considerations. The exit gas temperature should be above the water and acid dew point of the gas to avoid excessive corrosion of the casing.

To prevent corrosion, the temperature of tube and fin surfaces exposed to the gas should be maintained above the water and acid dew points unless special metallurgy is used.

Feedwater preheat sections are sometimes bypassed (run-dry) when firing oil to prevent corrosion of the section.

Feedwater preheat coils may contain water that has not been deaerated. Tube metallurgy other than carbon steel may be required.

For environmental consideration, HRSGs are often required to contain emission control equipment such as selective catalytic reduction systems for $NO_x$ control.

Emission control systems are located within the HRSG such that the flue gas temperature range in the system is correct for a selective catalytic reduction system operating temperature range. The location and operating temperature range is influenced by gas turbine/supplementary firing modes of operation.

When fouling is anticipated, cleaning provisions may be required. The configuration of the heat transfer surface may have to be modified to enhance cleaning.

Protection from freezing is especially important for HRSGs used in cyclic service. Provisions for rapid start-up may also be included such as steam sparging or steam coil heating in drums to maintain the pressure components in a warm condition.

## 5.4 Advantages

The HRSG can recover energy otherwise exhausted to the atmosphere rather than burning fuel in a fired boiler, reducing plant fuel consumption and emissions.

The low pressure steel casing design permits very large units that can handle high volumes of hot gases and produce large quantities of steam.

The HRSG is capable of rapid start-up.

The configuration may be varied to suit plant equipment and plot requirements. Different process steam users can be supplied from one piece of equipment.

Emission control equipment can be incorporated in the low pressure casing HRSG at optimum operating temperatures. Other HRSG types may not have this capability.

## 5.5 Disadvantages

The watertube low pressure casing HRSG is not suitable for small gas volumes.

The HRSG casing is limited to designs requiring 5 pounds per square inch gauge or lower.

HRSGs not enclosed in buildings must be winterized when installed in cold climate locations.

## 5.6 Mechanical Description

### 5.6.1 HORIZONTAL TUBE EVAPORATOR

The flow within a horizontal tube evaporator normally is forced circulation as described in Appendix B, and Figures 16 and 17. The steam drum is mounted remotely from the tubes.

It is possible to establish natural circulation through horizontal tubes by elevating the water outlet from the steam drum sufficiently above the tubes. However, hydraulic resistance and vapor blanketing in the tubes are potential problems. Forced circulation flow is generally preferred for horizontal tubes.

### 5.6.2 VERTICAL TUBE EVAPORATOR

The flow within a vertical tube evaporator normally is natural circulation as described in Appendix B and Figures 18 and 19. Downcomers can be external to the gas stream connecting the upper drum and lower drum. Downcomers can also be located within the gas stream. Circulation rates must consider heat input to an internal downcomer.

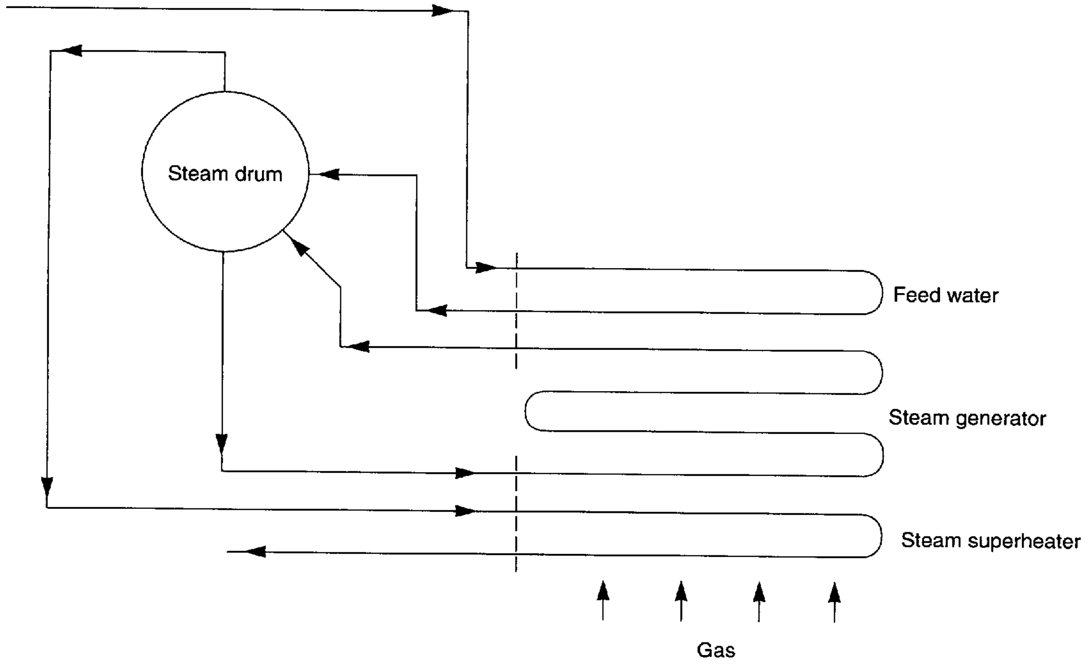



Figure 16—Basic Tubular Arrangement

### 5.6.3 INCLINED TUBE EVAPORATOR

The flow within inclined tube evaporator arrangements is from a lower drum or header upward through parallel inclined tubes to a collector drum, header, or the steam drum. Natural circulation is utilized, similar to that described for vertical tubes. The slope of the tubes and the configuration of the drums, headers, tubes, and exhaust gas path is critical to proper operation of an inclined tube arrangement.

### 5.6.4 PREHEATERS, ECONOMIZERS, AND SUPERHEATERS

In addition to the evaporator, the HRSG may include an economizer section to heat the feedwater and/or a superheater section for superheating steam. (See Figures 16, 17, and 19). Multiple pressure level HRSGs may have economizers or superheaters for more than one pressure level.

A steam reheater, feedwater preheater, or a deaerator/steam generating coil may be included at appropriate exhaust gas temperature locations.

The exhaust gas normally passes over the superheater, steam generator, and economizer (in that order) to optimize the heat transfer effectiveness of the HRSG. Alternative arrangements may be used, such as integrating economizers, evaporators, and superheaters of different pressure levels to optimize heat transfer rather than locating the sections of each pressure level together. Superheater sections may be located within steam generator sections to limit superheater tube metal temperatures or the variation of superheated steam temperature with variations in gas flow or temperature.

### 5.6.5 STRUCTURE AND CASING

The gas path enclosure is normally a rectangular box enclosed on four sides with steel casing plate and open on both ends for entry and exit of the gas stream. Figures 19 and 20 are examples of gas turbine exhaust and fired heater HRSG layouts, respectively. Transition ducts are normally provided at the inlet and exit of the HRSG for connection to the gas source and to a duct or stack exhausting to the atmosphere or gas cleaning system.

An external structural framework integral to the casing plate enclosure supports the tubes, headers, and steam drums. Vertical tubes and their drums or headers may be supported either from the top or bottom of the structure. Horizontal tubes may be supported by intermediate and end tube supports.

The gas path enclosure casing plate may be an internal casing or an external casing depending on whether thermal insulation is installed on the outside or inside of the casing plate.

External pressure casing designs are suitable for gas temperatures to 1800°F. The carbon steel casing is protected from hot gas temperatures by the internal insulation. External casing designs are suitable for rapid start-up, with start-up rates dependent on the type of internal insulation system used.

Less common, internal casing designs of carbon steel may be suitable for gas temperature of approximately 750°F or

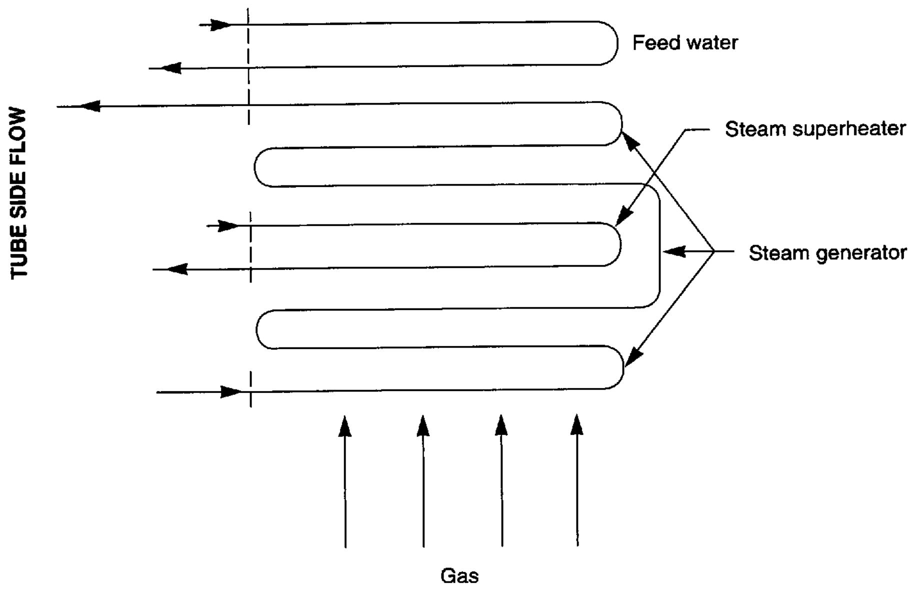



Figure 17—Interlaced Tubular Arrangement

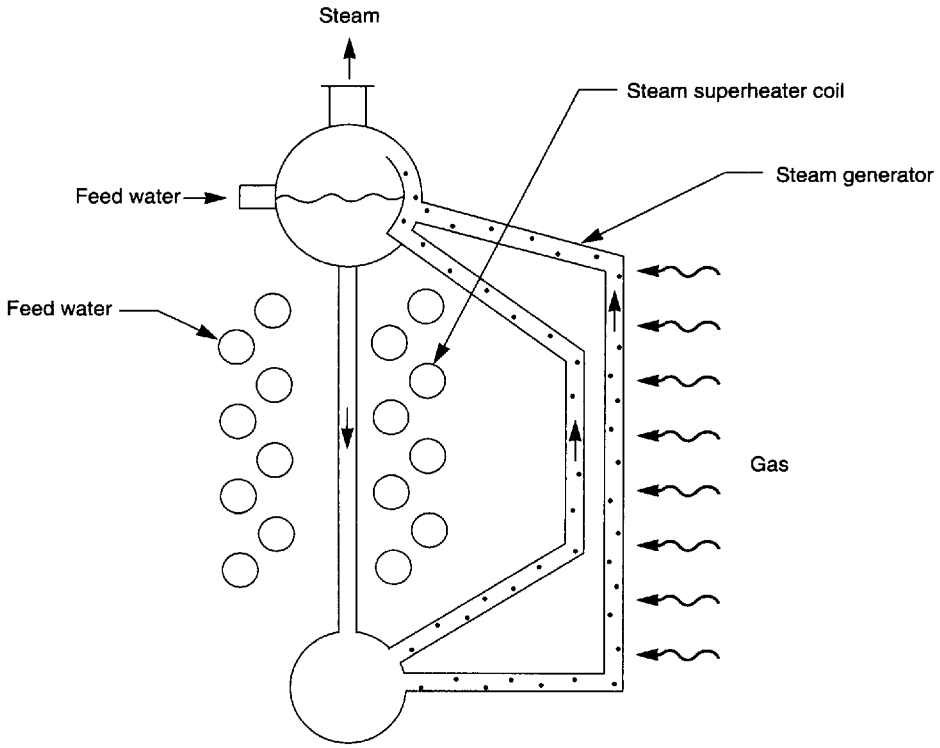



Figure 18—Natural Circulation HRSG

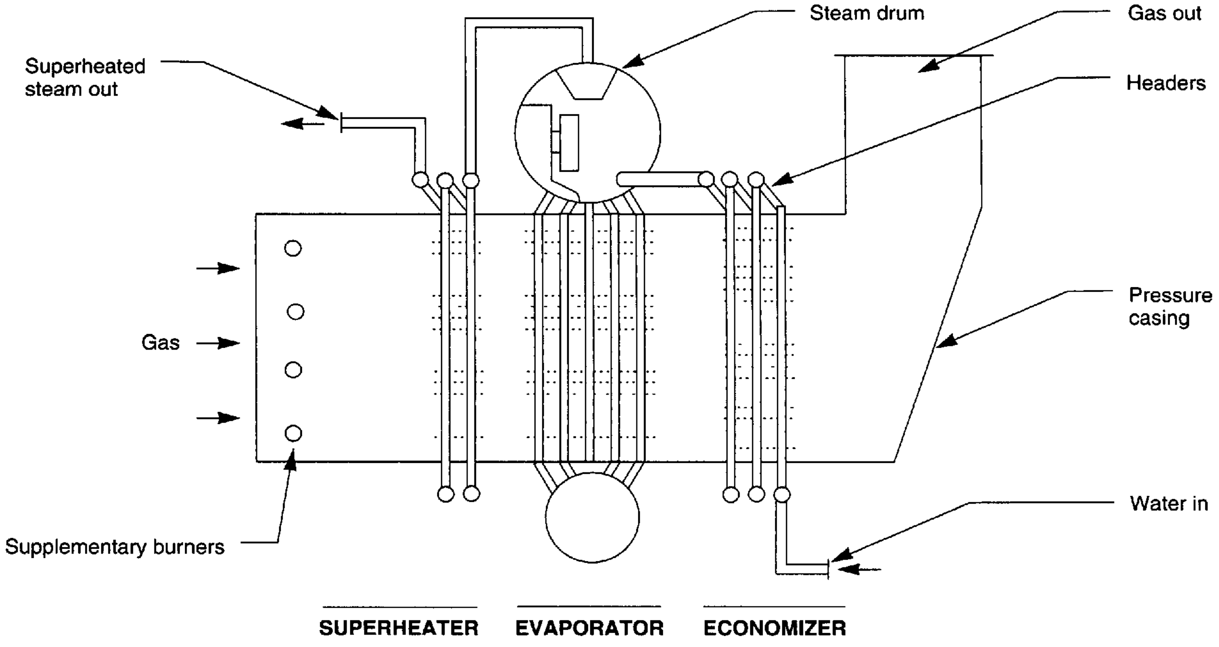



Figure 19—Typical Gas Turbine Exhaust Gas HRSG

lower. Thermal expansion stresses, thermal growth, and accelerated corrosion of the casing plate are considerations for internal casing designs. Carbon steel casing plate with increased copper content such as ASTM A 242 or A 588 may be used to improve corrosion resistance. Rapid start-up with internal casing designs must consider expansion capabilities due to the thermal stresses developed between the casing and structural supports or insulation.

### 5.6.6 INSULATION

Insulation is provided on the casing to minimize heat loss and provide personnel protection. If the gas temperature is above 750°F, an internal insulation system is normally used to protect the steel casing plate.

External insulation is normally block or blanket insulation with metal lagging for weather protection.

Internal insulation may be castable refractory, ceramic fiber, mineral wool block, or blanket insulation.

Internal castable refractory is normally used for fired heater or fluid catalytic cracking regenerator HRSGs. It is suitable for high gas velocities and resists erosion from tube cleaning devices. Various types of castable refractories are available for resistance to gas erosion and chemical attack. Castable refractories are suitable for HRSGs, particularly when the firing duct temperature exceeds 1600°F.

Internal block or blanket insulation is normally used for combustion turbine HRSGs. The insulation is normally a layered construction with the steel casing on the outside and a system of steel liner plates on the inside to prevent insulation damage from gas flow velocities or tube cleaning devices. The internal steel liner is constructed with panels overlapping in the direction of exhaust flow held in place by support pins and washers on the inside surface of the liner. The panels accommodate thermal expansion because the edges are free to slide over each other. Liner materials should be selected for gas temperatures and corrosion characteristics.

### 5.6.7 TUBES

Horizontal tube steam generators normally consist of multiple rows of tubes ranging in size from 1 inch to 4.5 inches outside diameter. The tubes may be headered into parallel passes. Tubes within the same pass are connected in series by return bends.

Natural circulation vertical tube steam generators normally consist of a group of parallel single tube circuits. Each tube is connected to the upper drum or header and a lower drum or header. Water enters each tube at the bottom and flows unobstructed vertically to the top drum or header. Tubes are normally 2 inches at the outside diameter.

Forced circulation vertical tube steam generators are commonly used for fluid catalytic cracking regenerator HRSGs. Multiple tube passes are used between the inlet and outlet headers. Tubes are connected with return bends.

The normal spacing between centers of adjacent tubes is two times the nominal tube diameter. The tubes in adjacent rows in the gas path may be arranged in an in-line or staggered pattern. For the same gas flow, staggered arrangements improve heat transfer over in-line arrangements, but gas pressure drop is increased.

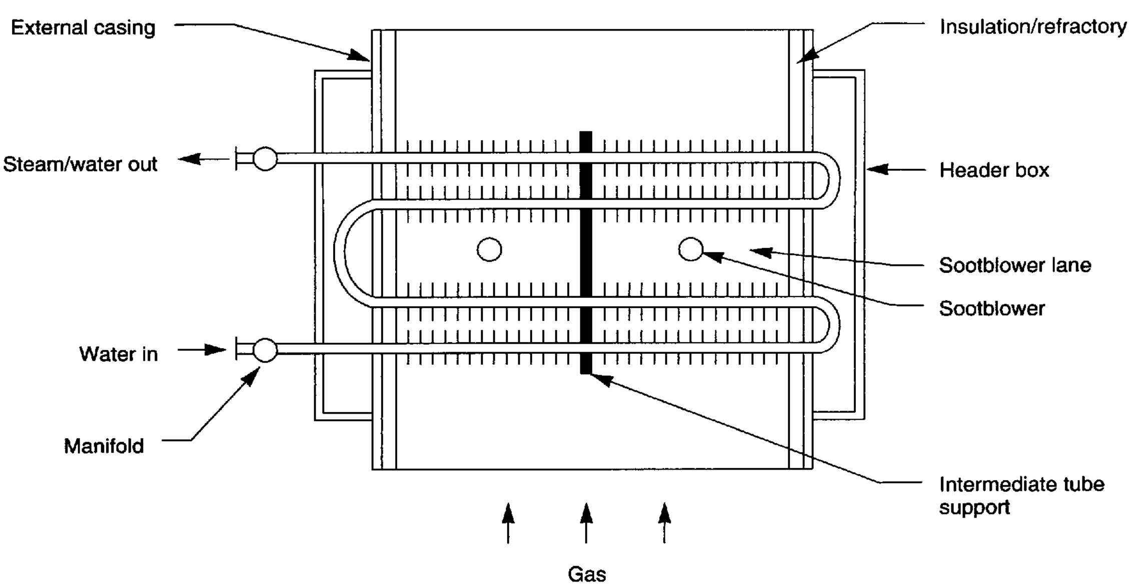



Figure 20—Typical Convection Section HRSG

Gas side extended surface is used to increase the heat transfer to the tubes. Welded spiral wound solid or serrated fins are normally used. Studs may be used when extreme fouling is expected.

The metallurgy of extended surface is selected for resistance to high temperature oxidation. Recommended maximum temperature for various materials are shown in Table 1.

A minimum temperature limit results from corrosion requirements. Keep the cold end metal temperature above the exhaust gas dewpoint to prevent acid attack of the metal. Metal temperatures required to avoid condensation and the resulting corrosion are shown in Figure 21.

### 5.6.8 PROVISIONS FOR CLEANING

Depending on the gas composition or type of fuel fired, particulate matter may be deposited on the outside surface of the tubes. Bare tubes are preferable if the foulant is adherent. Stud or fin configuration can be utilized and varied to minimize deposits and accommodate cleaning. Table 2 provides recommended fin configuration for various fuels and gases.

If external tube fouling is anticipated, cleaning provisions should be included. Access doors in the casing side walls are required to permit cleaning mechanically or with water

Table 1—Extended Surface Metallurgy

| | Maximum Extended Surface Metal Temperature, °F | |
|---|---|---|
| Surface Material | Studs | Fins |
| Carbon steel | 950 | 850 |
| 11–13% Cr | 1200 | 1100 |
| 18–8% Cr-Ni Tp 304 SS | 1500 | 1500 |
| 25–20% Cr-Ni Tp 310 SS | 1900 | 1900 |

Table 2—Fin Design

| Fuel or Gas | Minimum Thickness (inch) | Maximum Per Inch (number) | Maximum Height (inch) | Fouling Factor In./(Hr-°F-Ft.)/Btu |
|---|---|---|---|---|
| Natural gas | 0.05 | 6 | 1.0 | 0.001–0.003 |
| Distillate oil | 0.05 | 5 | 1.0 | 0.002–0.004 |
| Fouling gas | 0.05 | 5 | 1.0 | 0.002–0.004 |
| Heavy oil (No. 6) | 0.105 | 3 | 0.75 | 0.003–0.007 |
| Residual oil | 0.105 | 3 | 0.75 | 0.010–0.020 |
| Catalyst bearing gas | — | bare | — | 0.004–0.020 |

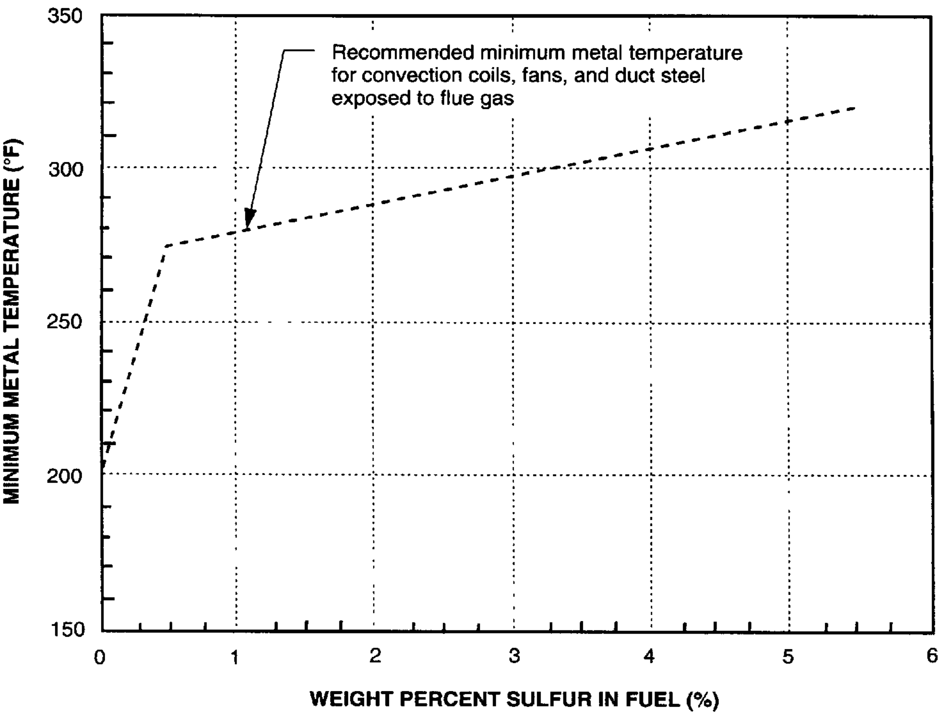



Figure 21—Recommended Minimum Metal Temperature

wash during maintenance shutdown. If heavy fouling is anticipated, the cleaning lanes should be equipped with automatic or manually operated sootblowers as described in Appendix C.

### 5.6.9 DAMPERS

A damper can be used for gas bypassing at the HRSG inlet. Tight gas sealing is important.

Guillotine dampers can be provided for isolating the HRSG from the gas source or for isolating individual HRSGs connected to a common exhaust stack. A double guillotine with gas-seal purge air can be provided to permit operation of the gas source or parallel HRSGs connected to a common stack while the HRSG is shut down for maintenance.

A damper can be installed in the gas outlet when the HRSG operates in cyclic service and is to be maintained in a warm standby condition when the gas turbine is not operating. The damper may be insulated.

### 5.6.10 SUPPLEMENTAL FIRING

Supplemental firing systems use the oxygen contained in the gas stream for combustion of the fuel.

A supplemental firing system is provided when gas turbine exhaust flow or temperature are insufficient to generate the required superheat temperature or steam flow rate. Increased gas temperature increases the temperature approach, that is, saturated steam temperature versus flue gas or economizer outlet temperature. Log mean temperature difference (LMTD) temperatures for the HRSG heat transfer surface also increase. Multiple pressure level HRSGs benefit similarly, especially the higher pressure sections. Flue gas heat available is reduced for the lower pressure steam. The effect is more pronounced with single-pressure level HRSGs than with multipressure level HRSGs.

Supplementary firing burners are normally grid duct burners for fuel gas and side-wall burners for fuel oil. Combination gas and oil firing can be accomplished by using both types of burners.

Grid burners are multiple fuel headers installed in a plane normal to the gas flow. Burners are equally spaced from each other and extend across the transition duct width. Fuel orifices or nozzles are installed over the length of each fuel burner header and flame stabilization is provided with diffuser plates upstream of the burner nozzle. Flame management systems including pilots and flame scanners are provided for each burner pipe.

Wall burners that are mounted in the duct sidewall fire transverse to the main gas flow. These burners are staggered and usually unopposed on the opposite wall, thereby allowing for long narrow flames. Flame stabilizing diffuser plates are installed upstream of the flames. The burner and combustion management system is similar to that of the grid burners. This burner may require a fan to supply its primary air. Oil firing is more easily handled with the wall burners than with grid burners.

### 5.6.11 FRESH-AIR FIRING

Fresh-air firing uses ambient air for combustion of the fuel. Forced draft systems are usually required to provide the air at sufficient pressure to overcome the gas pressure drop of the HRSG.

For combustion turbine HRSGs, fresh-air firing is used to produce steam when the combustion turbine is out of service. As a significant volume of fresh air would be required to produce the same amount of steam produced with the combustion turbine exhaust, the fresh-air firing system is often designed to generate only 50 percent of the HRSG rated steam capacity.

Fresh-air firing in combustion turbine HRSGs requires high temperature dampers in the exhaust gas stream and at the auxiliary burners. A damper and seal air fan is used to prevent exhaust gas leaks through the fan system, or the main combustion air fan must operate.

Fresh-air firing in combustion turbine HRSGs requires special attention in selection of the damper and fans.

Pilots, flame scanners, and a burner management system are required. Emergency automatic switch-over to fresh-air firing may be included.

Fresh-air firing can also be used in fired heater HRSGs. Since the flue gas is normally at less than atmospheric pressure, the flue gas does not leak to the atmosphere. Shutoff dampers are provided to prevent ambient air leaks into the HRSG. Forced draft burner systems are often used to provide automatic control of the burner and tight flame patterns.

### 5.6.12 EXPANSION JOINTS

Both corrugated metal bellows and fabric seal expansion joints are used to accommodate duct and casing expansion. Both designs rely on internal packed insulation to reduce the temperature of the expansion joint seal and external surface. The fabric seal expansion joint is preferred if significant lateral as well as axial expansions are anticipated. Expansion joints for HRSGs with internal liners should be designed without heavy metal components extending from the internal liner to the outside casing to avoid local overheating of the external casing plate.

### 5.6.13 GAS VELOCITY AND FLOW

Gas velocity in the HRSG is limited by gas side pressure drop and erosion of the casing insulation or heat transfer surface. At velocities below 20 feet per second, solids carryover, if present, will deposit on the heat transfer surface.

Higher gas velocities will create a self cleaning effect. Maximum gas velocities between tubes for minimizing erosion effects are shown in Table 3.

#### 5.6.14 TUBE VIBRATION AND ACOUSTIC RESONANCE

Combustion turbine and fluid catalyltic cracking regenerator HRSGs, particularly large units with long tubes, may be subject to flow-induced tube vibrations and resonant acoustic vibration. Tube vibration is controlled by intermediate tube supports using metal bars or lacing wires. Resonant acoustic noise is reduced by installing metal baffles parallel to the gas flow to change the resonant frequency of the gas path.

#### 5.6.15 FLOW DISTRIBUTION AND STRAIGHTENING DEVICES

The exhaust flow exiting combustion turbines is very turbulent and nonuniform in distribution. Some areas of combustion turbine HRSG inlet ducts may have reverse gas flow. Uniform gas flow is particularly important for satisfactory supplementary firing and superheater performance.

Perforated plates, flow redirection baffles, or other means are used to improve the flow distribution. HRSG inlet ducts may have perforated plates installed upstream of the burners and flow redirection baffles installed downstream of the burners. Flow redirection is often necessary for transition ducts diverging more than 30 degrees total included angle.

Flow model tests on combustion turbine HRSGs help predict the gas flow distribution and effectiveness of flow straightening devices. It is important that the test model correctly simulates the combustion turbine exhaust characteristics as well as the HRSG configuration.

#### 5.6.16 TEMPERATURE DISTRIBUTION

After the gas turbine diffuser, temperature isotherms of exhaust gas across the duct may be nonuniform for certain gas turbines. Multiple thermocouples are recommended when determining average cross-sectional duct temperature. High velocity thermocouples (HVT) are necessary for accurate temperature readings at exhaust gas temperatures above 1000°F. Other themocouple types, such as shielded, can provide relative readings but are not as accurate as the HVT.

Table 3—Maximum Gas Velocities

| Gas Source | Maximum Linear Gas Velocity (feet/second) |
|---|---|
| Clean fuel gas | 120 |
| Fuel oil | 100 |
| Fouling gas | 100 |
| Fluid catalytic cracking regenerator flue gas | 80–100[a] |

[a]The precise design velocity is related to particulate size distribution and loading.

### 5.7 Operations Description

Successful HRSG operation depends on using operating procedures which address HRSG design, modes of operation, and rampup rates.

**5.7.1** Protection devices should be provided and procedures followed as described in Appendix A for the water and steam pressure parts.

**5.7.2** Protection should be provided to prevent incidentally over-pressurizing the gas path enclosure casing. Control logic of HRSG and combustion turbines should be interlocked to prevent start-up until exhaust dampers are proven open and should shut down if a damper closes.

**5.7.3** Start-ups can impose significant thermal shock to components due to the rapid introduction of hot gas. Limitations may be appropriate on the rate of introduction of the hot gas, rate of temperature increase in the pressure parts, or conditions at which the HRSG is to be maintained prior to start-up. Hot restarts after sudden feedwater loss due to pump trip are even more severe and require special operating considerations.

**5.7.4** Protective systems should be included to shut down supplementary or auxiliary burners or the hot gas source when appropriate.

**5.7.5** Follow start-up and shut down procedures such as draining of superheaters prior to start-up to prevent damage to components. Combustion turbine HRSGs may be used in daily cyclical service and may be automatically controlled from a plant distributed control system. Operating provisions must follow the proper procedures either automatically or manually.

## SECTION 6—HEAT PIPE HRSGs

### 6.1 General

The heat pipe steam HRSG is basically a compact heat exchanger. In its simplest form it consists of a pressure vessel (steam drum) and a bundle of heat pipes. The heat pipes extract heat from a hot gas stream and transport it to the inside of the vessel, where steam is generated and separated from the water. As hot gas flows over the vaporizer section, the working fluid inside the pipe vaporizes. The vapor rises inside the heat pipe to the condenser section. In the condenser section, the working fluid releases its latent heat causing the working fluid vapor to condense. Through gravity assistance, the condensed working fluid flows back down to the vaporizer section. The cycle is then repeated. In this process, heat is conducted from the hot gases through the heat pipe to boil water in the steam drum. This vaporization/condensation cycle and the resulting heat transport continues as long as the temperature of the gas passing over the heat pipe is greater than the temperature of the water which surrounds the bare section of the pipe.

Each heat pipe passes through the pressure vessel wall. There is basically only one type of heat pipe HRSG; however, the heat pipes and the pressure vessel can be varied. In a heat pipe HRSG, the hot gas flows over the exterior of the heat pipe bundle as shown in Figure 22.

## 6.2 Application

**6.2.1** As a relatively new development, heat pipe HRSGs have been used less in industry than other types of HRSGs. Heat pipe HRSGs can be designed to recover energy from the hot gases of various installations such as:

a. Fired heaters.
b. Calciners.
c. Kilns.
d. Incinerators.
e. Gas turbines.

Flue gases from burning natural and refinery gas, oil, and coal fuels are acceptable.

**6.2.2** Heat pipe HRSGs typically generate low pressure (15 pounds per square inch gauge to 250 pounds per square inch gauge) steam. The unit can be designed for much higher pressures if the application justifies it. Inlet flue gas temperatures to 800°F can be accepted by proper overall design and careful selection of the working fluid.

## 6.3 System Consideration

### 6.3.1 DESIGN CONSIDERATIONS

Major design considerations of heat pipe HRSGs include:

a. Circulation.
b. Pressure drop.
c. Steam quality.
d. Cleaning.
e. Heat pipe sizing.
f. Selection of thermal transport fluid.

### 6.3.2 CIRCULATION

The heat pipe HRSGs can be designed to have high steam drum circulation ratios using natural circulation. The head space on each end of the drum can provide natural circulation for the water flow while the difference in the fluid density between the water in the heads and the water/steam mixture in the tube bundle provide the necessary circulation driving force. The tubes are generally finned on the gas side, and tube-to-tube spacing should be dictated by fin tip clearance requirements. This generally results in a large tube-to-tube clearance on the water side with the associated low pressure drop. High circulation rates and wide tube spacing permit the heat pipe unit to operate safely at heat fluxes of up to 50,000 Btu/hours per square foot (in the bare tube area of the condenser section). See 2.3.2.2 for additional information.

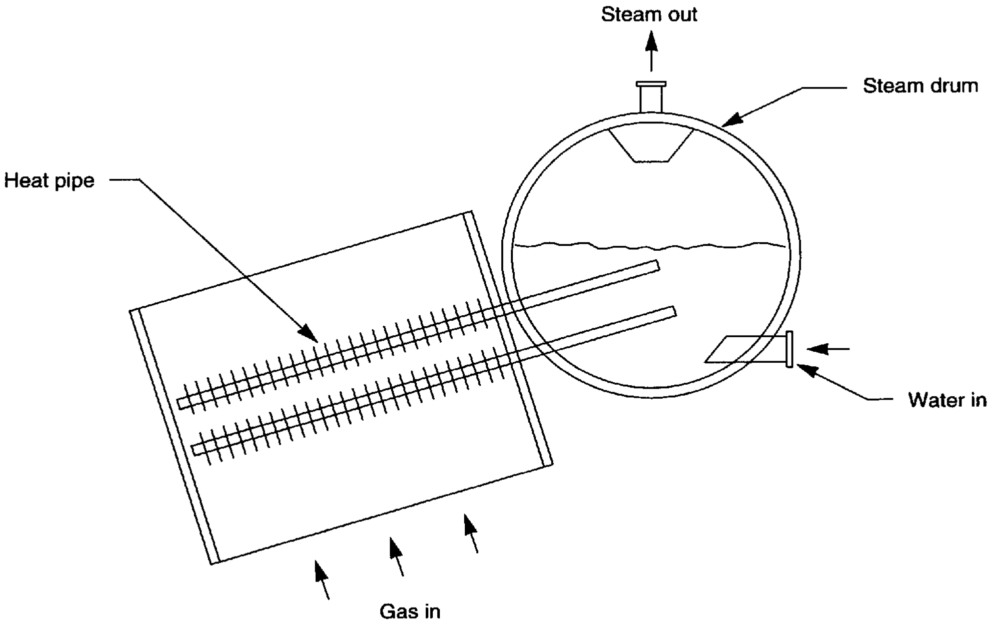



Figure 22—Heat Pipe HRSG

### 6.3.3 STEAM QUALITY

The steam drum must be large enough to provide space for the steam to separate from the water. Internal steam separators should be included to reduce water carryover in the steam. If adequate separation space is not available, a separate steam drum or an external in-line separator may be used. The steam produced is at saturation conditions at the outlet of the steam drum. See Appendix A.

### 6.3.4 PRESSURE DROP

The gas velocity may be limited by the available pressure drop. An increase in thermal performance can be obtained by adding rows, increasing the extended surface, or decreasing the tube pitch. All, however, result in an increase in gas side pressure drop. For a given pitch, increasing the gas side length of the tubes or adding more tubes per row will increase thermal performance while decreasing pressure drop.

### 6.3.5 HEAT PIPE SIZING

Selection of the heat pipe diameter, length, and hot/cold length ratios are all interdependent. Experience has shown that diameters in the range of 1.5 inches to 2 inches provide optimum heat transfer capacity. The hot/cold length ratio is determined by the capacity available in the heat pipe and the extended surface applied to the gas side. Generally, the most economical heat exchanger is one which has the longest heat pipes, limited to reasonable aspect ratios for connecting ductwork.

### 6.3.6 THERMAL TRANSPORT FLUID SELECTION

Selection of proper thermal transport fluids is based on the operating temperature range and the flux required. Typical fluids include water, toluene, and naphthalene. Operating temperature ranges for these and other fluids are indicated by Figure 23. By selecting different fluids for different rows, the appropriate film temperature of the transport fluid can be achieved. Degradation limits of the various transport fluids should be discussed with the manufacturer. Typically, heat pipe thermal transport limits will govern design.

### 6.3.7 FREEZE PROTECTION SYSTEM

During periods of shut down when freezing conditions exist, a protection system must be employed to maintain water based transport fluid temperatures above 32°F. Conventional precautions for steam systems apply to the steam generator side of the unit.

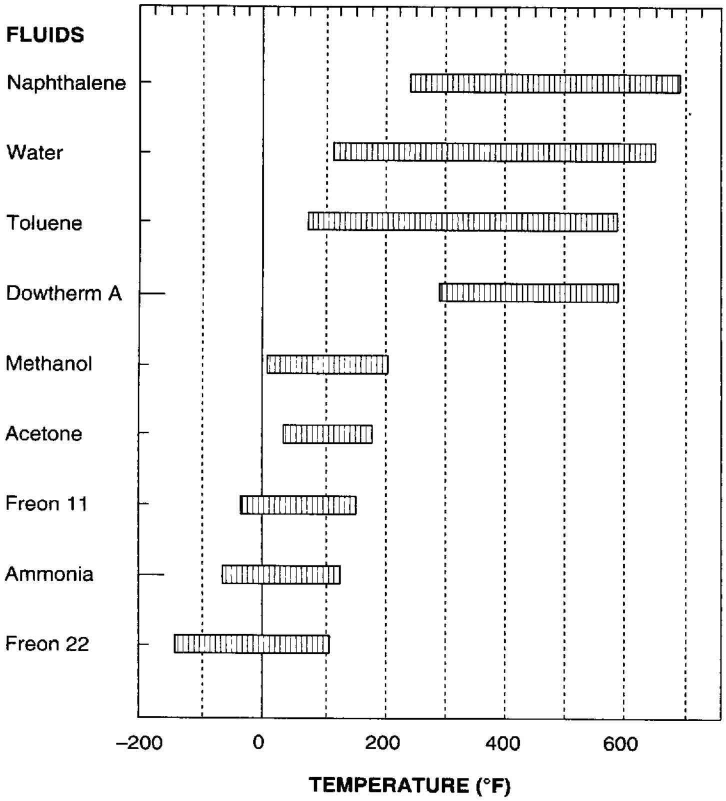



Figure 23—Operating Temperature Range for Typical Heat Pipe Working Fluids

## 6.4 Advantages

**6.4.1** Each heat pipe is an independent operating heat exchanger. If one heat pipe fails, shut down is not required due to the small impact on the overall unit performance.

**6.4.2** The heat pipes are fixed only at the center connection point to the pressure vessel. Thus, they are allowed to freely expand and contract thermally about the attachment point.

**6.4.3** The boundary between the steam and gas is composed of the two tube walls of the heat pipe rather than one tube wall in most other designs. For steam to pass to the gas, a heat pipe would have to have two holes, one on the steam side and one on the gas side, a very unlikely situation.

## 6.5 Disadvantages

**6.5.1** Due to transport fluid limitations, gas stream steady state temperatures in excess of 800°F are not currently practical in the heat pipes.

**6.5.2** Industrial experience is limited.

## 6.6 Mechanical Description

### 6.6.1 STEAM DRUMS

Steam drums used for heat pipe HRSGs are essentially conventional cylindrical pressure vessels except that a means must be provided for pressure boundary penetration by the heat pipes. One method of accomplishing this is by the addition of a large, flat pressure plate, containing multiple openings, in the side of the vessel. The steam drum and heat pipes are mechanically fixed to one another and cannot be separated.

The steam drum is penetrated by the heat pipes at a 6 degree to 90 degree angle from the horizontal. The units can be designed for flue gas flow in either direction.

### 6.6.2 HEAT PIPES

The heat pipe consists of a tube with fins on the hot gas end, a thermal sleeve (which isolates the high heat flux of the heat pipe from the joint at the pipe/vessel interface to reduce the possibility of crevice corrosion), and a thermal transport fluid. The tube is manufactured by capping both ends, evacuating, partially filling with thermal transport fluid, and then permanently sealing. See Figure 24.

### 6.6.3 TUBE SUPPORT

To prevent thermally induced stresses, the heat pipe utilizes a single fixed point located where the heat pipe penetrates the vessel. A support plate is often located at the lower end of the heat pipe. Radial clearance between the tubes and the support plates is such that the tubes are free to move in the axial direction but are supported laterally. This free sliding lateral support also helps to limit tube vibration.

### 6.6.4 INTERNALS

Major internal concerns are the type of fluid to be used, the condensing surface, the liquid distribution, and the separation of the liquid and vapor flows.

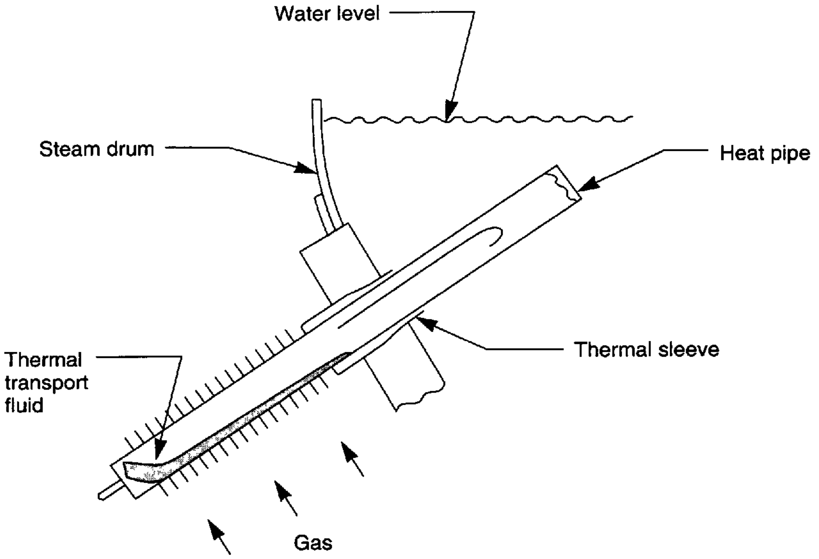



Figure 24—Heat Pipe Installation

A mechanism is required to wet the evaporator end of the heat pipe. Usually a capillary wicking structure is applied to the inner wall of the heat pipes. The wicking function is generally accomplished by grooving the inner wall or by a mesh screen installed on the inside of the pipe. The wick draws the liquid heat transfer fluid up around the inner wall of the tube, providing a completely wetted surface for evaporation. Although a capillary structure is also commonly employed in the condenser end of the heat pipe, it serves a different purpose. In this application the structure provides a roughened surface which functions to enhance the internal heat transfer.

Heat pipe internals require a return path for the liquid flow from condenser to evaporator. If the heat pipe is horizontal, the evaporator will be starved at any reasonable heat flux demand because there will be insufficient head to provide liquid flow. On the other hand, if the pipe is vertical, flow problems can occur because of the percolator effect if special internals are not incorporated. Therefore, most heat pipes are mounted at an angle. The angle should result in heat high enough to provide adequate liquid flow, but low enough so that the liquid has sufficient flow and velocity to wet the entire evaporator before it reaches the lower end of the heat pipe.

# APPENDIX A—STEAM DRUMS

## A.1 General

A steam drum is a pressure vessel whose primary purpose is to separate liquid and vapor phases. Steam drums also provide an operating water storage capacity.

**A.1.1** The steam drum should produce saturated steam approaching 100 percent quality. There should be minimal water solids carryover to downstream equipment. The steam drum shall be designed in accordance with the ASME Codes. It is attached to the steam generating section of an HRSG directly or indirectly through feedwater headers, risers, and downcomers.

**A.1.2** The drum provides for the following:

a. Steam separation internal devices.
b. Water storage capacity.
c. Instrumentation connections.
d. Blowdown facilities.
e. Chemical injection facilities.
f. Overpressure protection (safety valves).

**A.1.3** A typical steam drum with high purity steam separation internal devices is illustrated in Figure A-1.

**A.1.4** Steam purity is the ratio of the weight of total solids per unit weight of steam produced.

## A.2 Application

**A.2.1** A steam drum is installed in most HRSGs where the steam must meet specified requirements for steam purity. Steam drums, however, are not required for once-through forced circulation HRSGs.

**A.2.2** Several steam pressure levels may be generated in the HRSG. A separate steam drum, including related ancillary facilities, must be supplied for each pressure level.

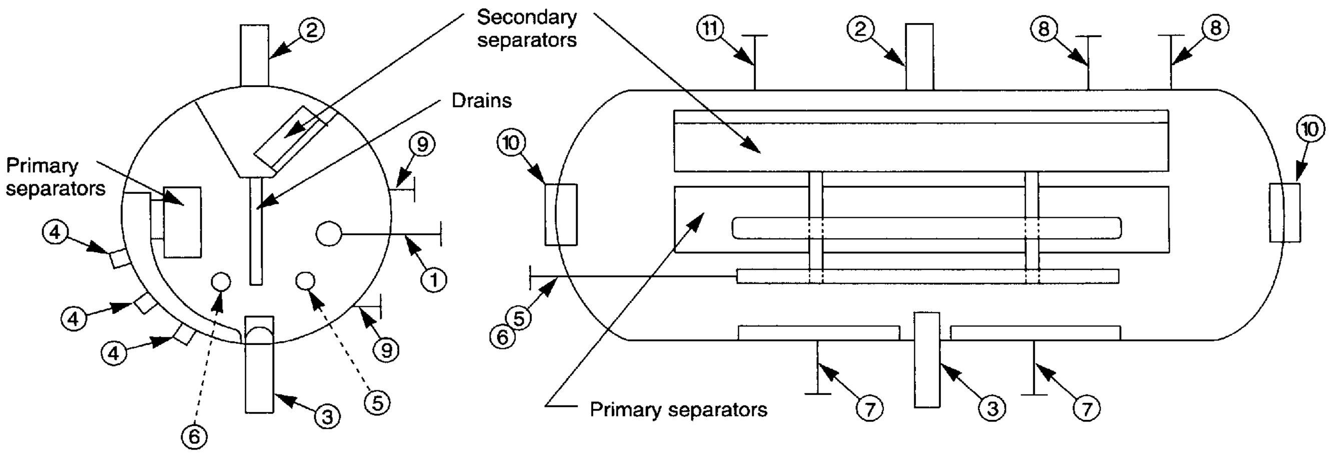
**A.2.3** The steam drum for an HRSG may be shared with other heat recovery systems. Each application is custom designed depending on the heat recovery systems' specific requirements.

## A.3 Steam Separation

**A.3.1** Water and solids leaving the steam drum with the steam is called carryover. Carryover is expressed in either parts per million (ppm) or parts per billion (ppb).

**A.3.2** Excessive carryover can lead to serious problems. Acceptable carryover rates depend on the steam use and the composition of the carryover. Detrimental effects of excessive carryover may include:

a. Superheater tube fouling, resulting in tube overheating and corrosion.
b. Reduction of steam turbine efficiency and corrosion resulting from blade and nozzle fouling.




**KEY**
1 Water in
2 Steam out
3 Downcomer
4 Riser
5 Chemical feed
6 Continuous blowdown
7 Intermittant blowdown
8 Safety valve
9 Level gauge connections
10 Manway
11 Vent

Figure A-1—Typical Steam Drum

c. Contamination of product or catalyst contacted by the steam.

**A.3.3** For steam turbine application or for downstream steam superheating it is prudent to establish limits for boiler water and steam purity. Tables A-1 and A-2 are published by different organizations and are presented as examples.

The following clarifications apply to Table A-1 for drum boilers:

a. Maximum 0.2 ppm total dissolved solids in the steam at or below 600 pounds per square inch gauge drum pressure, and 0.1 ppm total dissolved solids maximum above 600 pounds per square inch gauge are safe limits. Higher levels may be acceptable.
b. Steam purity should be achieved while operating with boiler water total dissolved solids at the high end of the range indicated in Table A-1. The drum supplier specifies the maximum total dissolved solids level in the boiler water at which a specified steam purity is guaranteed.

**A.3.4** Mechanical carryover is the carryover which is dissolved in the entrained water in the delivered steam. Drum internals designed for water removal directly affect the mechanical carryover quantity. Priming is the discharge of steam which contains excessive amounts of entrained water. Priming is a consequence of a high drum water level or of foaming.

**A.3.5** Steam quality leaving the drum is dependent on the efficiency of the steam/water separation, the solids concentration in the drum water, and on the required steam purity. Acceptable steam quality and purity for process or steam heating applications may be achieved by gravity separation alone. However, multiple stages of steam/water separation are usually necessary to deliver high quality and high purity steam.

**A.3.6** High purity steam drums use several stages of separation. The first stage removes the bulk of the water from the mixture; its design may require the following:

a. Deflectors.
b. Perforated plates.
c. Centrifugal vortex separators.
d. Other proprietary devices.

The steam/water mixture moves through several directional changes, allowing water droplets to fall out. The final stages of separation can employ the following:

a. Wire mesh.
b. Chevron driers.
c. Centrifugal separators.
d. Combinations of Items a, b, and c.

The difficulty of steam separation increases as drum pressure increases because the steam and water phase density difference decreases.

**A.3.7** Some carryover constituents such as silica dissolve in both the liquid and vapor phases. These constituents tend

Table A-1—Watertube Boilers Recommended Boiler Water Limits and Associated Steam Purity At Steady State Full Load Operation

| Drum Pressure (pounds per square inch gauge) | Maximum Range Boiler Water Total Dissolved Solids[a] (parts per million) | Range Boiler Water Total Alkalinity[b e] (parts per million) | Maximum Range Boiler Water Suspended Solids (parts per million) | Maximum Expected Value Range Steam Total Dissolved Solids[b,d] (parts per million) |
|---|---|---|---|---|
| Drum boilers | | | | |
| 0 – 300 | 700–3500 | 140–700 | 15 | 0.2–1.0 |
| 301–450 | 600–3000 | 120–600 | 10 | 0.2–1.0 |
| 451–600 | 500–2500 | 100–500 | 8 | 0.2–1.0 |
| 601–750 | 200–1000 | 40–200 | 3 | 0.1–0.5 |
| 751–900 | 150–750 | 30–150 | 2 | 0.1–0.5 |
| 901–1000 | 125–625 | 25–125 | 1 | 0.1–0.5 |
| 1001–1800 | 100 | Note c | 1 | 0.1 |
| 1801–2350 | 50 | Note c | Not applicable | 0.1 |
| 2351–2600 | 25 | Note c | Not applicable | 0.05 |
| 2601–2900 | 15 | Note c | Not applicable | 0.05 |
| Once-through boilers | | | | |
| 1400 and above | 0.05 | Not applicable | Not applicable | 0.05 |

[a]Actual values within the range reflect the total dissolved solids in the feed water. Higher values are for high solids, lower values are for low solids in the feed water.
[b]Actual values within the range are directly proportional to the actual value of total dissolved solids of boiler water. Higher values are for the high solids, lower values are for low solids in the boiler water.
[c]Dictated by boiler water treatment.
[d]These values are exclusive of silica.
[e]Expressed as equivalent calcium carbonate in ppm.
Source: American Boiler Manufacturer's Association.

to increase in concentration in the vapor phase as pressure increases. Liquid phase contaminants can be minimized by efficient steam/water separation. However, vapor phase contaminants can only be controlled by steam washing, by removal of the contaminant through proper treatment of the feed water, or increasing the blowdown rate. Silica carryover at higher pressures (over 1000 pounds per square inch gauge) results more from vaporization and solubility of silica in the steam than from entrained water.

In steam washing, the steam and silica vapor are contacted by low solids water, such as steam condensate. The silica in the steam dissolves in the wash water and reduces the silica vapor carryover.

## A.4 Water Storage

**A.4.1** During transient operation, the steam drum vapor volume will vary. As steam demand is increased, the system

### Table A-2—Suggested Water Quality Limits

Boiler: Industrial watertube, high duty, primary fuel fired drum
Makeup Water Percentage: Up to 100 percent of feedwater
Conditions: Includes superheater, turbine drives, or process restriction on steam purity
Saturated Steam Purity Target[i]

| Drum Operating Pressure[a] MPa (psig) | 0–2.07 (0–300) | 2.08–3.10 (301–450) | 3.11–4.14 (451–600) | 4.15–5.17 (601–750) | 5.18–6.21 (751–900) | 6.22–6.89 (901–1000) | 6.90–10.34 (1001–1500) | 10.35–13.79 (1501–2000) |
|---|---|---|---|---|---|---|---|---|
| Feedwater[g] | | | | | | | | |
| Dissolved oxygen (mg/l $O_2$) measured before oxygen scavenger addition[h] | <0.04 | <0.04 | <0.007 | <0.007 | <0.007 | <0.007 | <0.007 | <0.007 |
| Total iron (mg/l Fe) | ≤0.100 | ≤0.050 | ≤0.030 | ≤0.025 | ≤0.020 | ≤0.020 | ≤0.010 | ≤0.010 |
| Total copper (mg/l Cu) | ≤0.050 | ≤0.025 | ≤0.020 | ≤0.020 | ≤0.015 | ≤0.015 | ≤0.010 | ≤0.010 |
| Total hardness (mg/l $CaCO_3$) | ≤0.300 | ≤0.300 | ≤0.200 | ≤0.200 | ≤0.100 | ≤0.050 | — Not Detectable — | |
| PH range @ 25°C | 7.5–10.0 | 7.5–10.0 | 7.5–10.0 | 7.5–10.0 | 7.5–10.0 | 8.5–9.5 | 9.0–9.6 | 9.0–9.6 |
| Chemicals for preboiler system protection | | | | | | Use only volatile alkaline materials | | |
| Nonvolatile TOC (mg/l C)[f] | <1 | <1 | <0.5 | <0.5 | <0.5 | — As low as possible, <0.2 — | | |
| Oily matter (mg/l) | <1 | <1 | <0.5 | <0.5 | <0.5 | — As low as possible, <0.2 — | | |
| Boiler Water | | | | | | | | |
| Silica (mg/l $SIO_2$) | ≤150 | ≤90 | ≤40 | ≤30 | ≤20 | ≤8 | ≤2 | ≤1 |
| Total alkalinity (mg/l $CaCO_3$) | ≤350[c] | ≤300[c] | ≤250[c] | ≤200[c] | ≤150[c] | ≤100[c] | — Not Specified[d] — | |
| Free hydroxide alkalinity (mg/l $CaCO_3$) | | — Not Specified — | | | | | — Not Detectable[d] — | |
| Specific conductance (μS/cm) (μmho.cm) @ 25°C without neutralization | <3500[e] | <3000[e] | <2500[e] | <2000[e] | <1500[e] | <1000[e] | <150 | <100 |

[a]With local heat fluxes >473.2kW/m² (>150,000 Btu/hr/ft²), use values for the next higher pressure range.
[b]Minimum level of OH alkalinity in boilers below 6.21 MPa (900 psig) must be individually specified with regard to silica solubility and other components of internal treatment.
[c]Maximum total alkalinity consistent with acceptable steam purity. If necessary, should override conductance as blowdown control parameter. If makeup is demineralized water at 4.14 MPa (600 psig) to 6.89 MPa (1000 psig), boiler water alkalinity and conductance should be that in table for 6.90 to 10.34 MPa (1001 to 1500 psig) range.
[d]Not detectable in these cases refers to free sodium or potassium hydroxide alkalinity. Some small variable amount of total alkalinity will be present and measurable with the assumed congruent or coordinated phosphate-pH control or volatile treatment employed at these high pressure ranges.
[e]Maximum values often not achievable without exceeding suggested maximum total alkalinity values, especially in boilers below 6.21 MPa (900 psig) with >20 percent makeup of water whose total alkalinity is >20 percent of total dissolved solids naturally or after pretreatment by lime-soda, or sodium cycle ion exchange softening. Actual permissible conductance values to achieve any desired steam purity must be established for each case by careful steam purity measurements. Relationship between conductance and steam purity is affected by too many variables to allow its reduction to a simple list of tabulated values.
[f]Nonvolatile TOC is that organic carbon not intentionally added as part of the water treatment regime.
[g]Boilers below 6.21 MPa (900 psig) with large furnaces, large steam release space and internal chelant, polymer, or antifoam treatment can sometimes tolerate higher levels of feedwater impurities than those in the table and still achieve adequate deposition control and steam purity. Removal of these impurities by external pretreatment is always a more positive solution. Alternatives must be evaluated as to practicality and economics in each individual case.
[h]Values in table assume existence of a deaerator.
[i]No values given because steam purity achievable depends upon many variables, including boiler water total alkalinity and specific conductance as well as design of boiler, steam drum internals, and operating condition (Note e). Since boilers in this category require a relatively high degree of steam purity, other operating parameters must be set as low as necessary to achieve this high purity for protection of the superheaters and turbines or to avoid process contamination.
Source: American Society of Mechanical Engineers.

pressure will decrease. This results in flashing, and an instantaneous increase of steam generation. The water level rises because of the additional steam volume in the water phase. This is called surge or swell. The opposite happens during a reduction in steam demand. A properly tuned control system re-establishes normal water level when steady state operation is reached. Surge volume in the drum should be adequate to avoid either significant water carryover (priming) or low level alarm. This assumes operation initially at normal water level and load swings at a rate of plus or minus 20 percent of the maximum continuous rating per minute. Low pressure steam systems are more sensitive to this phenomenon.

**A.4.2** The difference in volume between the normal water level and the low-low level is called the storage capacity. Storage provides water to the HRSG if the feed water flow is interrupted or is momentarily inadequate. Typically, drum storage volume is a minimum of 3 minutes of design feed water flow for drum pressures of 750 pounds per square inch gauge and higher and 5 to 10 minutes at lower pressures. For critical service, steam drum water storage volumes may be higher and are a function of the reliability of boiler feedwater supply. Each system should be evaluated on a case-by-case basis. In some cases, surge volume may dictate drum size.

## A.5 Mechanical Description

**A.5.1** The ASME Code, either Section I or Section VIII, Division 1 is normally applied for the pressure vessel design of the steam drum. If the HRSG is fired, then Section I may apply. If there is no direct firing, Section VIII, Division 1 may be applied, depending on the local requirements. Some users specify Section I design with Section VIII, Division 1 stamping for an unfired HRSG. This establishes more stringent Section I design requirements while avoiding the more frequent system inspection requirements of Section I stamped HRSGs.

Compliance with regulations of local authorities is mandatory.

**A.5.2** The layout and size of the drum must allow for internal inspection, maintenance, and repair.

**A.5.2.1** The internals should be removable and sized to pass through a manway. A 12 inch by 16 inch minimum sized manway is installed in each drum head.

**A.5.2.2** The spacing of internals should allow maintenance personnel to pass around obstructions and work along the complete length of the drum. Baffle plates and other separation devices that cover tubes should be readily removable.

**A.5.2.3** The design should permit efficient tube removal and replacement. The area of the tube field must be clear of permanent obstructions to allow space for tube rolling and seal welding.

**A.5.2.4** A steam drum is usually not less than 36 inches in diameter in order to provide adequate access and volume.

**A.5.3** Steam drum design pressure should be sufficiently above the expected maximum operating pressure to preclude unnecessary discharges from the steam safety valves. The pressure margin is usually a percent of the valve set pressure, and is dependent upon the type of valve. With margins less than 10 percent, consult the valve manufacturer regarding valve suitability.

**A.5.4** Size of steam and water connections must provide acceptable fluid velocities and pressure drop under all operating conditions. The possibility of thermal stresses from relatively cool feed water or chemical feed entering the hot drum must be considered. In thick wall, high pressure designs, it may be necessary to provide thermal sleeves at the drum wall. A thermal sleeve is a pipe sleeve which penetrates the drum wall through which the feed water or chemical feed pipe is extended.

**A.5.5** Vapor-free water should enter the HRSG downcomers. The design and location of the first stage separators relative to the downcomers, and the use of baffles and vortex breakers, can effectively prevent vapor from entering the downcomer nozzles.

## A.6 Drum Operating Levels

The key operating levels in the steam drum are:

a. Normal water level.
b. High and low water level.
c. High-high water level.
d. Low-low water level.

**A.6.1** Normal water level is the water level which the control system maintains during steady state operation. The normal level is near the drum centerline to enhance moisture separation and to provide adequate water storage volume. This water level may be above the drum centerline for drums which have mechanical steam separators.

**A.6.2** High and low water level are those above and below the normal water level which establish the maximum operating range of operating levels to be expected during load swings. The distance between high and low levels and normal level is typically from plus or minus 6 inches to plus or minus 20 inches. Alarms are set for both high and low levels.

**A.6.3** High-high water level is the highest level at which the supplier will guarantee the steam purity because of the possibility of water being entrained in the leaving steam.

**A.6.4** Low-low water level is the lowest level at which the HRSG should be operated. Below this level the evaporator tubes may be improperly wetted, resulting in tube or drum overheating. Low-low level alarm is also used to shut down duct burners of fired HRSGs, to isolate unfired HRSGs from the hot process gas if equipped with a gas bypass system, or to start unloading the combustion turbine. Depending upon specific conditions, shut down may have to be initiated before low-low level is reached.

## A.7 Trim and Instrumentation

**A.7.1** The steam drum accommodates pressure safety valves; water level indication; and control, alarm, and shut-down instrumentation. Instrumentation must satisfy applicable codes and regulations.

**A.7.2** Safety valve(s) installed above the vapor space of the drum provide part or all of the required relieving capacity of the HRSG. If two valves are required, they are either identical or the smaller valve is normally set to lift first. Relief of the full steaming capacity must be provided on the steam drum or in combination with superheater safety valves in accordance with ASME Code.

**A.7.3** Level indication is provided by one or more level gauges, level transmitters, or remote level indicators, connected to the drum or water columns. Drum level can be observed by direct vision at the drum platform level. Level indication may also be transmitted to grade or a control room.

Redundancy of instrumentation is desirable to avoid shut downs for repair. It is helpful on long drums to show end-to-end level variations on the drum, particularly when riser and downcomer connections are not symmetrical along the drum length. The useful range of the level gages should be carefully selected so that the total desired range is obtained. The ASME Code requirements may not provide the desired range of level coverage. Transmitters and other remote indicators generally cover the range from high-high to low-low level and it is desirable to provide similar full range gage glass coverage.

**A.7.4** Two-element or three-element systems are used for control.

**A.7.4.1** A two-element system monitors the drum water level and the delivered steam flow. A feed-back signal is based on the steam flow, and the demand for changes in the feed water is anticipated before the level actually changes.

**A.7.4.2** A three-element system monitors drum water level, discharge steam flow, and feed water flow. The steam flow is compared to the water flow and level change is anticipated; the feed water flow is adjusted before the level changes significantly. Three-element control is usually more responsive than two-element control.

**A.7.4.3** The level control system can be tuned, or can incorporate computerized programs to minimize the transient effects.

## A.8 Control of Water Chemistry

**A.8.1** Provisions are incorporated in the steam drum to control the concentration of solids in the drum water. Solids in the drum water will concentrate as steam is generated. If the drum water solids concentration exceeds certain levels, foaming may occur which can lead to entrainment of water and solids in the steam. (Certain organics such as oil and grease in the drum water can also cause foaming.)

Table A-1 (from ABMA) contains general recommendations for drum water chemistry. Table A-1 values are exclusive of silica. At pressures above 1000 pounds per square inch gauge, silica concentration in vapor form increases, requiring special control. Analysis of the steam is necessary to detect carryover. A sample connection using an isokinetic probe as described in ASTM D1066 should be installed to extract a representative steam sample. The sample connection should be installed on the steam outlet line or lines.

**A.8.2** Solids concentration in the drum water is controlled by removing some of the high solids drum water, which is replenished with low solids feed water. This process is called blowing down. At steady state, the flow balance around the steam drum is:

$$F = S + B$$

*Where:*

$F$ = Feedwater flow rate, in pounds per hour.
$S$ = Steam flow rate, in pounds per hour.
$B$ = Continuous blowdown flow rate, in pounds per hour.

The total dissolved solids balance is:

$$C_f F = C_s S + C_b B$$

*Where:*

$C_f$ = Total dissolved solids in feedwater, in parts per million.
$F$ = Feedwater flow rate, in pounds per hour.
$C_s$ = Total dissolved solids in steam, in parts per million.
$S$ = Steam flow rate, in pounds per hour.
$C_b$ = Total dissolved solids in drum water, in parts per million.
$B$ = Continuous blowdown flow rate, in pounds per hour.

Using the above relationships and assuming no carryover, the minimum blowdown rate may be determined from the maximum drum water total dissolved solids as follows:

$$B = \left(\frac{C_f}{C_b}\right) F$$

For a particular application, the type of feed water treatment selected establishes feed water solids concentration.

**A.8.3** To provide for steam drum water chemistry control, the drum is provided with the following facilities:

a. A feed water pipe perforated to evenly distribute feed water over the length of the drum.
b. The chemical feed pipe, similar in design to the feed water pipe, and usually near the feed water pipe to promote mixing.
c. The continuous blowdown pipe, a perforated pipe located in the drum near the low water level whose function is to control the total dissolved solids level of the boiler water and thereby the steam purity. This area is where drum water solids are judged to be most detrimental to steam purity. If the level drops below the low level, continuous blowdown ceases but level drop rate is reduced. If possible, the continuous blowdown pipe should be located where the boiler water total dissolved solids level is highest to reduce blowdown rates.
d. Intermittent blowdown: If the drum has undisturbed zones at its bottom, a collector can be used to remove solids which precipitate from the drum water. Otherwise, a mud drum or a low velocity header located at a low elevation in the circulation system can be used for intermittent blowdown location.

# APPENDIX B—HEAT FLUX AND CIRCULATION RATIO

## B.1 General

Circulation, heat flux, and boiling flow regimes are fundamentals applicable to all HRSGs, regardless of whether the system is forced or natural circulation, watertube or firetube design.

## B.2 Heat Flux

### B.2.1 FILM BOILING

Heat flux is the heat transfer rate per unit area of tube surface measured at the surface where boiling occurs. If heat flux is excessive, steam is generated so rapidly that a steam film is formed at the tube wall. This steam film displaces the water and keeps it from rewetting the tube. This phenomenon is known as film boiling or departure from nucleate boiling and results in a sudden increase in the tube metal temperature. This can cause tube failure resulting from high metal temperature.

The heat flux at which departure from nucleate boiling occurs depends on several variables including:

a. Orientation and geometry of the surface.
b. Quantity of steam in the water.
c. Steam/water mixture velocity.
d. Pressure.

The maximum heat flux allowed in HRSG design should be based on the most stringent combination of these variables.

### B.2.2 NUCLEATE BOILING

Since boiling heat transfer coefficients are much greater than those on the hot gas side, tube metal temperatures approach that of the saturated water. This assumes nucleate boiling where steam bubbles generated at the tube wall are alternately displaced by water rewetting the tube.

Steam blanketing can also occur at low heat fluxes with nucleate boiling if the forming steam bubbles are not continuously removed. However, at heat fluxes above 400,000 Btu/hour-foot squared, nucleate boiling changes to film boiling. At this point even the most vigorous circulation cannot prevent the formation of an insulating steam film on the heating surface.

### B.2.3 LOCAL HEAT FLUX

Table B-1 shows typical ranges of maximum allowable local heat fluxes. The maximum heat flux should be calculated in the area of highest temperature difference based on fluid properties at that temperature and under clean conditions. Both tubewall temperature and heat flux should be analyzed to determine the operating limits for the HRSG.

Table B-1—HRSG Firetube and Watertube Local Heat Flux

| HRSG Type | Maximum Allowable Local Heat Flux (Btu/Hr-Ft$^2$) | Comments |
|---|---|---|
| Firetube | | |
| Kettle | 25,000–30,000 | — Pool boiling; circulation pattern is not well defined<br>— Tube spacing must be carefully considered for larger units |
| Thermosyphon | 70,000–100,000 | — Separate steam drum, well defined circulation pattern<br>— May not be applicable to transfer line exchanger in ethylene plants<br>— Higher fluxes possible in some proprietary designs |
| Watertube | | |
| Natural circulation | 100,000 | — Vertical tubes prevent flow stratification<br>— Need to check circulation ratio at the exit of the hottest tube |
| Forced circulation | 40,000–50,000 | — Design to avoid horizontal tubes stratification<br>— Need to control high steam/water mixture velocity |
| Forced circulation Once-through ($4^1/_2$ inches max. tube diameter) for enhanced oil recovery application | 40,000 | — Need to control hardness of water used |
| Heat pipe | | |
| Natural circulation | 50,000 | — Pool boiling<br>— Circulation pattern not well defined |

Many industrial HRSG designs have much lower local heat fluxes than the maximum specified in Table B-1. This may be due to low temperature difference or low overall heat transfer coefficients.

## B.3 Circulation

### B.3.1 CIRCULATION RATIO

The circulation ratio (CR) is the ratio of total steam/water flow in the circuit to the steam flow at the exit of the riser.

$$CR = \frac{\text{total riser steam/water mass flow rate}}{\text{steam mass flow rate at riser outlet}}$$

The designer sets the circulation ratio to maintain nucleate boiling for all operating conditions, that is, to avoid departure from nucleate boiling. However, corrections for two-phase flow regime should be used in conjunction with circulation ratio rather than merely specifying minimum circulation ratio.

Bubble flow is the required two phase flow regime for HRSG tubes. Bar-Cohen, Ruder, and Griffith found that undesired stratified or plug flow regimes are possible when circulation flow is either too low or heat fluxes too high. Taitel and Dukler present a model predicting flow regimes as a function of tube diameter and orientation, fluid properties and steam/water mass velocity.

### B.3.2 NATURAL CIRCULATION

HRSG risers and downcomers form a flow circuit by connecting the steam drum at the top and a mud drum or header at the bottom. During operation, the steam/water mixture in the risers is less dense than the water in the downcomers. Flow occurs within the circuit at a rate where the difference in static head between the risers and downcomers balance the resistance to flow. A typical natural circulation circuit (typically 10:1 to 15:1 water to steam weight ratio) is shown in Figure B-1.

The circulation ratio depends on the static head differences, resistance to flow in the circuit, system pressure, and quantity of steam generated. The designer can increase circulation ratio by raising the height of the steam drum and/or by reducing flow resistance, for example, larger downcomers or increased flow area. A typical performance curve for a particular system is shown in Figure B-2. This curve shows that an increase in the heat transfer and steam generation rate decreases the circulation ratio.

The circulation ratio should be calculated for the anticipated range of operation. Low circulation ratio can result in departure from nucleate boiling and tube overheating. Natural circulation HRSGs generally use vertical or inclined tubes to allow steam to rise freely.

### B.3.3 FORCED CIRCULATION

Forced circulation HRSGs use a pump to maintain circulation through the steam generating tubes of the evaporator, steam drum and headers. A typical forced circulation circuit (typically 5:1 water to steam weight ratio) is shown in Figure B-3. Water is distributed to parallel tube circuits from an inlet header and the exiting steam/water mixture is collected in an outlet header. The steam/water mixture is returned to the steam drum where the steam is separated and water is recirculated to the evaporator.

Steam generator tubes may have any orientation. Fired heater applications are usually horizontal. Tubes are connected in series in a serpentine arrangement to form each single tube pass. With this arrangement water flows upward and improves flow stability between multipass parallel circuits. The buoyancy of the two phase flow assists the forced circulation and minimizes the potential for steam pocketing.

Forced circulation HRSGs generally have larger tubes, longer tube circuits, and higher flow resistance than natural circulation HRSGs.

### B.3.4 ADVANTAGES AND DISADVANTAGES

**B.3.4.1** Natural circulation advantages are:

a. No pumping systems are required.
b. Less maintenance.
c. More reliable.

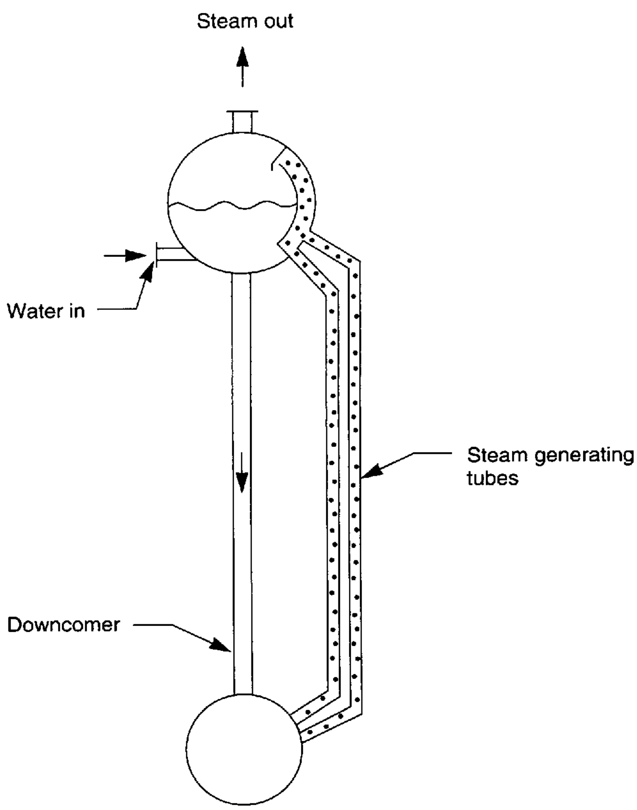



Figure B-1—Typical Watertube HRSG

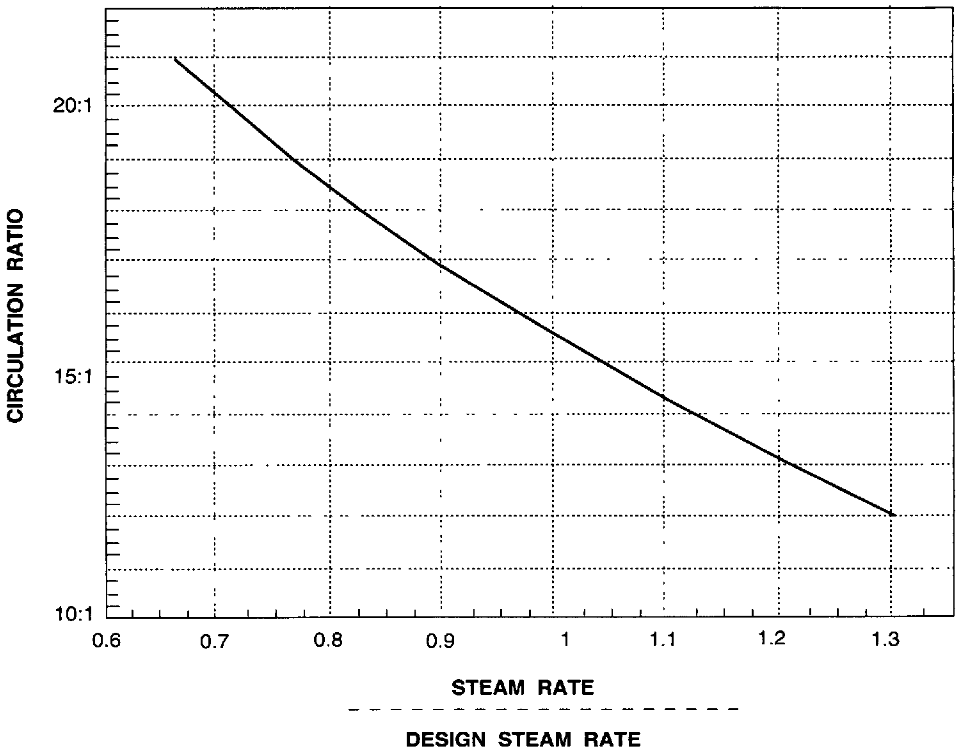



Figure B-2—Typical Circulation Rate

**B.3.4.2** Natural circulation disadvantages are:

a. Usually restricted to vertical or inclined tube applications.
b. Usually installed at grade, thus, more plot space is required.
c. Steam drum location requires higher elevation.

**B.3.4.3** Forced circulation advantages are:

a. Horizontal or vertical tube arrangements may be used.
b. Forced circulation arrangements can be installed in vertical heater flue gas ducts.
c. Smaller plot requirements. The steam drum location is not restricted.

**B.3.4.4** Forced circulation disadvantages are:

a. Pumping systems are required.
b. Higher maintenance due to pumps.
c. Vertical tube arrangements require design expertise.

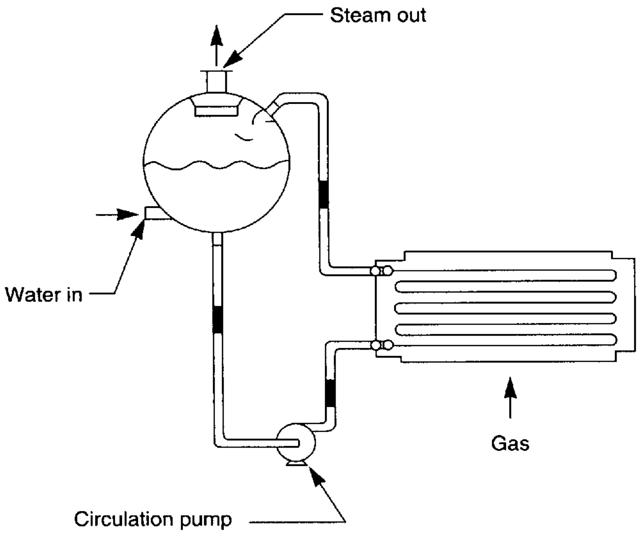



Figure B-3—Typical Forced Circulation System

# APPENDIX C—SOOTBLOWERS

## C.1 General

**C.1.1** Flue gas side tube cleaning devices are primarily blowing media cleaners or sootblowers. Sonic cleaning and shot cleaning are seldom used. This appendix will address only sootblowers.

**C.1.2** Sootblowers are either fixed position rotary or retractable. Retractable sootblowers may be either fully or partially retractable.

**C.1.3** Fixed position rotary sootblowers have a multinozzle element permanently located within the flue gas stream. The element is supported at both ends and within the flue gas stream by brackets usually attached to the tubes.

**C.1.4** Retractable sootblowers have a lance that normally contains two nozzles, 180 degrees opposed and located at its end. The lance traverses across the tube bank while rotating. The cleaning action is produced by directing the jets of blowing media in a helical path across the tube bank.

**C.1.5** Sootblowers are placed in lanes between rows of tubes. The sootblower lane is the free space between the nearest row of tubes upstream and downstream of the cleaning element. (See Figure C-1.)

## C.2 Application

**C.2.1** Sootblowers are required when heavy oil is fired and extended surface tubes (studs or fins) are present. Provisions for future cleaning are required when heavy oil is fired and only bare tubes are present. Such provisions can include sootblower lanes or mechanical cleaning capability.

**C.2.2** Sootblowers are required when catalyst bearing gases are present.

**C.2.3** Provisions for future cleaning should be considered when light oil may be fired.

**C.2.4** Fuel gas fired units do not normally require cleaning. The fuel gas composition should be reviewed for fouling potential and future provision for sootblowers made when there is a remote possibility of fouling.

**C.2.5** When ammonia and sulfur compounds are present, the potential for fouling and possible sootblower use should be considered.

**C.2.6** For temperatures over 1000°F, a combination of retractable and rotary blowers may be desirable due to the potential oxidation and drooping of the rotary sootblowers element.

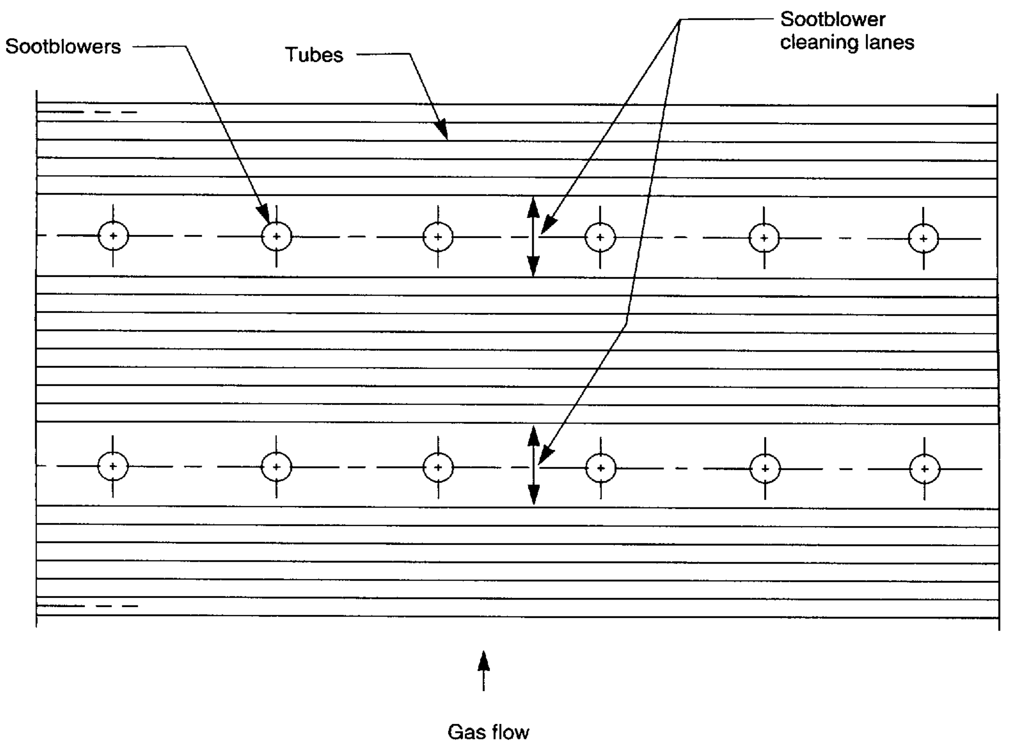



Figure C-1—Sootblower Cleaning Lanes for Square and Triangular Pitch Tubes (Bare or Finned)

## C.3 System Considerations

### C.3.1 HRSG DESIGN

**C.3.1.1** Internal refractories should be protected from damage by the blowing media. Protection may include either metallic shrouds or dense castable lining for the cleaning lane and impingement area or for the entire tube bank.

**C.3.1.2** Inspection doors shall be provided in the lanes to permit inspection of the tube surfaces.

**C.3.1.3** Tube arrangement and extended surface choice and orientation should be compatible with the choice of sootblower.

**C.3.1.4** The number of rows of sootblowers and the size of the sootblower lanes should accommodate the cleaning characteristics of the sootblower used.

**C.3.1.5** The interference of tube supports, guides, and baffles must be considered when laying out cleaning devices.

**C.3.1.6** The blowing media may be steam or air. The manufacturer should be consulted about the optimum pressure. Operation at pressures lower than those recommended by the manufacturer decreases the cleaning ability of the sootblower. Blowing pressure is typically 100 pounds per square inch gauge to 300 pounds per square inch gauge.

### C.3.2 FIXED POSITION ROTARY SOOTBLOWERS

**C.3.2.1** Rotary sootblowers mounted on opposing sides of the tube bank are required if the tube bank exceeds 15 feet.

**C.3.2.2** Sootblower lanes should be a minimum of 3.5 inches clear between tube outside diameters for bare tube application, 10 inches between the tips of fins or studs when the sootblower element is parallel to the tubes, 18 inches when the element is perpendicular to the tubes.

**C.3.2.3** Sootblower rotation may be manual or mechanical drive, such as a pneumetic or electric motor. The element, combination gear drive, and cam actuated blowing media admission valve are shown in Figure C-2.

**C.3.2.4** Typical gas temperature limits for element materials are:

a. Carbon steel: 800°F.
b. Chrome plated or calorized steel: 1000°F.
c. Stainless steel (22 percent Cr minimum): 1500°F.

**C.3.2.5** Support brackets that are attached to tubes should be of the same material as the element. If the bracket temperature exceeds 1100°F and the vanadium content of the fuel exceeds 50 parts per million, 50 Cr-50 Ni (Cb) brackets shall be used.

**C.3.2.6** The support brackets shall not be attached to the element.

**C.3.2.7** Support bracket spacing is a function of flue gas temperature. Typical spacing limitations are:

a. 40 inches apart: 900°F.
b. 30 inches apart: 1500°F.
c. 20 inches apart: 1800°F.

**C.3.2.8** The number of nozzles for a perpendicular element typically shown by Figure C-2 is based on providing one nozzle per space between tube rows. After establishing

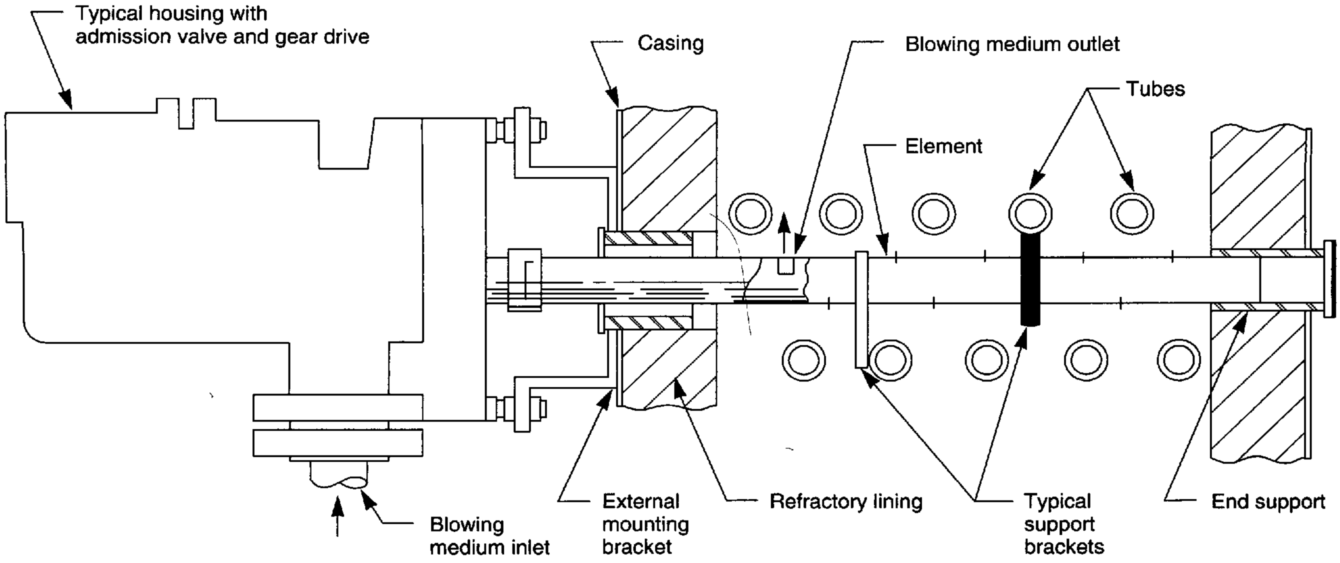



Figure C-2—Typical Fixed-Position Rotary Mounting Arrangement the number of nozzles, the blowing media consumption per element may be estimated from Figures C-3 or C-4. Actual consumption rates are a function of sootblower construction details. To provide adequate coverage for most industrial applications, multiple elements are normally installed.

### C.3.3 RETRACTABLE SOOTBLOWERS

**C.3.3.1** Cleaning lanes for bare tubes should be a minimum of 15 inches clear between tube outside diameters. Cleaning lanes for extended surface tubes should be 18 inches between the tips of fins or studs when the sootblower element (lance) is parallel to the tubes and 24 inches when the element is perpendicular to the tubes.

**C.3.3.2** The sootblower is supported at the casing wall by a sleeve yoke and from a platform or structure outside the casing near the outboard end. Figure C-5 shows a typical support arrangement.

**C.3.3.3** Positive pressure wall sleeves with sealing air are required to prevent flue gas leaks in positive pressure HRSGs.

### C.3.4 SOOTBLOWER SPACING

**C.3.4.1** The spacing of sootblower elements should be based on the effective cleaning radii. The effective cleaning radii is a function of the following:

a. Tube bank temperatures.
b. Blowing media.
c. Blowing media pressure.
d. Nozzle size and number.
e. Fuel characteristic (potential for soot formation).
f. Tube arrangement (pitch) and size.
g. Extended surface type and orientation.
h. Orientation of sootblower element to tubes.
i. Type of HRSG.

**C.3.4.2** Typical sootblower spacing for staggered tube banks depends on whether the sootblower is a rotary or a retractable one.

For rotary sootblowers, the maximum horizontal or vertical coverage is 3 feet from the element or 3 tube rows, whichever is less.

For retractable sootblowers, the maximum horizontal or vertical coverage is 4 feet from the element or 4 tube rows, whichever is less.

High fouling fuel will require more sootblowers. The sootblower vendor should be consulted for his recommendations for the specific system and its effective cleaning radii.

### C.3.5 EXTERNAL PIPING

Sootblower external piping arrangements should include the following:

a. Individual block valves to each blower.
b. Warm up piping.
c. Steam bleeds.
d. Steam traps.

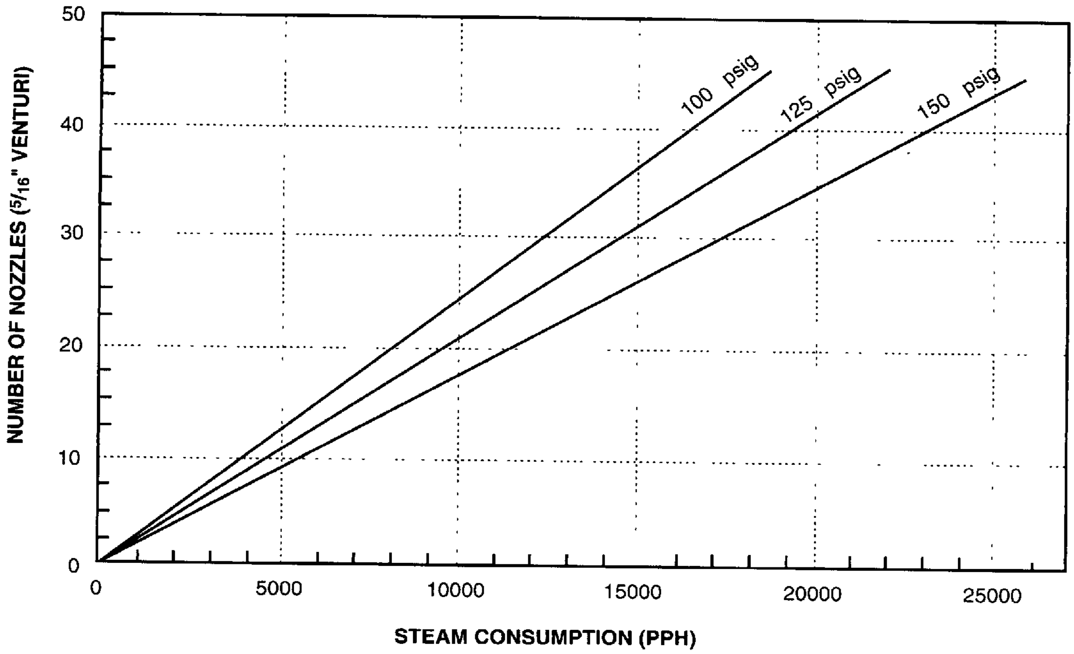



Figure C-3—Steam Flow Rate for Rotary Sootblowers

### C.3.6 CONTROLS

Local start/stop push button stations, main steam control valve, and sequential control panel are normally provided by the sootblower manufacturer.

## C.4 Advantages

### C.4.1 FIXED-POSITION ROTARY SOOTBLOWERS

The advantages of fixed-position rotary sootblowers include:

a. Construction is less complex.
b. External platforms and structure are minimized.

### C.4.2 RETRACTABLE SOOTBLOWERS

The advantages of retractable sootblowers include:

a. The lance can be used at any flue gas temperature.
b. Internal supports are not required for the lance.
c. More effective cleaning is provided than with fixed-position rotary sootblowers.

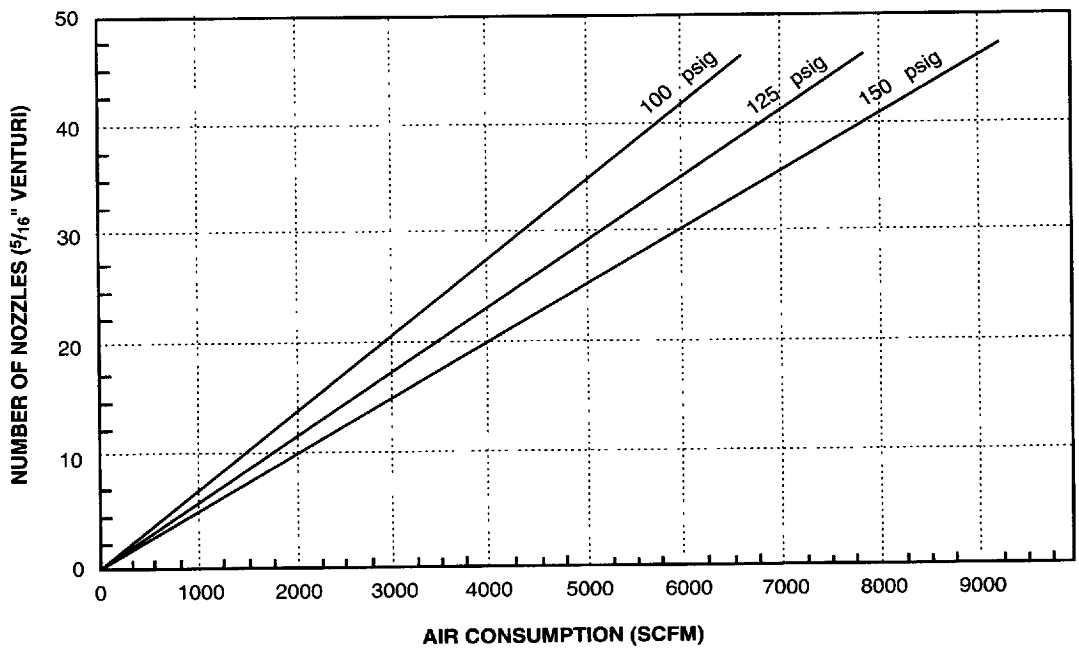



Figure C-4—Air Flow Rate for Rotary Sootblowers

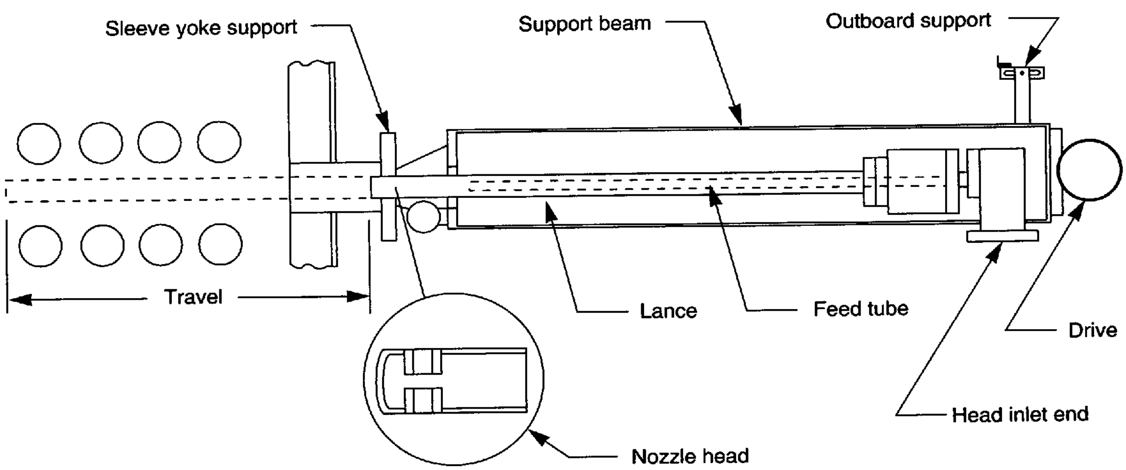



Figure C-5—Typical Retractable Mounting Arrangement

d. Fewer sootblowers are required than with fixed-position rotary sootblowers.

## C.5 Disadvantages

### C.5.1 FIXED-POSITION ROTARY SOOTBLOWERS

The disadvantages of fixed-position rotary sootblowers include:

a. Elements are continually exposed to the flue gases.
b. More frequent maintenance is required than with retractable sootblowers.
c. The cleaning radius is short.
d. Nozzles are subject to plugging.
e. Rotary sootblowers are not recommended when the sootblower element sees temperatures in excess of 1100°F or fuel oils containing large quantities of heavy metals (over 50 parts per million vanadium).
f. Rotary sootblowers may not be suitable when certain high fouling fuels are employed.

### C.5.2 RETRACTABLE SOOTBLOWERS

The disadvantages of retractable sootblowers include:

a. Significant platforms and structural supports are required.
b More routine maintenance is required.
c. Flue gas seals are more susceptible to leaks.
d. Construction is more complex.

## C.6 Operations Description

Sootblower operation frequency varies depending upon the equipment, the structure and orientation of the tube bank, and the fouling tendency of the fuel. Sequential operation of the sootblowers is required to prevent too great a load on utilities, and to prevent unstable operation of the HRSG due to excessive quantities of the blowing media being added to the flue gas.

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**American Petroleum Institute**
1220 L Street, Northwest
Washington, D.C. 20005

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