

CRTD-Vol. 103

**CONSENSUS ON ■
BEST TUBE ■
SAMPLING PRACTICES ■
FOR BOILERS & ■
NONNUCLEAR ■
STEAM GENERATORS ■**

AN ASME RESEARCH REPORT



CONSENSUS ON BEST TUBE SAMPLING PRACTICES FOR BOILERS & NONNUCLEAR STEAM GENERATORS

CRTD-Vol. 103

Prepared by the
Water Technology Subcommittee of the ASME Research and Technology
Committee on Water and Steam in Thermal Systems

March 2014

Copyright © 2014, ASME, Two Park Avenue, New York, NY 10016, USA (www.asme.org)

All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

INFORMATION CONTAINED IN THIS WORK HAS BEEN OBTAINED BY THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS FROM SOURCES BELIEVED TO BE RELIABLE. HOWEVER, NEITHER ASME NOR ITS AUTHORS OR EDITORS GUARANTEE THE ACCURACY OR COMPLETENESS OF ANY INFORMATION PUBLISHED IN THIS WORK. NEITHER ASME NOR ITS AUTHORS AND EDITORS SHALL BE RESPONSIBLE FOR ANY ERRORS, OMISSIONS, OR DAMAGES ARISING OUT OF THE USE OF THIS INFORMATION. THE WORK IS PUBLISHED WITH THE UNDERSTANDING THAT ASME AND ITS AUTHORS AND EDITORS ARE SUPPLYING INFORMATION BUT ARE NOT ATTEMPTING TO RENDER ENGINEERING OR OTHER PROFESSIONAL SERVICES. IF SUCH ENGINEERING OR PROFESSIONAL SERVICES ARE REQUIRED, THE ASSISTANCE OF AN APPROPRIATE PROFESSIONAL SHOULD BE SOUGHT.

ASME shall not be responsible for statements or opinions advanced in papers or printed in its publications (B7.1.3). Statement from the Bylaws.

For authorization to photocopy material for internal or personal use under those circumstances not falling within the fair use provisions of the Copyright Act, contact the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923, tel: 978-750-8400, www.copyright.com.

Requests for special permission or bulk reproduction should be addressed to the ASME Publishing Department or submitted online at:

<https://www.asme.org/shop/books/book-proposals/permissions>

ISBN: 978-0-7918-6035-9

Book no.: 860359

FOREWORD

The Water Technology Subcommittee of the ASME Research and Technology Committee on Water and Steam in Thermal Systems, has established a Consensus on Best Tube Sampling Practices for Boilers & Nonnuclear Steam Generators.”

This publication is an important companion to previously published documents prepared to inform and educate the reader and to develop good chemistry control and operating practices for steam and water usage in thermal systems. The earlier publications are “Consensus on Operating Practices for the Control of Feedwater and Boiler Water Chemistry in Modern Industrial Boilers”; “A Practical Guide to Avoiding Steam Purity Problems in the Industrial Plant”; “Consensus for the Lay-up of Boilers, Turbines, Turbine Condensers, and Auxiliary Equipment” “Consensus on Operating Practices for the Sampling and Monitoring of Feedwater and Boiler Water Chemistry in Modern Industrial Boilers” and “Consensus on Operating Practices for Control of Water and Steam Chemistry in Combined Cycle and Cogeneration Power Plants.”

This consensus was prepared by a task group of this subcommittee under the guidance of Robert D. Bartholomew of Sheppard T. Powell Associates, LLC. The task group consisted of representatives of manufacturers, operators and consultants involved with the design, manufacture, operation and monitoring of industrial and utility boilers, steam generators and associated equipment.

The ASME Research Committee may review, revise and reissue this document from time to time as necessary to comply with advances in technology in the design of these units.

Colleen M. Layman, P.E.

Chair, Water Technology Subcommittee of the
ASME Research and Technology Committee
on Water and Steam in Thermal Systems

ACKNOWLEDGMENTS

This document was prepared by the Tube Sampling Task Group of the Water Technology Subcommittee of the Research and Technology Committee on Water and Steam in Thermal Systems of the American Society of Mechanical Engineers. Recognition is given to the following members of this group for their contributions in the preparation of this document.

Robert D. Bartholomew, P.E.,
Chair, Tube Sampling Task Group

A. Banweg
E. Beardwood
J. Bellows
W. Bernahl
D. Bloom
I. Cotton
D. Daniels
P. Desch
D. Dewitt-Dick
J. Dromgoole
V. Durham
M. Esmacher
F. Gabrielli
R. Holloway

J. M. Jevec
C. M. Layman
R.W. Light
E. Mitchell
V. Olson
J. Robinson
M. Rootham
A. Rossi
J. Schroeder
K. Shields
D. E. Simon II
K. Sinha

TABLE OF CONTENTS

FOREWORD	iii
ACKNOWLEDGMENTS	v
INTRODUCTION	1
ROUTINE TUBE SAMPLING FOR CLEANLINESS	
ASSESSMENTS	1
Sampling Frequency	2
Tube Sample Location for Routine Evaluation	2
Initial Deposit Weight Survey for Units with No Tube Sampling History	12
Deposit Analyses	13
Multiple Tube Samples	17
TUBE SAMPLING FOLLOWING TUBE FAILURES	18
Tube Sampling	18
Sampling Fire Tube Boilers for Failure Analysis	18
Failure Analyses	19
TUBE SAMPLE REMOVAL, IDENTIFICATION AND SHIPPING	19
Sample Removal	19
Tube Sample Identification	20
Packaging and Shipment	22
SUMMARY	23
REFERENCES	23

INTRODUCTION

Due to personnel turnover at both industrial steam plants and power plants, some facilities are not sufficiently familiar with standard practices for tube sample collection and analysis. This document is designed to provide consensus information for the sampling and analysis of tubes in boilers and nonnuclear steam generators. Information is grouped into the following sections.

- Routine Tube Sampling for Cleanliness Assessments
- Tube Sampling Following Tube Failures
- Tube Sample Removal, Identification, and Shipping Basics

ROUTINE TUBE SAMPLING FOR CLEANLINESS ASSESSMENTS

As a general rule, *routine tube sampling* is employed to assess the condition and cleanliness of tubes which are filled with steam/water mixtures during service. The primary objectives of routine tube sample collection are to measure the internal deposit weight per unit area and determine the deposit composition. This information is used to determine if a cleaning is required and can be used to assess the performance of the feedwater and boiler water treatment programs.

Waste heat boilers or process coolers with a shell and tube design are usually excluded from routine tube sampling. Collection of tube samples often is impractical due to the steam generator geometry or materials of construction.

In current practice, steam-cooled tubes generally are not sampled for routine cleanliness assessments. Steam tubes are sampled for the purposes of assessing the condition of the tubes and determining the remaining life. Such considerations are beyond the scope of this document. The procedures for sampling steam tubes in the event of a failure are covered by this document in the "Tube Sampling Following Tube Failures" section.

The deposit weight per unit area can be referred to as the deposit weight density (DWD), deposit density, deposit loading and the specific deposit weight. This document refers to this measurement as the deposit weight.

Standard methods for deposit removal and deposit weight measurement are presented in References 1 and 2. Some boiler manufacturers have provided suggestions for maximum acceptable deposit weights (3, 4). EPRI also has presented guidance on deposit weight limits for boilers and heat recovery steam generators (HRSG) as well as presenting other recommendations for determining the need to clean these units (5, 6). There is ongoing research in deposit weight limits (7).

Another objective of tube sampling is to perform dimensional measurements to assess and track changes in wall thicknesses and the depths of any pits or depressions that are present. Information on recommended tests for routine tube samples is provided in the subsequent section "Routine Analyses".

INTRODUCTION

Due to personnel turnover at both industrial steam plants and power plants, some facilities are not sufficiently familiar with standard practices for tube sample collection and analysis. This document is designed to provide consensus information for the sampling and analysis of tubes in boilers and nonnuclear steam generators. Information is grouped into the following sections.

- Routine Tube Sampling for Cleanliness Assessments
- Tube Sampling Following Tube Failures
- Tube Sample Removal, Identification, and Shipping Basics

ROUTINE TUBE SAMPLING FOR CLEANLINESS ASSESSMENTS

As a general rule, *routine tube sampling* is employed to assess the condition and cleanliness of tubes which are filled with steam/water mixtures during service. The primary objectives of routine tube sample collection are to measure the internal deposit weight per unit area and determine the deposit composition. This information is used to determine if a cleaning is required and can be used to assess the performance of the feedwater and boiler water treatment programs.

Waste heat boilers or process coolers with a shell and tube design are usually excluded from routine tube sampling. Collection of tube samples often is impractical due to the steam generator geometry or materials of construction.

In current practice, steam-cooled tubes generally are not sampled for routine cleanliness assessments. Steam tubes are sampled for the purposes of assessing the condition of the tubes and determining the remaining life. Such considerations are beyond the scope of this document. The procedures for sampling steam tubes in the event of a failure are covered by this document in the "Tube Sampling Following Tube Failures" section.

The deposit weight per unit area can be referred to as the deposit weight density (DWD), deposit density, deposit loading and the specific deposit weight. This document refers to this measurement as the deposit weight.

Standard methods for deposit removal and deposit weight measurement are presented in References 1 and 2. Some boiler manufacturers have provided suggestions for maximum acceptable deposit weights (3, 4). EPRI also has presented guidance on deposit weight limits for boilers and heat recovery steam generators (HRSG) as well as presenting other recommendations for determining the need to clean these units (5, 6). There is ongoing research in deposit weight limits (7).

Another objective of tube sampling is to perform dimensional measurements to assess and track changes in wall thicknesses and the depths of any pits or depressions that are present. Information on recommended tests for routine tube samples is provided in the subsequent section "Routine Analyses".

Fire tube boilers generally are not sampled for deposit weight assessments. Normal practice is to obtain a tube sample following tube failure to determine the failure mechanism.

Sampling Frequency

Tube samples should be collected on a schedule established by a risk assessment of potential failure in boilers operating at or above pressures of 600 psig (4.1 MPa). The goal over time is to have sufficient data to define the trend in deposit accumulation.

Tube sampling recommendations for power boilers and HRSG units are cited in the references (5, 6, 8). These references may prove useful when developing a sampling plan for a specific facility. Also, contact with the equipment supplier is suggested to see if there are recommendations regarding tube sampling frequency for the unit.

The consensus recommendation is that tube sampling be performed every one to five years and after any major boiler (or HRSG) water chemistry upset or tube failure. Tube sampling may not be an option for some specialty steam generators. Some plants prefer to chemically clean based on a fixed time period and do not routinely collect tube samples. However, a representative tube sample should still be collected in the outage prior to the scheduled cleaning outage to plan the cleaning process properly.

If a tube has failed and is being removed for failure analysis, both the failed tube and an adjacent tube, which has not failed, should be collected for analysis. When a tube fails, the failure process often blows out much of the internal deposits.

Tube Sample Location for Routine Evaluation

Collection of one or more tube samples from the area(s) of highest heat transfer is commonly recommended. However, this area is not always the location with the greatest amount of accumulated deposit. Collection of tube samples from the areas of highest heat flux and deposit weights are suggested. All of the following conditions have been known to cause greater deposition to occur in a localized area:

- Highest heat flux (highest heat transfer)
- Highest metal temperature
- First pass flow
- Settling
- Circulation problems (low water circulation or flow disruptions)

High Heat Flux. – Holmes and Mann cited a 1960 work by Mankina that studied the effect of heat flux on the rate of iron and copper oxide deposition (9). Oxide deposition increased with the square of the heat flux (9). More recent studies have shown different relationships between heat flux and deposition rates (10, 11).

Under equivalent conditions, all studies performed to date have indicated that waterside deposition rates are greater in areas of high heat flux. Also, excessive heat flux can also contribute to steam blanketing –although this usually is related to circulation problems, (see the

Circulation Problems section). Deposition on waterside surfaces results in a barrier which insulates the tube and leads to higher metal temperatures. High tube metal temperatures can lead to overheating of the tube microstructure.

Deposits, particularly metal oxide deposits, can also have significant porosity which has been found to contribute to the underdeposit concentrating mechanism. Higher heat fluxes result in greater rates of evaporation (steam generation) per unit area. During operation, water diffuses through porous deposits and evaporates at the tube/deposit interface. This results in evaporative concentration of salts and other dissolved materials. In drum type and other subcritical boilers and steam generators, this evaporative concentration of salts and other materials at the tube surface can result in under deposit corrosion (UDC).

For boilers, the best means of assessing the area(s) of highest heat flux is to perform thermal imaging studies of the furnaces. For HRSG units, arrays of thermocouples have been installed to detect areas of sudden temperature changes. These data also may be used to locate areas with the highest gas temperatures. Flue gas velocity profiles also can indicate those areas in HRSG units that are expected to have the greatest heat flux (at a constant gas temperature the highest gas flow corresponds to the highest heat flux). Sometimes temperature data from boilers or HRSG units are evaluated using computational fluid dynamic (CFD) analyses to target specific areas prone to high heat flux. Most facilities have not performed these types of temperature or CFD evaluation. Sometimes, plant personnel have observed the furnace well enough during operation to know the area of highest heat transfer (e.g., areas experiencing flame impingement during operation).

High Metal Temperature. – In the preceding list, a distinction was made between areas with the highest heat transfer and areas with the highest temperature. In drum type units, these areas usually will be the same. However, in once through supercritical (OTSC) boiler designs they could be first pass tubes, second pass tubes, or both first and second pass tubes. In one type of design the first pass is a center or division wall between two furnaces and the second pass tubes are in separate (outer) walls. In other OTSC boilers, first and second pass tubes often are literally adjacent tubes in the same wall and have the same heat flux on the fireside surface, but the fluid travels from the first pass to the second pass and so the fluid and the tube itself will be hotter in the second pass. Since there is no phase change at supercritical pressures, when fluids are heated the temperature of the fluid continues to rise as it flows through the first and second pass waterwall tubes.

In supercritical boiler designs, the fluid's thermal conductivity decreases significantly as the temperature increases (See Figure 5 in Reference 8). For example, for water starting at 4000 psig (27.6 MPa) and 590°F (310°C), the relative thermal conductivity drops to 82% of the original value at 680°F (360°C) and to 32% at 770°F (410°C) (calculated from data available in Reference 12). As stated by Weick "The low thermal conductivity of the water filling the pores is responsible for the insulating effect of the magnetite layer" (8). Therefore, a deposit layer in a second pass tube will be more insulating than the same deposit layer in a first pass tube as a result of the higher fluid temperatures. Deposits in first pass tubes usually will have a higher proportion of corrosion products transported from the preboiler cycle. Samples of both first pass and second pass tubes should be collected and the deposit weights and compositions analyzed for one first pass tube sample and one second pass tube sample.

First Pass Flow. – The preceding discussion explained that deposits in first pass tubes in OTSC boilers will be dominated by feedwater corrosion products. However, this general principle of deposition of feedwater contaminants on first pass tubes also can apply for some types of drum type boilers. There are basically two locations for this type of deposit: high-temperature economizer tubes and traditional generation bank type tubes.

If the feedwater temperature in the economizer is greater than 500-550°F (greater than 260-288°C), iron oxides and other materials have been known to deposit in the economizer in some instances. This is primarily a concern in units that have experienced periods of very high iron oxide concentrations in the feedwater (e.g., during commissioning or frequent startups) or that have operated for many years without chemical cleaning of the economizer (e.g., 15-20 years or more).

In boilers with a drum-type generation bank (tubes between a mud drum and a steam drum), the downcomer tubes also can be subject to localized deposition. In this design, the water passes through these tubes before reaching other areas of the furnace. Therefore, the composition of deposits in the downcomer will be more reflective of feedwater contamination. In industrial boilers with hardness in the feedwater, the proportion of hardness compounds (e.g., calcium hydroxyapatite [calcium phosphate], serpentine [magnesium silicate], and munsonite [magnesium phosphate]) in the generation bank can be quite high.

Because of the relative ease of hydrojetting generation bank tubes and the difficulty of removing a tube sample from this location, generation bank tubes generally are not collected. Most facilities elect to hydrojet these tubes if they appear to be dirtier than the waterwall tubes. If dispersants are routinely added during operation, precipitation in the drums and generation bank tubes may be inhibited and heavier deposit accumulations may be found elsewhere in the boiler.

Gravity Settling. – Areas susceptible to settling are obvious by looking at a side view diagram of the unit. Areas closer to horizontal are expected to experience settling during shutdown periods, when the boiler or HRSG is drained, and during operation if there is heat flux on the lower surface. Such areas include nose tubes, roof tubes, sloped screen tubes, and bent tubes around ports in the walls. Sludge also can be left on sloped tubes following chemical cleanings. Residual solids can bake on tube surfaces during subsequent operation and lead to excessive deposit accumulations. Sometimes rapid drains of the boiler can effectively remove loose solids. Occasionally, flushing of individual tubes is required after a cleaning, but flushing can be impractical for many units.

Circulation Problems. – Water circulation problems can occur in both forced circulation and natural circulation units. In forced circulation units, orifices can be improperly sized or become obstructed with deposits or debris. In OTSC boilers, with small diameter tubes, weld penetration can cause reductions in the internal diameter and flow disruptions. Also, bolts and other debris have been found to obstruct tubes in such boilers. In natural circulation boilers, large debris (e.g., paint can lids or remnants of tubing removed from other locations) has restricted water flow as well.

Circulation problems in natural circulation boilers and HRSG units can be a consequence of design. Natural circulation relies on the fluid density differential between the riser tubes and downcomer pipes/tubes. The density difference depends primarily on the amount of steam (steam quality) and the height (or length) of the portion of the riser tube containing steam.

Circulation problems can be caused by low or high steam qualities or short riser lengths. While rare, if the steam quality is sufficiently high, deposits can form because there is not enough water present in the steam to hold the deposits in suspension. Gas/fireside conditions such as slagging, gas lane short circuiting and other factors which affect the amount of heat entering the tube also can contribute to imbalanced circulation. If there is insufficient water circulation, boiling on heat transfer surfaces can change from numerous tiny bubbles (nucleate boiling) to a continuous film of steam, which is commonly called departure from nucleate boiling or film boiling. This can happen in areas of high heat flux due to extremely rapid startups and in areas of low heat flux. In areas with low heat transfer and extremely poor water circulation, there have been cases of a tube experiencing flow stagnation and acting as a collector for a mixture of water soluble salts and other material.

Steam blanketing can also occur due to a combination of tube geometry and circulation problems when the heat flux is not excessive. Such an effect usually happens because inclined tubes, which are prone to steam/water stratification, are more commonly installed in low heat flux areas. One example is in reverse slope tubes in which the steam generation occurs on the top side of the tube in an area of relatively low heat flux. Sloped nose, roof and floor (also called lower slope) tubes can experience a similar phenomenon.

Typical Sample Locations. – Table 1 was developed to serve as a quick reference of routine tube sample locations and is a compilation of suggestions provided in reference 8 that have been modified to reflect the experience of the committee. Table 1 provides a good starting point for collecting one or two samples from base loaded units when determining boiler or HRSG cleanliness.

Table 1. Summary of Routine Tube Sample Locations for Boilers & HRSG Units

Burner Location	Tube Sample Location		
	Wall / Row	Elevation	Horizontal Position
Front Wall Fired (Single Burner) Package Boiler	Side Wall (radiant wall enclosure, "A" or "O" type, "D" type, "D" wall or baffle wall)	Centerline of Burner	1/4 to 1/3 from Burner Wall (1/2 to 2/3 from Burner Wall, with low NOx burner)
Single Wall (Set of Burners) Fired Boiler	Target Wall & Division Wall (If Present)	Centerline to 10ft (3m) Over Top Burner Row or Top Commonly Used Row (a)	Center of Target Wall and 1/3 from Target Wall for Division Wall
Opposed Wall Fired Boiler	Nonburner Wall	Centerline to 10ft (3m) Over Top Burner Row or Top Commonly Used Row (a)	1/3 to 1/2 Distance from Burner Walls
Tangentially Fired Boiler	Side Wall & Division Wall (If Present)	Centerline to 10ft (3m) Over Top Burner or Top Commonly Used Burner Row (a)	Center of Side Wall & about 1/3 from Front Wall
Black Liquor Recovery Boiler	Side Wall	Between Primary & Secondary Air Ports	Center of the Wall
	Any Wall	Immediately At & Above Composite Tube Cut Line	--
Once Through Boiler (Supercritical and Subcritical):	Both 1st Pass and 2nd Pass (a) from		
(Opposed Wall Fired)	Nonburner Wall	Centerline to 10ft (3m) Over Top Commonly Used Burner Row	1/3 to 1/2 Distance from Burner Walls
(Tangentially Fired)	Side Wall & Division Wall (If Present)	Centerline to 10ft (3m) Over Top Burner Row or Top Commonly Used Burner Row	Center of Side Wall & about 1/3 from Front Wall
Horizontal HRSG (Vertical Tube) Unit with Duct Firing	First Row of HP Evaporator	As High as is Convenient or 2 ft (0.6 m) Above The Bottom Duct Burner. Videoscope Above and Below to Evaluate Sample Representativeness	1/3 of Distance from Wall from which the Gas is Supplied to the Duct Burners
(a) In some spiral wall boilers, the second pass is straight tubing, which forms a wall starting just above the overfire air ports. The second pass sample should be collected just above the entrance to this wall.			

The preferred horizontal position of tube samples can vary depending on the shape, alignment and heat input of the burner flame. For example, the table includes two single wall fired designs with different sample walls. Package boilers can have a relatively narrow furnace and the flame can be relatively short and wide, which tends to put more heat in the side walls. Larger single wall fired boilers will tend to have a design that allows more heat to reach the target (opposite) wall. This is especially true if low NOx burners are installed.

For boilers that are not consistently operated with all of their burners in service, the area of high heat flux may change. Normally, the upper burners are the last burners placed in service. Therefore, Table 1 suggests tube sample locations in reference to the top set of burners that are commonly used. Also, if the unit is operated at low loads, the flame may be shorter and the horizontal position of tube samples may need to shift closer to the burners.

Figures 1-5 provide simplistic sketches of the basic firing designs referenced in Table 1. Since the preferred sample location can be unit specific, angle wall fired boilers (Figure 6) are not included in Table 1, but these boilers are discussed subsequently. ***In Figures 1-6, the arrows show the basic flow of fuel into the furnace.*** For information on the nomenclature used for samples, see the Tube Sample Identification section.

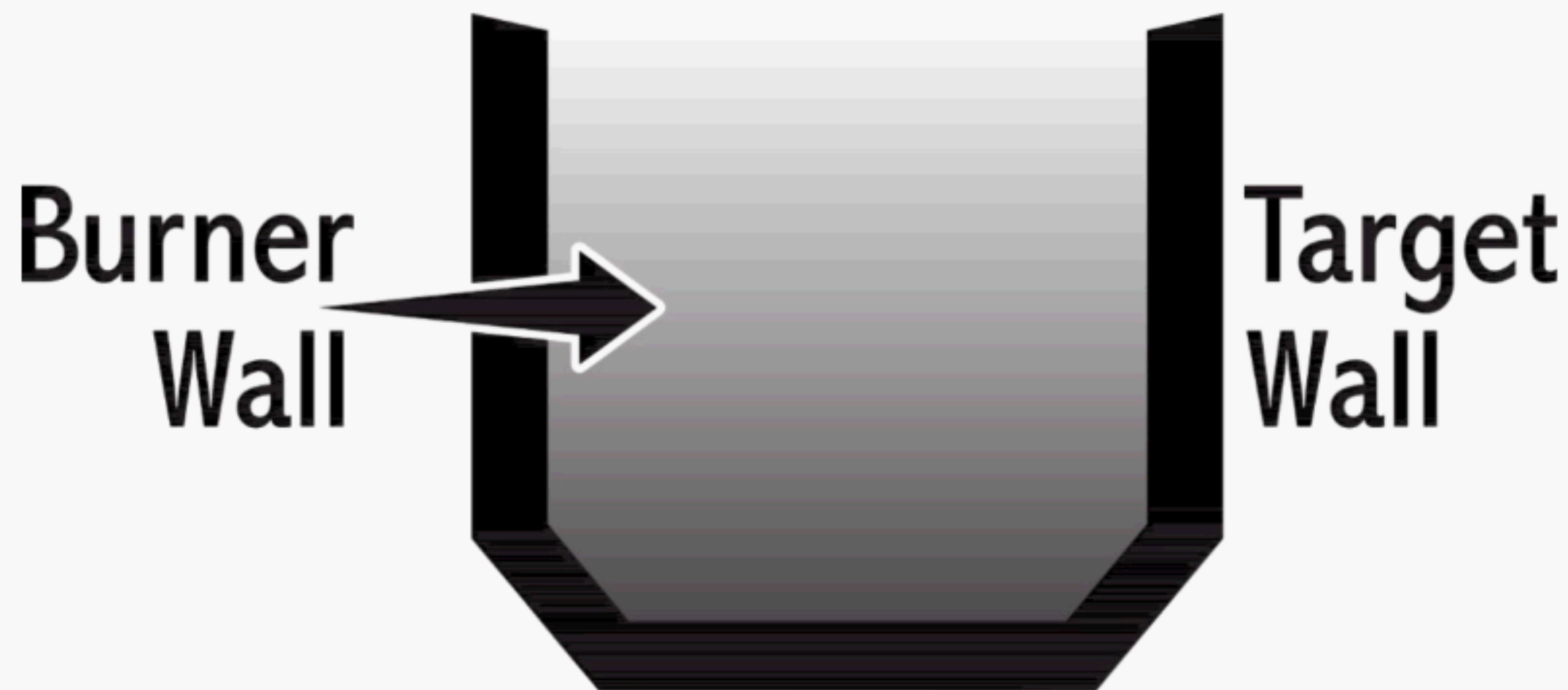


Figure 1. Single Wall Fired Boiler, Side View

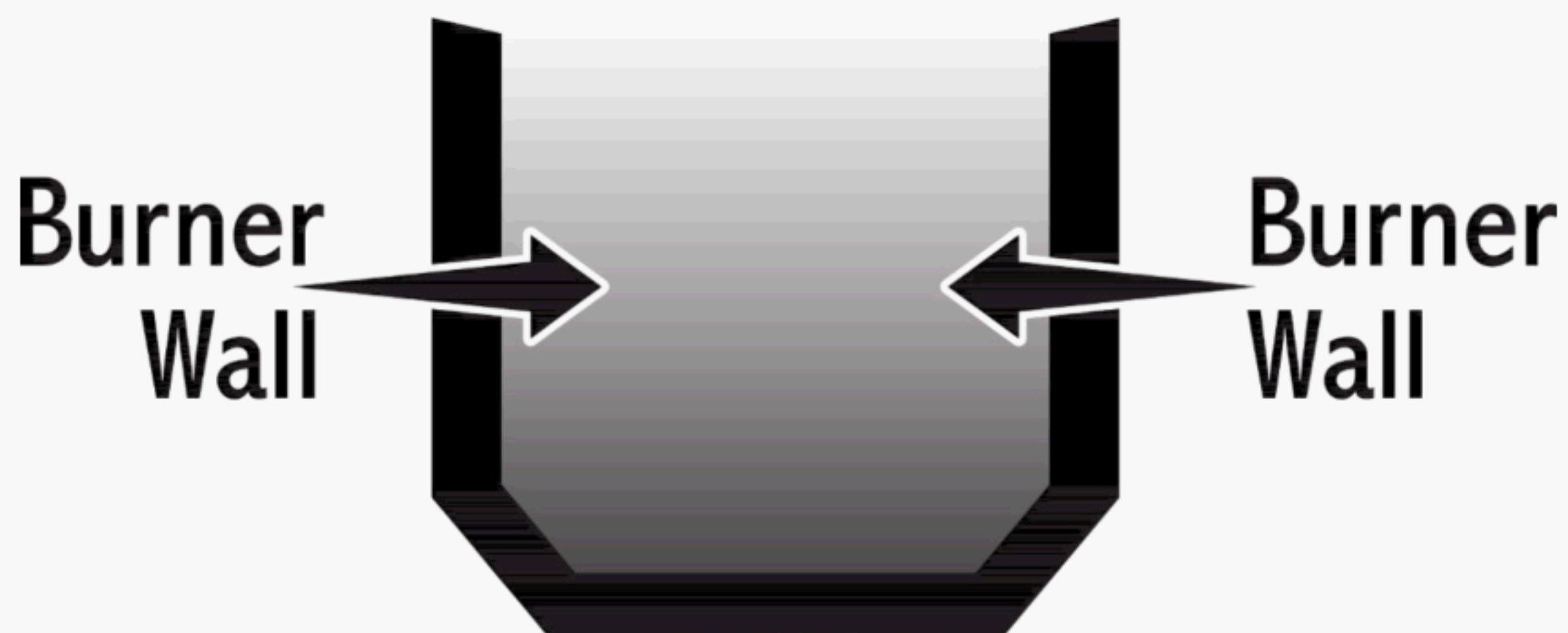


Figure 2. Opposed Wall Fired, Side View

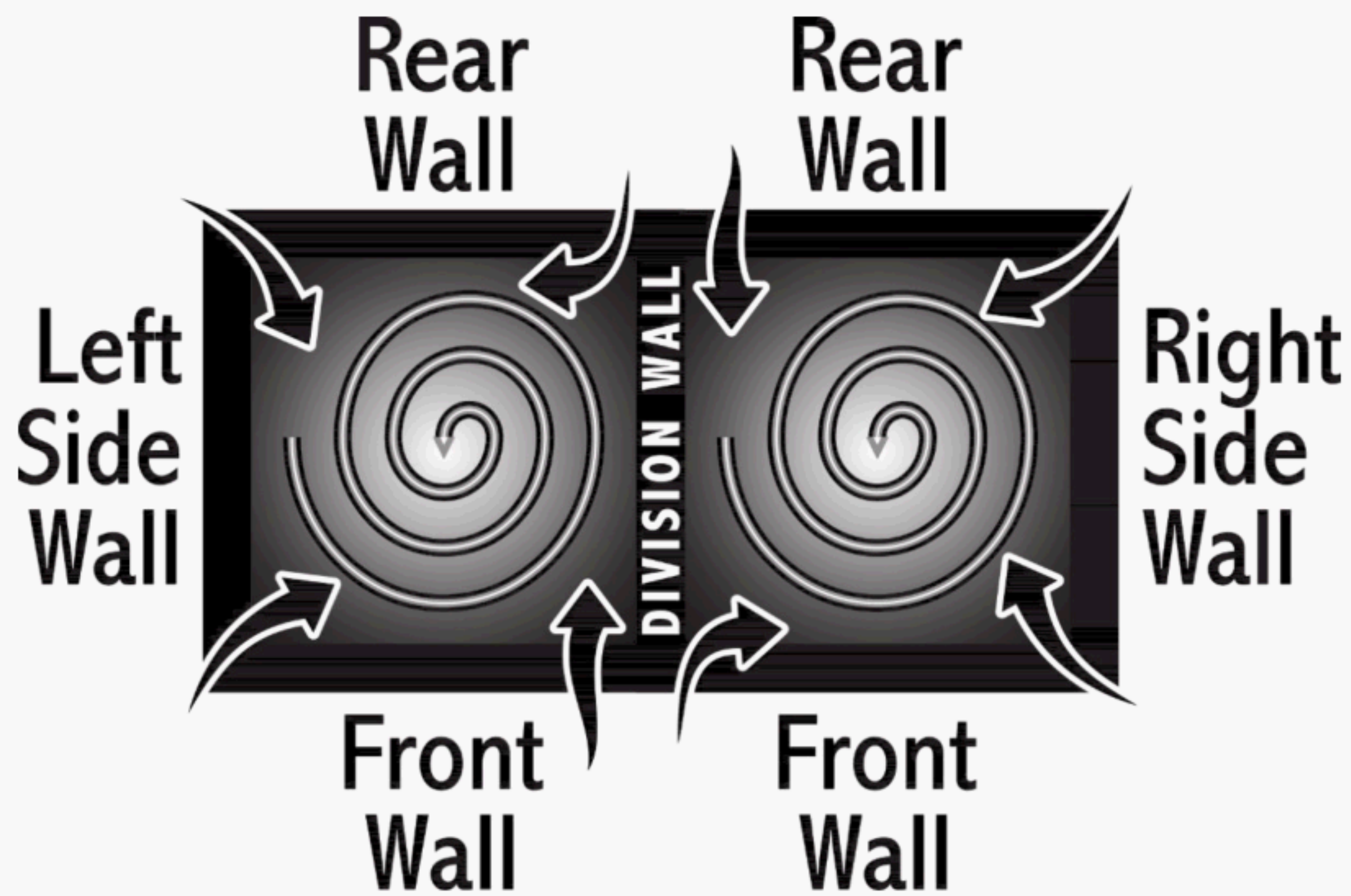


Figure 3. Tangential Fired Boiler with Division Wall, Top View

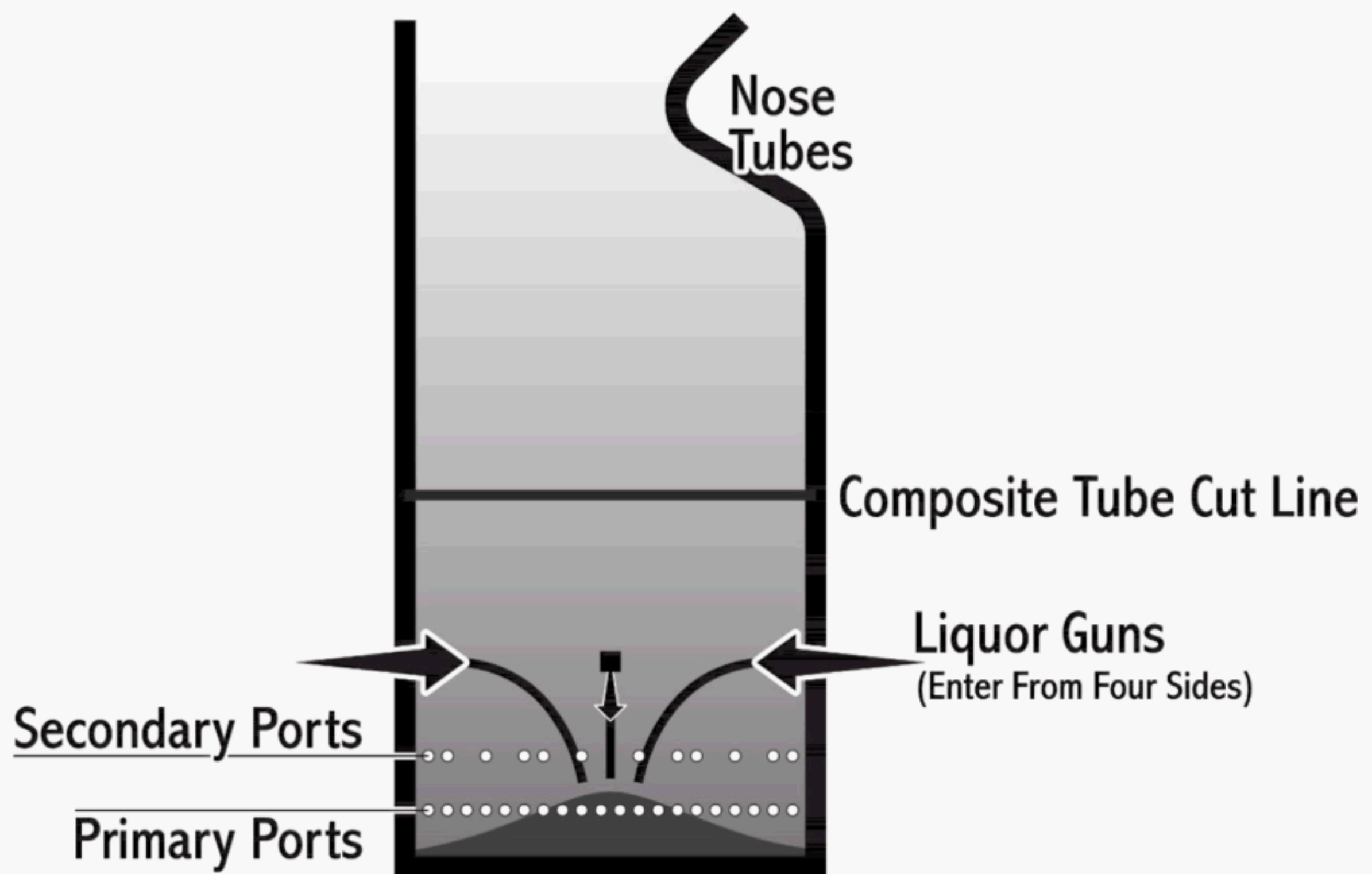


Figure 4. Black Liquor Recovery Boiler, Side View

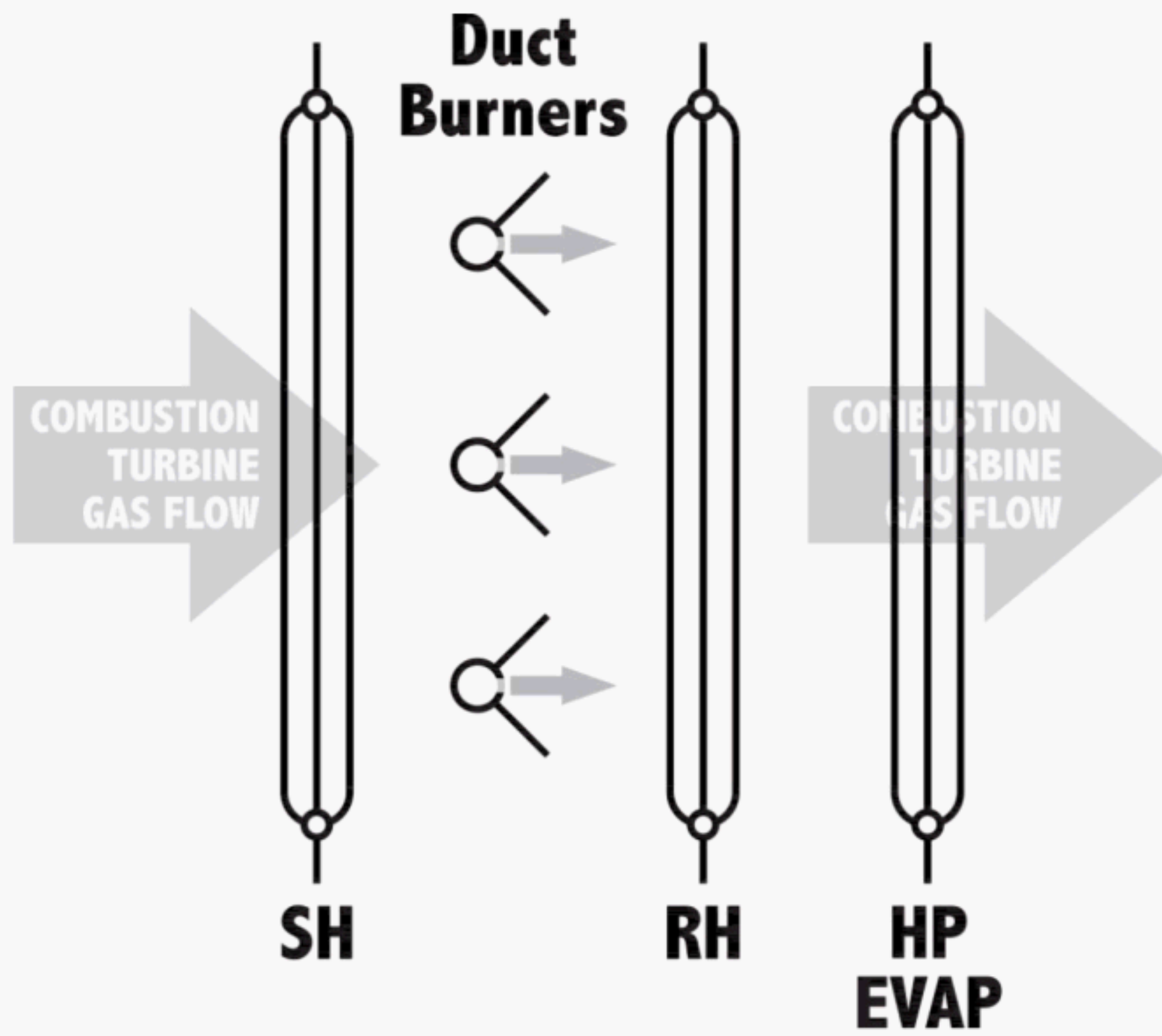


Figure 5. Horizontal Gas Pass HRSG with Duct Burner, Side View

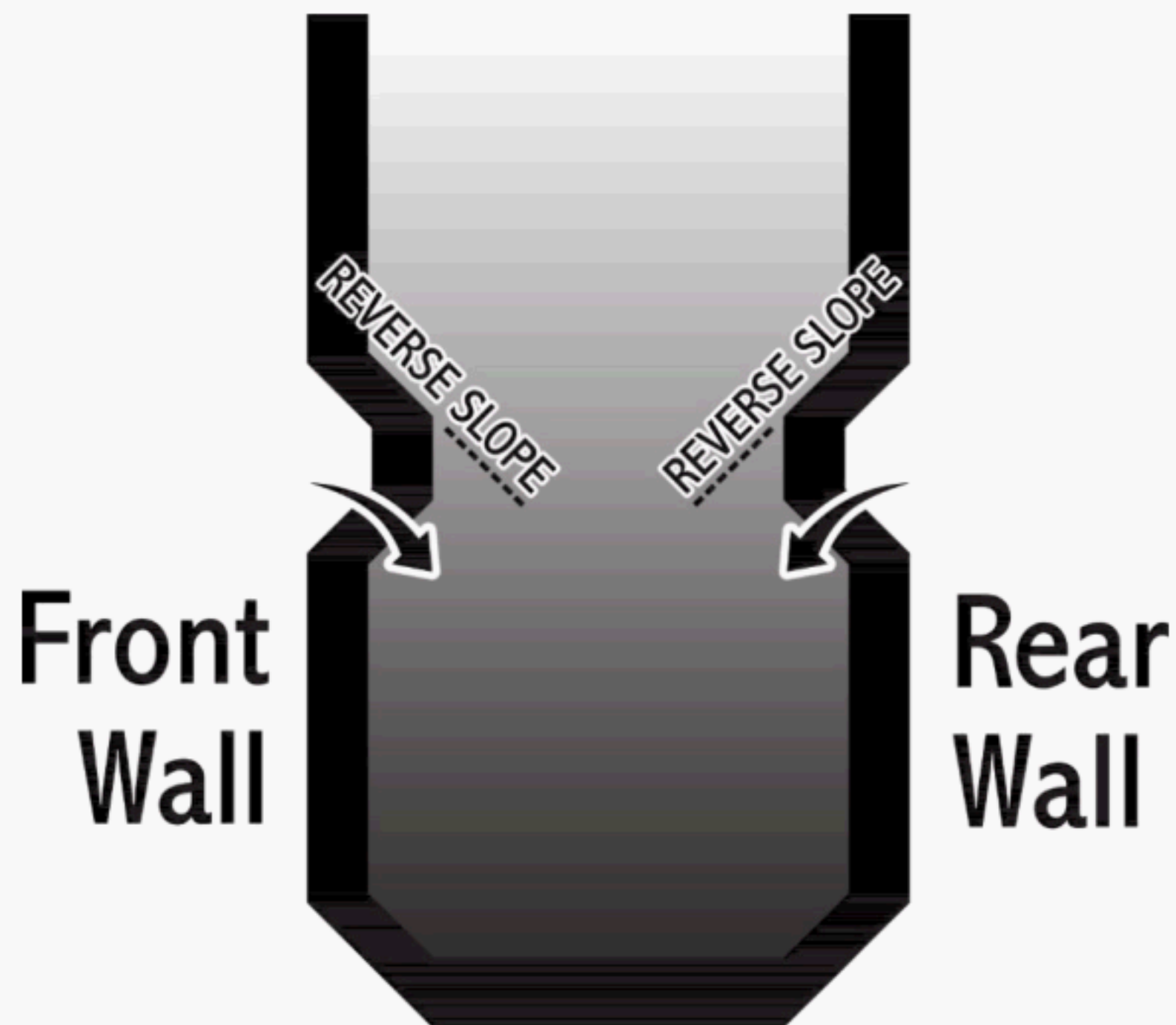


Figure 6. Angle-wall Fired Boiler, Side View

The boiler or HRSG manufacturer recommendations, Table 1, and consideration of the preceding criteria should aid the user in identifying appropriate tube sample locations. The following list provides other areas and factors to consider for these and other boiler or HRSG designs when selecting tube sample locations.

- Angled Wall-Fired (Turbo Furnace) Boilers. In this design (Figure 6) the middle of the furnace is narrower than above or below the burners. In units with burners mounted in angled front and rear walls (i.e., in which the burners protrude directly from these downward sloped sections of walls and therefore angle down into the furnace), consider the following areas: in the slope around the burners, in the reverse slope tubes just above the burners and from the side wall about 1/5-1/4 of the distance from the rear burner wall. The preferred locations can be unit-specific and so they were not included in Table 1.
- Wall-Fired Boilers with Roof or Nose Tubes. Over extended periods (two or more decades), these sloped tubes can accumulate sufficient deposits to cause tube failures despite fairly low heat fluxes. For roof tubes, the deposits tend to be greatest just above (within first 2-5 feet or 0.6-1.5 m of) the turn from the vertical wall. In some boiler designs, the nose tubes can experience significant heat flux and can accumulate heavy deposits and experience tube failures in much shorter service intervals.
- Wall-Fired Boilers with Lower Slope. Many wall-fired boilers have a lower slope well below the burners. While excessive deposits are not common, at least a few units have been found to have localized deposits in these tubes.
- Cyclone-Fired Furnaces. It used to be customary to sample the re-entrant throat tubes. However, in recent years one manufacturer has recommended sampling screen tubes from the centerline of the cyclones directly in front of one of the cyclone furnaces (samples should alternate between the cyclones).
- Fluidized Bed Boilers. Waterwall tubes should be sampled just above the region with the refractory. Also, if used, the steam generating tubes that are immersed in the fluidized fuel (e.g., an in-bed steam generating tube, or an external fluidized bed heat exchanger) should be sampled.
- Grate-Fired Boilers. Grate-fired boilers are commonly used to burn various forms of biomass (bark, sawdust, bagasse) and other materials (tires, refuse, coal). Waterwall tube samples should be collected 2-8 feet (about 0.6-2.4 m) above the grate. The actual locations of highest heat flux can be in the side wall 1/3 distance from the ash discharge wall or from the center of the ash discharge wall itself. Heavy deposits have also been found around air ports for some grate-fired boilers.
- Black Liquor Recovery Boilers. Samples should be collected from waterwall tubes between the primary and secondary air ports, or immediately above the cut line between the composite tube region and the upper furnace tubes. Upper furnace tubes have also been found to contain heavy deposits on a few units.
- Red Liquor Recovery Boilers. Lower screen tubes and tubes that have lost refractory in the primary furnace should be sampled. If the nose in the primary furnace loses refractory, severe deposition may be expected.

- HP Evaporator Tubes in Horizontal Gas Path (Vertical Tube) HRSG. If the units have duct burners, target 1/3 of the distance from the wall with the gas burner supply. For vertical tube evaporators, the following elevations have been recommended by three different HRSG suppliers:
 1. Two feet (about 0.6 meter) above the bottom duct burner,
 2. In the center of the tubes, and
 3. Near the tops of the tubes (location of highest steam quality).
- For Horizontal Gas Path HRSG Units, it can be difficult to collect a sample at the upper two elevations (items 2 and 3 listed above) during the typically short outages used at HRSG plants. Collecting a sample closer to the bottom (as high as can be reasonably removed without scaffolding or at 2 feet (about 0.6 m) above the bottom duct burner) may not represent the location with the highest deposit weight (worst case). However, these samples can provide useful information to indicate whether deposit accumulation may be a problem in the unit. Therefore, this was the elevation included in Table 1. This information can be used to justify more extensive scaffolding of the furnace in a future outage.

Some owners select outer lane tubes if there are indications of gas bypassing the upstream superheaters. If the unit has experienced plugging of the gas pass or loss of baffles, one should focus on areas expected to have the highest flue gas flow rates. Typically, the first row tubes are sampled. While it has been common to expect the first row tubes to be those experiencing the highest heat flux, one also has to consider the amount of fins applied to the tube. In some cases a second row tube with more fins may absorb more heat than a first row tube without fins.

- For Vertical Gas Path HRSG Units (with Horizontal Tubes). The greatest deposits can be at the point at which steam first starts to form. Consult the HRSG manufacturer regarding suitable sample locations.
- Failed Tubes in Boilers and HRSG Units. It usually is best not to select a tube that has experienced a failure, especially a failure that results in deformation of the metal (such as bulging or rupture) for deposit weight analysis. This can result in spalling of the deposits from the tube surface and result in a lower deposit weight than actually present. Samples for deposit weight analysis should preferentially be removed from tubes next to those that have experienced a failure. However, failed tubes should also be sampled and analyzed to determine the failure mechanism.

If only the failed tube is sampled, a sufficient tube length should be removed to assess the deposition on both sides of the failure. In some units, circulation problems can result in an adjacent tube having vastly less deposit and a deposit weight assessment is needed on both the failed tube and the adjacent tube. Flow disruptions can occur downstream from circumferential welds used for tube replacement, and this typically results in higher localized deposit loading values. If a tube is sampled that contains a circumferential weld that protrudes from the internal surface of the tube, then remove a section that extends at least 2 feet (about 0.6 m) from the weld on either side. As a boiler is only as clean as the dirtiest area, the weld location is a valid sample. Sometimes the deposit weight is

determined both at the weld and away from the weld to characterize average and localized deposit accumulations.

- **Sampling Newer Tubes.** Tubes that have been repaired or replaced since the last chemical cleaning will not be representative of the heaviest deposits, but can be used to indicate deposit accumulation since the tube was installed. This can be useful when there have been chemistry upsets or major changes in the treatment program.
- **Boilers and HRSG Units with Prior Cleaning Problems.** Cleaning problems may be related to inadequate solvent movement or insufficient flushing. Videoscopic inspections of each type of circuit can be particularly useful in evaluating this possibility.

Initial Deposit Weight Survey for Units with No Tube Sampling History

Each boiler and HRSG is a little different, and localized, heavy deposits have been found in nearly every region of the boiler furnace and HRSG. For boilers this has included the following areas: upper furnace of the waterwalls, roof tubes, lower slope, floor tubes, screen tubes, and generation bank tubes. For boilers and HRSG units that do not have an established deposit history, an initial deposit weight survey consisting of the following activities is suggested.

- **Collection of one tube sample from each type of water circuit.** Since deposits on the walls can vary, each wall is considered a separate circuit. In some cases, segregated top and bottom headers and differences in localized heat input can require several samples along a wall to sample the different circuits properly. For some units, sampling and analyzing each of these circuits is not practical (e.g., one unit had 17 unique circuits) and lesser numbers of tubes are used for the initial survey.
- **A videoscopic inspection of surfaces above and below each removed tube section to aid in assessing the representativeness of the samples collected.** This inspection can also be used, if necessary, to adjust sampling elevation if greater deposit accumulation appears to be at a location away from the sample point. Determining the relative amount of deposition on the internal surface of a tube may be difficult by videoscopic inspection, unless there is a considerable difference in the amount of material, the texture of the deposits, or possibly coloration.
- **A videoscopic inspection of generation bank tubes** because these banks generally cannot be sampled.
- **A videoscopic inspection of evaporator tube bundles via access ports in the belly plates in the HRSG steam drum.** Such access ports are incorporated in the original equipment by some HRSG manufacturers. In other cases, such access ports have been installed subsequently in HRSG units following a period of operation to aid in identifying areas of tubes with localized deposition or wall thinning.

A survey of tube sample locations will indicate which areas will tend to have more deposition. Once identified, the area(s) with the greatest accumulation of deposits will be used as the reference or preferred location for subsequent tube sampling. Once tube deposit weight measurements have been obtained for tube samples collected from multiple sampling locations, future tube samples can be collected from only those areas found to have the greatest deposit weights. However, it is good to occasionally review the full list since deposits can sometimes

preferentially remain or settle in other areas following chemical cleanings (e.g., sloped tubes). Also, changes in fuel, burner design, burner usage, air distribution, excess air, startup frequency, or startup firing practices can shift the areas in which the heaviest deposits form and require more extensive tube sampling to assess the effects of these changes on deposition rates.

Some facilities have started to routinely perform a videoscopic inspection of interior surfaces of tubes above and below tube sample locations. This information can be used to evaluate the representativeness of the samples, to determine more appropriate future sample locations, and to provide additional information on boiler cleanliness. This practice is suggested for units which have had a chemistry upset, variable chemistry control, circulation problems, or use dispersant treatment.

Deposit Analyses

Waterside deposit weight and composition should be determined separately for both hot and cold side surfaces of the tube specimens. Comparison of the amount and type of deposits on each side can provide valuable information. If a large number of tubes are collected as part of a tube survey, deposit weight should be determined for each sample. The compositions of the hot and cold side deposits may be analyzed for a limited number of representative tube samples, but only if the deposition appearance is consistent on the collected samples.

Deposit Weight. – Preferred deposit weight removal methods are the mechanical method (ASTM D3483, Method A) and the bead blast method (ASTM Method C or NACE procedure (1, 2). The bead blast method was added (as Method C) to ASTM D3483 in 2005 (1). Preferably, the same method should be used for deposit weight trending over time. If the method is switched, both methods should be performed to have comparison data for future reference. The mechanical method and the bead blasting procedures yield comparable results (1, 2) when they are properly performed.

ASTM Method A (mechanical method) uses wording that may be interpreted incorrectly to mean that scraping may be sufficient and vibrational removal of tube deposits is optional (1). However, complete removal of waterside deposits from boiler and HRSG tubes always requires the use of a vibrating tool for this method. Boiler tubes can appear to be clean after scraping and still have large amounts of uniform, adherent scale present. Close inspection of the tube surface is required to assure complete removal of all material if this method is used.

The chemical cleaning (solvent removal) method (ASTM, Method B) may be used, but the results are less accurate at lower deposit weights. This makes trend analysis of deposit accumulation rates difficult (1, 8). Also, the results from the chemical cleaning method (ASTM, Method B) are consistently higher than actual, since they include a contribution from iron dissolved from the tube surface during the cleaning process. Deposit removed by the mechanical method can be used directly for composition analysis. If either the glass bead or solvent methods are used, a separate step will be required to obtain a sample for deposit analysis.

Metallographic Deposit Thickness. – For once through supercritical boilers, a metallographic evaluation of a cross section of deposits has been found to provide useful information when assessing the need to chemically clean. This provides the deposit thickness and can be used to assess if a duplex oxide is present. Measuring the deposit thickness with a micrometer usually is not sufficiently accurate for the low thicknesses allowed in these boilers.

Deposit Composition. – Table 2 presents a summary of the chemical constituents which are commonly quantified or assessed as part of the deposit composition analysis. As indicated in the table, most of the elements are normally expressed as oxides. This can facilitate subsequent estimation of the compounds present in the deposits.

Table 2. Common Analyses for a Waterside Deposit Composition Analysis

Species Name	Symbol	Commonly Expressed as Weight Percent as Following Oxide, *
Iron	Fe	Fe ₃ O ₄ **
Copper	Cu	CuO
Nickel	Ni	NiO
Zinc	Zn	ZnO
Chromium	Cr	Cr ₂ O ₃
Molybdenum	Mo	MoO
Aluminum	Al	Al ₂ O ₃
Manganese	Mn	MnO
Calcium	Ca	CaO
Magnesium	Mg	MgO
Sodium	Na	Na ₂ O
Phosphorus	P	P ₂ O ₅
Sulfur	S	SO ₃
Chlorine	Cl	Cl
Silicon	Si	SiO ₂
Lead	Pb	PbO
Carbon	C	Presence or Relative Amount
Carbonate	CO ₃	Presence or Relative Amount
Loss On Ignition Also Should Be Determined On At Least One Tube From Sample Sets Unless Other Means Are Used To Demonstrate That Carbon Is Not Present In Significant Amounts In The Deposits. *Laboratories Have Different Reporting Conventions (E.G., As Elements Or As Various Oxides). Be Sure To Understand The Convention Used - Particularly When Comparing Results From Different Laboratories. ** Some laboratories report iron as Fe ₂ O ₃ . Multiply % iron as Fe ₂ O ₃ by 0.9666 to convert to % iron as Fe ₃ O ₄ .		

Table 3 presents additional elements, which are occasionally found and require quantification in waterside deposits. ASTM D933 indicates that some of these elements along with nitrate, sulfite and sulfide should be quantified (13). However, nitrate and sulfite usually are not expected in boiler waterside deposits and sulfide can be difficult to quantify. Qualitative tests for sulfide are advised for industrial boilers, which may have sulfide contamination of the feedwater. If sulfide is detected by a qualitative test, total sulfur should be quantified in the deposits.

The presence of carbonate in deposits can be inferred by effervescence upon acidification of a deposit sample, use of various loss on ignition or thermogravimetric tests, and hypothetical combinations of the deposit composition test results. Carbonate compounds are crystalline and can be detected by x-ray diffraction analysis.

Table 3. Supplemental Elements Occasionally Requiring Quantification in Waterside Deposits from Boilers or HRSGs

Element Name	Elemental Symbol	Commonly Expressed as Following Oxide
Barium	Ba	BaO
Cobalt	Co	CoO
Lithium	Li	Li ₂ O
Potassium	K	K ₂ O
Strontium	Sr	SrO
Tin	Sn	SnO ₂
Titanium	Ti	TiO ₂

Deposits usually consist of two or more layers. A representative composition analysis requires a representative sample. If Method A of ASTM D3483 was properly used for the deposit weight analysis, then a representative sample will be available already. If the glass bead blasting method was used, additional deposit must be removed from a separate section of tube for composition analysis. As discussed earlier for ASTM D3483, merely scraping the surface deposits is not sufficient and a vibrating tool is required for complete deposit removal. Mechanical deformation of the tube sample can be used to crack hard, tenacious deposit layers from the tube surface in some cases.

A number of different methods are available to analyze the composition of deposits. The following paragraphs discuss the most common methods currently used.

A reliable means of elemental composition analysis involves digesting the sample and performing a quantitative analysis on the solution (e.g., via atomic absorption spectrophotometry (AA) or inductively-coupled plasma (ICP)). Detection or quantification of chlorine or certain sulfur species requires supplemental procedures by the laboratory. The ability to detect chloride or sulfur depends on the solvents used by the laboratory for digestion of the deposit sample. Such procedures are considered proprietary by some laboratories. As discussed later, a separate leaching and analysis procedure may be used to accurately quantify soluble ions.

X-ray fluorescence (XRF) is also a reliable method for direct analysis of the elements in the deposit. However, XRF usually requires one to two grams of deposit, which is a much larger sample size (see ASTM D2332-08) than is typically available from tube deposit weight analyses (14).

Semi-quantitative methods such as Scanning Electron Microscopy Energy Dispersive X-ray Spectroscopy (SEM/EDXS) are also often used for determining deposit composition. An advantage of SEM/EDXS and XRF is that they simultaneously detect all of the expected elements (Table 2) and most of the unexpected elements (Table 3 - except for lithium), which may be present in boiler tube deposits. However, elements with an atomic number less than boron, such as lithium, cannot be quantified by these techniques. Also, since SEM/EDXS only analyzes a very small portion of the deposit, it may provide misleading results due to a local sample variation. Therefore, homogenizing the sample is more critical for SEM/EDXS than for the other methods of analysis. For example, localized variation has occasionally been noted in boiler tube samples containing metallic copper. Since it is a very fast analysis method, SEM/EDXS is often used when a quick indication of deposit composition is required.

The loss on ignition (LOI) should be determined for all deposit samples from industrial boilers or boilers for which carbon contamination is expected. This involves heating the sample at high temperatures until a constant weight is obtained. ASTM D4025 specifies a temperature of 900°C, which can be obtained in a muffle furnace (15). The problem with a muffle furnace is that the sample cannot be observed during the heating process. Some laboratories have had good results using staged heating with an open electric heater and then a propane torch to view the sample during the LOI test, and they only use the fixed high temperature muffle furnace approach if a constant weight is not rapidly obtained with the observed heating steps. A slow weight change when heated usually means that there is significant carbonate present, which requires about 900°C for prompt removal. Water of hydration, methylene chloride extractables, organic compounds (carbon, hydrogen, and nitrogen), many sulfur compounds, and the carbon dioxide from most carbonates are typically removed during an LOI test.

Thermo-gravimetric analysis (TGA) can be used by heating the sample in air. Weight loss that occurs from 45 to 220°C is attributed to waters of hydration, from 220 to 600°C organic carbon is lost, and finally from 600 to 900°C the weight loss is from decomposition of carbonates. The sum of these weight losses should equal the LOI at 900°C.

SEM/EDXS analyses cannot reliably quantify organic matter in the deposits, but it can indicate if carbon content is elevated. Carbon can be present as inorganic carbon (e.g., as calcium carbonate from raw water contamination) or as organic carbon (e.g., as carbon from oil contamination). For tube samples with high deposit weights and those suspected of having significant amounts of organic matter present, the total carbon content should be determined. Metallic copper will oxidize during the LOI test and gain weight. This effect can obscure the presence of carbon in deposits analyzed by LOI. Performing SEM/EDXS analysis of the deposit sample remaining after the LOI test may result in slightly more representative indications of the total copper content because the metallic copper should be oxidized. For samples with significant amounts of sulfur present, the total sulfur content should also be determined.

The total carbon and sulfur analyses are generally not required for routine deposit analyses for power industry and other high pressure boilers. Also, the sample size required for these tests can be greater than is typically obtained from tube samples during routine tube sample analysis.

Boiler and HRSG deposits usually contain little or no water soluble compounds. However, if significant amounts of sodium, potassium, chloride or sulfate are present, then the proportions of water soluble elements should be determined. This is sometimes requested as part of an analysis of a tube that has indications of active corrosion, steam blanketing, or evaporation to dryness on waterside surfaces. First the water soluble compounds must be leached from the deposits into a known volume of demineralized water. Then, the leachate is filtered and analyzed. There was not a consensus on use of a leaching procedure.

Boiler tube deposits generally do not contain sufficient amounts of solvent extractable materials. However, for deposits from boilers receiving treated produced water or other steam systems in which significant tar or hydrocarbon contamination may be present, solvent extraction procedures should be considered. Partial guidance for this approach is provided in ASTM D4025 (15).

X-ray diffraction (XRD) analysis is a definitive means of identifying crystalline compounds present. XRD analysis is a supplement to elemental analyses of a deposit sample, rather than a substitute. Sometimes a significant amount of material in tube deposits has a noncrystalline

(amorphous) structure. The XRD pattern will provide an indication if noncrystalline material is present, but specific amorphous compounds are not identifiable without detailed analysis of the pattern and knowledge of the elements in the material. Commercial laboratories are generally not able to perform this type of detailed analysis. XRD analyses generally are not required for the characterization of high pressure boiler deposits. ASTM D934 states that XRD results can be reported as major (>5%), minor (0.5-5.0%) and trace (<0.5%) compounds (16). However, it is more common for laboratories to report the approximate percentages of crystalline compounds identified by XRD, which can be obtained by methods that model the diffraction pattern.

Some laboratories have proprietary hypothetical combination models that estimate the compounds present in the deposit from the elemental analysis and LOI results. This technique may also involve proprietary procedures that supplement the elemental analysis and aid in determining the types of compounds present.

If deposit weights warrant chemical cleaning, tube cleaning tests could subsequently be performed in the laboratory. This requires a representative tube ring of sufficient length for testing. Be sure to request this testing within 2-3 months of receiving the deposit weight results to increase the likelihood that remaining portions of the tube sample are still available at the laboratory. If tube failures were experienced, see the "Tube Failures" section.

In addition to the standard dimensional analysis, deposit weight assessment, and deposit composition analyses, some organizations may be able to provide useful assistance in evaluating the results of analyses. This may be requested as part the contractual scope of work. Additional suggestions regarding analyses of water formed deposits may be found in Reference 17.

Multiple Tube Samples

If multiple tube samples are collected for analysis from each boiler or HRSG, the following instructions for the laboratory are suggested.

Please determine the hot and cold side deposit weight (by mechanical removal or bead blast method), photograph the sample as received, and perform a visual and dimensional assessment including diameter, wall thickness, and pit depths for each specimen. Use the tube specimens with the highest hot side deposit weight and the highest average deposit weight from each boiler (which may be different tubes) to determine the waterside deposit composition of each hot-side and cold-side deposit by a quantitative method of analysis. Deposit composition on the other tube samples can be determined by quantitative or semiquantitative method of analysis (e.g., SEM/EDXS with LOI). Please provide a metallurgical report and interpretive cover letter summarizing all analyses and findings. Please also cut tube rings for a possible future laboratory cleaning assessment.

If multiple tube samples are collected, do not average the results when determining the need to clean. The determination to chemically clean a boiler should be based on the highest hot side deposit weight. A boiler or HRSG is only as clean as its dirtiest tube.

In preparation for a chemical cleaning of a boiler or HRSG, it is sometimes desired to analyze the composition of the separate or combined side deposits of other tubes. One approach has been to analyze a combination of the hot and cold sides of the tube with the lowest deposit weights in addition to the separate hot and cold side deposits of the tube with the highest deposit weights. This provides an indication of the range of deposit compositions in the unit. For once

through supercritical boilers, a metallographic evaluation of the deposit for the tube with the heaviest deposits should be considered.

If a single tube is collected from each boiler or HRSG, the laboratory should be instructed to do the following.

Please determine the hot and cold side deposit weight (by mechanical removal or bead blast method), photograph the sample as received, and perform a visual and dimensional assessment including diameter, wall thickness, and pit depths. Determine the composition of the separate hot-side and cold-side deposits by a quantitative method of analysis. Please provide a metallurgical report and interpretive cover letter summarizing all analyses and findings. Please also cut tube rings for a possible future laboratory cleaning assessment.

TUBE SAMPLING FOLLOWING TUBE FAILURES

Tube Sampling

If a tube has failed and is being removed for failure analysis, both the failed tube and an adjacent tube should be collected. When a tube fails, much of the internal deposit may be dislodged from the surface eliminating evidence that would indicate whether internal surface deposition contributed to the failure. Additional information and general procedures for tube sample removal and shipping are provided in the Tube Sample Removal, Identification and Shipping section.

An additional consideration on handling of failed tube samples involves the preservation of fracture surfaces. The morphology and composition of deposits on fracture surfaces are critical to proper metallurgical evaluation. The following procedure is effective for some types of failures:

1. Assuming that the failure is not on the ends of the tube sample, seal each end of the tube sample with plastic or plastic wrap.
2. Firmly wrap duct tape around the plastic on the tube at each end of the tube sample.
3. Place the tube in a large, loose-fitting clear plastic bag.
4. Seal the bag shut
5. The tube should be packaged so that it is secured during shipment.

Sampling Fire Tube Boilers for Failure Analysis

Failures in fire tube boilers are often along the tube length or at the tube-to-tube sheet joint. Failures near tube sheets generally will need to include a portion of the tube sheet since the failure can be due to problems with the joint. A dry, nonlubricated saw or grinding wheel has been used for this purpose. If a portion of the tube sheet is not removed, it is imperative to minimize damage to the tube during extraction from the tube sheet (both from cutting and deformation of the metal). Alteration of the tube at the location of failure should be avoided.

through supercritical boilers, a metallographic evaluation of the deposit for the tube with the heaviest deposits should be considered.

If a single tube is collected from each boiler or HRSG, the laboratory should be instructed to do the following.

Please determine the hot and cold side deposit weight (by mechanical removal or bead blast method), photograph the sample as received, and perform a visual and dimensional assessment including diameter, wall thickness, and pit depths. Determine the composition of the separate hot-side and cold-side deposits by a quantitative method of analysis. Please provide a metallurgical report and interpretive cover letter summarizing all analyses and findings. Please also cut tube rings for a possible future laboratory cleaning assessment.

TUBE SAMPLING FOLLOWING TUBE FAILURES

Tube Sampling

If a tube has failed and is being removed for failure analysis, both the failed tube and an adjacent tube should be collected. When a tube fails, much of the internal deposit may be dislodged from the surface eliminating evidence that would indicate whether internal surface deposition contributed to the failure. Additional information and general procedures for tube sample removal and shipping are provided in the Tube Sample Removal, Identification and Shipping section.

An additional consideration on handling of failed tube samples involves the preservation of fracture surfaces. The morphology and composition of deposits on fracture surfaces are critical to proper metallurgical evaluation. The following procedure is effective for some types of failures:

1. Assuming that the failure is not on the ends of the tube sample, seal each end of the tube sample with plastic or plastic wrap.
2. Firmly wrap duct tape around the plastic on the tube at each end of the tube sample.
3. Place the tube in a large, loose-fitting clear plastic bag.
4. Seal the bag shut
5. The tube should be packaged so that it is secured during shipment.

Sampling Fire Tube Boilers for Failure Analysis

Failures in fire tube boilers are often along the tube length or at the tube-to-tube sheet joint. Failures near tube sheets generally will need to include a portion of the tube sheet since the failure can be due to problems with the joint. A dry, nonlubricated saw or grinding wheel has been used for this purpose. If a portion of the tube sheet is not removed, it is imperative to minimize damage to the tube during extraction from the tube sheet (both from cutting and deformation of the metal). Alteration of the tube at the location of failure should be avoided.

Failure Analyses

If the failure may be related to water/steam-side deposits, a deposit weight and composition analysis should be performed on an adjacent, nonfailed tube sample. After a failure, the following analyses should be performed on the failed sample.

- Failure analysis (metallographic analysis) with in situ SEM/EDXS analysis of the deposits while they are still adhering to the tube surface
- Tube metal composition analysis (if other than plain carbon steel)

Because of the many failure mechanisms and a wide variety of factors that can influence these mechanisms, other tests may be deemed necessary by the laboratory to help determine the cause of the failure. There are two basic approaches to handling a vague scope. (1) Pre-approve a much larger scope, or (2) approve the basic analysis with the option that supplemental work can be authorized following presentation of preliminary findings. Often supplemental analyses will require the involvement of multiple laboratories. Additional tests may include the following.

- pH of 0.1-1.0 weight % slurry of deposits
- Metal hardness testing
- Tensile testing

TUBE SAMPLE REMOVAL, IDENTIFICATION AND SHIPPING

Sample Removal

Great care must be used in removing boiler tube samples to preserve the physical and metallurgical characteristics of the tube, prevent debris from entering the opening, and provide a surface for quality tube replacement.

A 1.5-2.0 foot (0.5-0.6 m) long specimen is usually sufficient for a routine laboratory cleanliness assessment. The laboratory only needs about 0.5 ft (0.2 m) for the test. The larger length is specified to help ensure that the sample analyzed will be representative and free of contamination. Similarly for failure analysis, laboratories request samples that are 1-3 feet (0.3-0.9 m) long that adequately bridge the failure. One laboratory specifies a sample that is 1.5 ft (0.5 m) on each side of the failure.

The tubes should be dry cut with a nonlubricated saw or grinding wheel. Since grinding wheels can introduce a lot of contamination, nonlubricated saws are generally preferred. Torch cutting or other methods that result in melting the tube metal should be avoided if possible, since these methods can introduce metal spatter to the tube surface and alter the adjacent metal microstructure. If a torch cutting must be used, a 4 foot (1.2 m) long specimen should be removed and the torch-affected ends cut off in the metallurgical laboratory with a dry saw. The

Failure Analyses

If the failure may be related to water/steam-side deposits, a deposit weight and composition analysis should be performed on an adjacent, nonfailed tube sample. After a failure, the following analyses should be performed on the failed sample.

- Failure analysis (metallographic analysis) with in situ SEM/EDXS analysis of the deposits while they are still adhering to the tube surface
- Tube metal composition analysis (if other than plain carbon steel)

Because of the many failure mechanisms and a wide variety of factors that can influence these mechanisms, other tests may be deemed necessary by the laboratory to help determine the cause of the failure. There are two basic approaches to handling a vague scope. (1) Pre-approve a much larger scope, or (2) approve the basic analysis with the option that supplemental work can be authorized following presentation of preliminary findings. Often supplemental analyses will require the involvement of multiple laboratories. Additional tests may include the following.

- pH of 0.1-1.0 weight % slurry of deposits
- Metal hardness testing
- Tensile testing

TUBE SAMPLE REMOVAL, IDENTIFICATION AND SHIPPING

Sample Removal

Great care must be used in removing boiler tube samples to preserve the physical and metallurgical characteristics of the tube, prevent debris from entering the opening, and provide a surface for quality tube replacement.

A 1.5-2.0 foot (0.5-0.6 m) long specimen is usually sufficient for a routine laboratory cleanliness assessment. The laboratory only needs about 0.5 ft (0.2 m) for the test. The larger length is specified to help ensure that the sample analyzed will be representative and free of contamination. Similarly for failure analysis, laboratories request samples that are 1-3 feet (0.3-0.9 m) long that adequately bridge the failure. One laboratory specifies a sample that is 1.5 ft (0.5 m) on each side of the failure.

The tubes should be dry cut with a nonlubricated saw or grinding wheel. Since grinding wheels can introduce a lot of contamination, nonlubricated saws are generally preferred. Torch cutting or other methods that result in melting the tube metal should be avoided if possible, since these methods can introduce metal spatter to the tube surface and alter the adjacent metal microstructure. If a torch cutting must be used, a 4 foot (1.2 m) long specimen should be removed and the torch-affected ends cut off in the metallurgical laboratory with a dry saw. The

tube should not be split prior to shipment, since this may alter the deposit integrity for subsequent analyses.

Following tube removal, a new tube will need to be reinstalled. It is critical that the replacement tube be consistent with the original specification on the diameter, wall thickness, and material designation. In HRSG units, it can be difficult to install a replacement finned tube section. In such cases, contact with the HRSG manufacturer is suggested regarding appropriate tube replacement procedures or baffling requirements.

To minimize overlapping flow effects of the upstream and downstream replacement welds during operation, ensure that the tube segment reinstalled in the boiler or HRSG is over 15 internal diameters in length.

Tube Sample Identification

Always mark the tube exterior with the location (such as tube number and row) and orientation (such as top and bottom) prior to removal so that this information is not lost once the tube has been removed. It is also good to indicate the hot and cold sides of the tube, if applicable. If fireside attack is suspected, avoid writing on areas of attack by taking a longer tube sample and marking above or below the area to be analyzed.

Many facilities use directions (North, South, East, and West) to designate locations within a boiler. Unfortunately, those who are not familiar with the particular boiler or HRSG, will not understand the significance of this nomenclature. Therefore, the terms Front, Rear, Left, and Right should be used to identify the HRSG or boiler tube sample location. If compass directions were previously used to describe location in past sample sets, specify which direction corresponds to the front of the boiler or HRSG to help compare current and past data.

For field erected water tube boilers and HRSG units, the rear of the furnace is always the end of the unit with the exhaust stack. The front of the unit is the opposite end from the rear. Front, rear, left and right directions are from the perspective of someone standing at the front and looking at the boiler or HRSG unit.

For package, water-tube steam boilers, the burners are located in the front wall of the boiler. The boiler exhaust can be at the front or rear of the boiler - depending on the boiler design.

For fire tube boilers, the front of the boiler has the burner. In most fire tube boilers, the boiler is fired from the front side; the furnace gas passes down through a set of tubes to the rear of the boiler and then returns to the front of the boiler through another set of tubes. In this design, the exhaust stack happens to be at the front of the boiler. As with water tube boilers, directions of front, rear, left and right directions are from the perspective of someone standing at the front and looking at the boiler.

Sometimes tabs or rings have to be welded to the tube sample to keep the tube from falling when the last cut is completed. If a tab is required, use light tack welding and do not weld near failure locations or other areas of importance. Also, weld on the cold side rather than hot side for samples collected for deposit weight assessments.

During tube extraction, do not use hammers or pry bars, if possible, since these can dislodge significant amounts of deposit.

Provide as much information as possible with the sample. This should include:

- Mill/plant name, name of company that owns and operates the facility, contact person, mailing address, telephone number(s), fax number, e-mail address, and preferred mode of communication.
- Billing company name and address if different than the facility of origin.
- Steam generator/boiler designation (e.g., Boiler 1, HRSG 3)
- Work desired.
- Date results needed. This will indicate the level of priority for the analysis. Most laboratories have a variable cost structure depending on how fast the results are required.
- General type of tube (e.g., waterwall, nose, screen, generation bank, floor, roof, division wall, HP evaporator, etc.).
- General location (left furnace, first pass tube, etc.).
- Wall (front, rear, left, right) for waterwall tubes.
- Bundle (e.g., left/right), tube row (1st Row) and harp (position from the lead harp) for HRSG tubes. (Note: sometimes bundles are called modules).
- Elevation of the specimen location in the boiler or steam generator.
- Location along the wall (e.g., tube number, x feet from x wall).
- Direction of fluid flow (mark away from the failed surface).
- Top and bottom of the sample (mark away from the failed surface).
- Hot (furnace side in boiler or combustion turbine side in a HRSG) or cold side (refractory side in a boiler or stack side in a HRSG) of the sample (mark away from the failed surface).
- Position relative to pertinent equipment (e.g., five feet (1.5 m) from the bark burning grate, 8 feet (2.4 m) from top row of burners, adjacent to C3 sootblower, above the primary air ports, in line with duct burners, distance from upper/lower harp header, etc.).
- Including boiler diagrams with the sample location identified is extremely helpful to understand the system and possible influences on deposit formation or tube damage.
- Operating pressure.
- Date tube was removed (date of the start of the outage is sufficient).
- Date of last cleaning.
- Date tube was installed (if installed since the last cleaning)

The inside of the tubes should be dry. The open ends of the tubes should be sealed shut with plastic and secured with duct tape or equivalent. If analysis of fireside deposits or corrosion is needed, the tube(s) should be wrapped in clean plastic. The following additional information should be provided for failed tubes.

- Date of tube failure (failed tubes only).

- Date the boiler was initially placed into service.
- Date that the tube was installed. This may be different from the startup date if the tube was replaced during the service life of the boiler.
- Operating temperature (for superheater, reheater, and economizer tubes) in this location, if known. Inlet and outlet temperatures can usually be provided, if the temperature at the specific location is not available.
- Material specification (alloy designation, specified heat treatment, nominal diameter, minimum wall thickness).
- Past results of nondestructive examination of this area (To indicate if this may be ongoing or new attack).
- Summary of other failures in the unit, especially if the problem is recurrent.
- Fuels used during operation.
- Typical operating status (base-loaded, cycle load, periodic operation, occasional operation).
- Changes in boiler design or operation.
- Lay-up procedures, if applicable.
- Type of water treatment program (e.g., sodium phosphate, dispersant, all-volatile, reducing, oxygenated).
- Information on significant chemistry upsets suspected of having contributed to the failure.
- Photograph(s) of failure area before and after tube extraction are often useful. This is especially true in instances of superheater tube failures, since these tubes can be severely twisted as a result of failure.

Fins should be removed onsite before shipment if samples are collected just for deposit weight or dimensional assessment (e.g., wall thickness and pit depth measurements). Plant maintenance personnel will usually have fin removal equipment and are better prepared to perform such operations. However, do not remove the fins if a failure analysis is to be performed. Also, it is a good idea to photograph the tube onsite before fin removal.

Packaging and Shipment

Tubes should be shipped in sturdy containers with packing material to minimize movement during transport. The main objective is to stabilize the tube so that the deposit is not dislodged from the tube surface.

One method that has been effective is to ship the specimen in a polyvinyl chloride (PVC) pipe with threaded (preferred) or plug caps. The diameter of the PVC pipe should be slightly larger than that of the tube sample. The sample should easily slide into and out of the tube. Do not force a tube sample into the PVC tube. Such shipping containers are waterproof, very durable, and easy to cut.

Heavy-duty cardboard containers have also been used effectively when the container is not overloaded and the ends are sufficiently sealed by taping, but they are not recommended. There have been a number of instances in which the cardboard container was damaged during shipment, causing the loss of a portion of the samples. Wooden boxes are a better choice for secure shipment.

A common method that has been used for all shapes of samples is to mount the tube in a wooden box in such a way that the tube is firmly clamped in place at each end (away from the actual failure). In this way, the tube will not bounce around in the box and the failure surfaces will not be touched during shipment. The disadvantage of this method is that it has a much higher shipping weight.

SUMMARY

The preceding information is designed to serve as a general introduction to the subject and to provide consensus recommendations for tube sample selection, collection, handling, shipment and analysis so that existing in-house programs can be reviewed and, if appropriate, improved.

REFERENCES

1. *Standard Test Methods for Accumulated Deposition in a Steam Generator Tube*, D3483-05 (2009), Annual Book of ASTM Standards, Vol. 11.02, American Society for Testing and Materials (ASTM), 2009.
2. *Standard Test Methods for Measuring Deposit Mass Loading (Deposit Weight Density) Values for Boiler Tubes by the Glass Bead-Blasting Technique*, TM0199-2006, National Association of Corrosion Engineers (NACE), 2006.
3. *Chemical Cleaning Guide*, Plant Service Bulletin 44 (PSB-44B) Babcock & Wilcox, 1999.
4. *A Method for Determining Need for Chemical Cleaning of High Pressure Boilers*, K. L. Atwood & G.L. Hale (of Combustion Engineering), in Proceedings of the American Power Conference, Vol. 33, pp. 710- 720, 1971
5. *Guidelines for Chemical Cleaning of Conventional Fossil Plant Equipment*, 1003994 EPRI, Palo Alto, CA: November, 2001.
6. *Heat Recovery Steam Generator (HRSG) Chemical Cleaning Guidelines*, 1004499, EPRI, Palo Alto, CA: 2003.
7. R. Barry Dooley & Wendy Weiss, *The Criticality of HRSG HP Evaporator Deposition: Moving towards an Initial Understanding of the Process*, PowerPlant Chemistry, Vol. 12, No. 4, April, 2010.

One method that has been effective is to ship the specimen in a polyvinyl chloride (PVC) pipe with threaded (preferred) or plug caps. The diameter of the PVC pipe should be slightly larger than that of the tube sample. The sample should easily slide into and out of the tube. Do not force a tube sample into the PVC tube. Such shipping containers are waterproof, very durable, and easy to cut.

Heavy-duty cardboard containers have also been used effectively when the container is not overloaded and the ends are sufficiently sealed by taping, but they are not recommended. There have been a number of instances in which the cardboard container was damaged during shipment, causing the loss of a portion of the samples. Wooden boxes are a better choice for secure shipment.

A common method that has been used for all shapes of samples is to mount the tube in a wooden box in such a way that the tube is firmly clamped in place at each end (away from the actual failure). In this way, the tube will not bounce around in the box and the failure surfaces will not be touched during shipment. The disadvantage of this method is that it has a much higher shipping weight.

SUMMARY

The preceding information is designed to serve as a general introduction to the subject and to provide consensus recommendations for tube sample selection, collection, handling, shipment and analysis so that existing in-house programs can be reviewed and, if appropriate, improved.

REFERENCES

1. *Standard Test Methods for Accumulated Deposition in a Steam Generator Tube*, D3483-05 (2009), Annual Book of ASTM Standards, Vol. 11.02, American Society for Testing and Materials (ASTM), 2009.
2. *Standard Test Methods for Measuring Deposit Mass Loading (Deposit Weight Density) Values for Boiler Tubes by the Glass Bead-Blasting Technique*, TM0199-2006, National Association of Corrosion Engineers (NACE), 2006.
3. *Chemical Cleaning Guide*, Plant Service Bulletin 44 (PSB-44B) Babcock & Wilcox, 1999.
4. *A Method for Determining Need for Chemical Cleaning of High Pressure Boilers*, K. L. Atwood & G.L. Hale (of Combustion Engineering), in Proceedings of the American Power Conference, Vol. 33, pp. 710- 720, 1971
5. *Guidelines for Chemical Cleaning of Conventional Fossil Plant Equipment*, 1003994 EPRI, Palo Alto, CA: November, 2001.
6. *Heat Recovery Steam Generator (HRSG) Chemical Cleaning Guidelines*, 1004499, EPRI, Palo Alto, CA: 2003.
7. R. Barry Dooley & Wendy Weiss, *The Criticality of HRSG HP Evaporator Deposition: Moving towards an Initial Understanding of the Process*, PowerPlant Chemistry, Vol. 12, No. 4, April, 2010.

8. R.H. Weick, *Internal Boiler Tube Deposit Weights as a Basis for Chemical Cleaning*, Paper No. 208, Corrosion 94, NACE, 1994.
9. Holmes, D. R., and Mann, G. M. W., *A Critical Survey of Possible Factors Contributing to Internal Boiler Corrosion*, Corrosion, NACE, Vol. 21, November, 1965.
10. Tomlinson, L., et al., *Sodium Heated Steam Generator Tubes: Effect Of Heat Flux On The Deposition Of Magnetite From Solution And Corrosion Of The Underlying Steel*, Corrosion 84, Paper 188, 1984.
11. Petrova, Tamara I., et al., *Effect of Heat Flux on Deposition Rate of Iron Corrosion Products in Boiler Tubes*, PowerPlant Chemistry, Vol. 9, No. 7, 2007.
12. The NIST Chemistry WebBook, Webbook.nist.gov, U.S. Secretary of Commerce, 2011.
13. *Standard Practice for Reporting Results of Examination and Analysis of Water-formed Deposits*, D933-84 (Reapproved 2007), Annual Book of ASTM Standards, Volume 11.02.
14. *Standard Practice for Analysis of Water-Formed Deposits by Wavelength-Dispersive X-ray Fluorescence*, D2332-13, ASTM International, Annual Book of ASTM Standards, Volume 11.02.
15. *Standard Practice for Reporting Results of Examination and Analysis of Deposits Formed from Water for Subsurface Injection*, D4025-08a, ASTM International, Annual Book of ASTM Standards, Volume 11.02.
16. *Standard Practice for Identification of Crystalline Compounds in Water Formed Deposits by X-ray Diffraction*, ASTM D934-13, Annual book of ASTM Standards, Volume 11.02.
17. *Standard Practices for Preparation and Preliminary Testing of Water-Formed Deposits*, ASTM D 2331-08 (2013), Annual book of ASTM Standards, Volume 11.02.