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Revision Memo

11/03 The highlights of this revision are:

Burner Clearance revised. Editorial and typographical corrections.

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SCOPE

This section gives the calculation procedures to be used for designing all process heaters. Separate procedures required for air preheaters are handled separately in Section VIII-K. Convection section and stack design procedures are given in Section VIII-C. Forced-draft systems, burners, and manifolding and other components that may go into the total specification are handled in other sections.

No special distinction is given to auxiliary services, such as steam superheaters, contained in the furnace. These duties are considered to be part of the overall heater duty. However, some of the specific procedures must sometimes be modified to fit the requirements of the particular situation.

REFERENCES

DESIGN PRACTICES (BESIDES OTHER SECTIONS OF THIS SECTION)

Section XII	Instrumentation
Section XIV	Fluid Flow
Section XV	Safety in Plant Design

GLOBAL PRACTICES

GP 3-4-1	Piping for Fired Equipment
GP 7-1-1	Fired Heaters
GP 15-1-1	Instrumentation for Fired Heaters
GP 18-3-2	Statically Cast Steel and Alloy Pressure Containing Parts, and Tube Supports for Fired Heaters
GP 19-3-3	Linings for Fired Heaters

OTHER LITERATURE

1. EMRE *Blue Book*, Manual Numbers 012 and 011.
2. EMRE *Refinery Construction Materials Manual*, Manual No. EETD 028.
3. API 530, *Calculation of Heater Tube Thickness in Petroleum Refineries.*
4. ASME Standard B31.3, *Process Piping.*

DEFINITIONS

See Design Practice VIII-A, *Fired Process Heaters*

DETERMINING HEATER EFFICIENCY

TOTAL HEAT DUTY Q_a

From the process requirements, determine the total heat duty. This must include all flexibility requirements. An allowance need not be added to the heater duty to compensate for preheat exchanger fouling, since this is normally covered by the exchanger fouling factors.

Q_a = Total heat absorbed by the heater, Btu/hr (MW)

STACK TEMPERATURE T_S

Procedures for determining economical stack temperature are given in Section VIII-A.

DESIGN EXCESS AIR RATE

As discussed in Section VIII-A, the design excess air is based on the type of combustion system and the fuel:

- Use 15% excess air for forced-draft firing of all fuels and natural draft firing of gas fuels.
- Use 20% excess air for natural draft oil or combination gas/oil firing.

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DETERMINING HEATER EFFICIENCY (Cont)

HEAT AVAILABLE FROM FUEL

Heat available from the fuel fired can be determined from the flue gas enthalpy (heat available, HA) curve for the design excess air rate in Figures 4 to 10 of Section VIII-M. The ordinate of these charts (heat available, Btu/lb (MJ/kg) of fuel fired) represents the amount of heat that has been extracted from the flue gas (and absorbed by the process fluid) when the flue gas temperature has been reduced to that shown on the abscissa. The total heat obtained from the fuel is the value read from the chart if the temperature on the abscissa is the stack temperature.

The particular heat available chart selected should be the one for a fuel which most closely resembles the design fuel. There is no significant difference between calculations based on different fuels of the same type. Heaters designed for combination gas/oil firing should be based on oil firing. Once a chart is selected, all calculations must be based on heating values and flue gas rates consistent with the selected fuel.

For unusual fuels, the heat available curve should be calculated. Computer Program No. 3558 may be used for this purpose.

The heat available curves in Section VIII-M are based on combustion air temperatures of 60°F (15°C), for heater applications involving preheated combustion air, these curves must be adjusted to include the additional heat content of the combustion air.

NET FUEL REQUIREMENT F_n

$$F_n = \frac{Q_a}{(HA)_s} \qquad \text{Eq. (1)}$$

where: F_n = Net fuel required, lb/hr (kg/s)
Q_a = Total heat absorbed in heater, Btu/hr (MW)
$(HA)_s$ = Heat available at stack temperature, Btu/lb of fuel (MJ/kg of fuel)

Net fuel is used for all flue gas enthalpy calculations in the furnace.

GROSS FUEL REQUIREMENT F_g

F_g = 1.01 F_n for heaters larger than 100 MBtu/hr (29 MW) heat absorbed — Eq. (2a)

= 1.02 F_n for heaters between 15 and 100 MBtu/hr (4 and 29 MW) — Eq. (2b)

= 1.03 F_n for heaters smaller than 15 MBtu/hr (4 MW) — Eq. (2c)

where: F_g = Gross fuel requirement, lb/hr (kg/s)

Gross fuel is used to determine total heat fired, efficiency, combustion air requirements, stack gas velocity, and flue gas mass velocity and pressure drop. The difference between net fuel and gross fuel accounts for radiation and other heat losses from the heater (excluding stack losses).

HEAT FIRED Q_f

$$Q_f = F_g \times LHV \qquad \text{Eq. (3)}$$

where: Q_f = Heat fired, Btu/hr
LHV = Fuel lower heating value, Btu/lb (Figures 4 to 10 of Section VIII-M)

By convention, lower heating value is always used in all heater and burner calculations.

HEATER EFFICIENCY E_{LHV}

$$E_{LHV} = \frac{100\ Q_a}{Q_f} \qquad \text{Eq. (4)}$$

where: E_{LHV}= Thermal efficiency of heater, based on lower heater value, percent

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LAYOUT OF RADIANT SECTION

TUBE SIZE AND NUMBER OF PASSES

Mass Velocity G - As discussed in Section VIII-A, adequate flow rate inside the heater tubes is necessary to develop a satisfactory film coefficient so that heat transfer from the tube wall to the fluid is obtained with a reasonable differential temperature across the film. Table 1 gives suggested design fluid mass velocities for different services. Since the heater throughput (lb/sec, kg/s) is determined by the process requirements, the total tube internal cross-sectional area required for the flowing fluid is the throughput divided by the mass velocity. This cross-sectional area determines the inside diameters of the tubes and the number of parallel passes through the radiant section (and usually also through the convection section):

$$G = \frac{W}{p\,A_x} \qquad \text{Eq. (5)}$$

where: G = Fluid mass velocity through the coil, lb/sec ft^2 (kg/s m^2)
W = Flow rate through the heater, lb/sec (kg/s)
p = Number of parallel passes
A_x = Cross-sectional flow area through one tube, ft^2 (m^2)

Available Tube Sizes - Wherever possible, tube diameters should be selected from standard nominal pipe sizes in the range of 2 to 8 in. (50 to 200 mm). These sizes are listed in Section XIV-A, *Fluid Flow*. Non-standard sizes should be used only on special occasions, when design parameters cannot be met with standard sizes. In such cases, tubing can be obtained in 1/8 in. (3 mm) (or sometimes even smaller) increments of outside diameter, with 5.0, 6.0, and 7.625 in. O.D. (127, 152, and 194 mm O.D.) being some of the more common sizes.

Most heaters are designed using 4 to 8 in. (100 to 200 mm) tubes. These tubes, with the most commonly specified wall thicknesses, are listed in Table 2. Unless experience indicates otherwise, a first assumption of a 0.285 in. (7.24 mm) minimum wall thickness should be made for alloy radiant section tubes. Note that the wall thickness for carbon steel should be specified as standard schedule sizes, whereas alloy tubes should be specified for the actual minimum wall thickness required. Table 2 merely lists the most commonly used sizes for the convenience of the designer.

ECONOMICAL TUBE SIZE AND NUMBER OF PASSES

1. The most economical size tubes to use are 4, 5, and 6 in. (100, 125, and 150 mm) pipe sizes. In some cases, to obtain the required mass velocities, it may be necessary to use smaller sizes, but more than one pass of a smaller size should usually be avoided.
2. In vaporizing or all-liquid services, the difficulty of uniformly distributing flow to multiple passes increases with the number of passes. Therefore, the number of passes should be minimized, consistent with the heater arrangement. This tends to favor selection of larger size tubes. The same number of passes should be maintained throughout the heater.
3. In all-vapor services, even distribution of flow to individual passes is obtained by proper manifold design (see Section VIII-J, *Fired Heater Manifolds*). Therefore, the selection of tube size and number of passes should be based on layout considerations. A different number of passes and different tube sizes can be used for the radiant and convection sections, since the convection section outlets can be combined and then redistributed at the radiant section inlets.

DESIGN RADIANT HEAT DENSITY ϕ_r

Process Considerations - As discussed in Section VIII-A, the permissible radiant heat density from process considerations is a function of several factors which include heater geometry, feed stock, service, and oil outlet temperature. Maximum allowable heat densities are, therefore, established by experience, as well as from theoretical considerations. Table 1 lists are recommended average radiant heat densities for most services. These heat densities, along with other recommended heater design criteria, will insure satisfactory maximum heat densities.

Mechanical Considerations - Using average radiant heat densities dictated by process conditions will usually result in flue gas temperatures of about 1600 to 1800°F (870 to 980°C) leaving the radiant section (bridgewall temperature). At this temperature level, good mechanical service can be expected from conventional tube supports and refractory materials. A lower radiant heat density should be used if the bridgewall temperature exceeds 1800°F (980°C).

CALCULATION OF TOTAL RADIANT SURFACE

Bridgewall Temperature T_{bw} - The "bridgewall temperature" is the temperature of the flue gas leaving the radiant section. Since the shield tubes "see" the radiant section, they absorb part of the total radiant heat to be transferred. This shield radiant duty is included in the heat absorbed in cooling the flue gas down to the bridgewall temperature.

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LAYOUT OF RADIANT SECTION (Cont)

The bridgewall temperature is primarily a function of average radiant heat density, average radiant tube metal temperatures and the basic shape of the heater. Figures 1 to 5 present bridgewall temperature as a function of these variables for the various types of fired heaters designed by ExxonMobil Engineering. Figure 6 presents bridgewall temperature information for horizontal tube box heaters which, although no longer specified for new heater applications, are still in use at many locations.

In reality bridgewall temperature is also a function of fuel type, excess air level, combustion air temperature, and radiant tube spacing. However, for typical heater designs the effect of these variables is small and can be ignored for design purposes. On the other hand, if any of these variables are outside the recommended limits summarized below, the Heat Transfer Equipment Section of EETD should be contacted so appropriate bridgewall temperature correction factors can be developed and applied.

Fuel Type - Figures 1 to 6 are only valid for typical refinery fuel gases and fuel oils. Unusual fuels with higher or lower than normal adiabatic flame temperatures may require adjustment of the bridgewall temperature curves.

Excess Air - Figures 1 to 6 are valid for excess air levels from 15 to 50%.

Combustion Air Temperature - Figures 1 to 6 are valid for combustion air temperatures from ambient up to about 850°F (450°C).

Radiant Tube Spacing - Figures 1 to 6 are based on the assumption that the majority of the radiant tubes will have a tube spacing of two times the nominal diameter.

When starting a design, assume that the average radiant tube metal temperature is about 100°F (50°C) above the average bulk fluid temperature. The "average" radiant tube metal temperature is usually based on "uncoked" radiant tubes. Corrections listed on these figures must be made to the temperature read from the curves, since the bridgewall temperature depends on heater height. This requires a trial-and-error solution to determine final bridgewall temperature, radiant heat density, tube surface, etc.

TOTAL RADIANT HEAT DUTY Q_{tr}

$$Q_{tr} = (HA)_{bw} F_n \qquad \text{Eq. (6)}$$

where: Q_{tr} = Total radiant section heat duty (including shield section radiant duty), Btu/hr (MW)
$(HA)_{bw}$ = Heat available at bridgewall temperature, Btu/lb of fuel (MJ/kg of fuel)
F_n = Net fuel required, lb/hr (kg/s) [see Eq. (1)]

Shield Radiant Heat Duty Q_{sr} - This is the radiant heat absorbed by the shield section Btu/hr (MW). Calculation procedures for shield radiant duty are found in Section VIII-C, *Design of Convection Sections and Stacks*.

RADIANT SECTION HEAT DUTY Q_r

$$Q_r = Q_{tr} - Q_{sr} \qquad \text{Eq. (7)}$$

where: Q_r = Heat absorbed by the radiant section surface, Btu/hr (MW)

RADIANT SECTION SURFACE A_r

$$A_r = \frac{Q_r}{\phi_r} \qquad \text{Eq. (8)}$$

where: A_r = Radiant section tube surface, ft^2 (m^2)
ϕ_r = Radiant section average heat density, Btu/hr ft^2 (W/m^2)

RADIANT SECTION LAYOUT

General - The radiant section layout is developed from a number of requirements, as outlined below. Since these are interrelated to some extent, a trial layout must first be developed and then modified as the design progresses.

The radiant section layout must provide sufficient space for mounting burners and installing the required heat transfer surface. The required clearances between burners and tubes (see **Burner Clearances**, below) determine the minimum tube envelope around the burners. In many heaters, this envelope is governing, and either the required tubes must be spread out on this envelope or more tubes must be added to the minimum number required.

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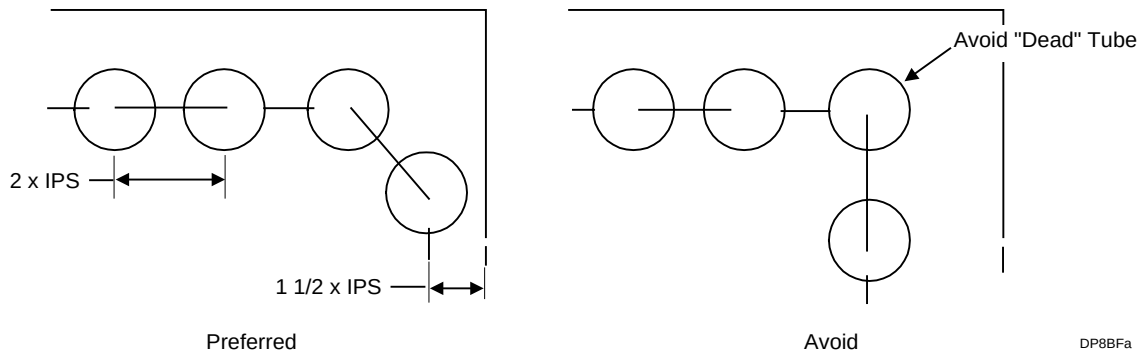
LAYOUT OF RADIANT SECTION (Cont)

The tube size and number of passes are selected to give the desired mass velocity. The number of passes must be consistent with the heater type, so that each pass receives the same amount of heat. While vertical cylindrical heaters can be designed for almost any number of passes, cabin heaters usually require an even number of passes so that they can be symmetrically arranged in the heater.

The convection section layout must be determined before the radiant section can be finished, since the length of each section depends upon the other. Also, the radiant duty in the shield section depends upon the size of the convection section. Therefore, design of the convection section (see Section VIII-C) must be done concurrently with design of the radiant section.

The following general layout criteria should be used with all heater configurations (see sketch below):

1. Centerline-to-centerline spacing of adjacent radiant tubes should be two times the nominal diameter (short radius U-bend).
2. Radiant wall tube centerline should be located a distance of 1-1/2 time the nominal diameter away from the wall.
3. Corner tubes in the radiant section should be located so that there is no “dead” tube, which is partially shielded by adjacent tubes and receives substantially less than the average amount of heat. See the sketch below:



4. To assure adequate visibility from radiant section observation doors, tube spacing at these doors shall be 3 times the nominal diameter (long radius U-bend).
5. Compatibility with the layout of inlet distribution and outlet collection piping should be kept in mind when the tube layout is being set.

Tube Lengths - The proper choice of tube length has a marked effect on the cost of any heater being designed. Guidelines for selecting economical tube lengths are presented below for cabin and vertical-cylindrical heaters. The particular lengths given are approximations and can vary in individual cases. For vertical tube box heaters, the number of tubes and layout are usually developed first, with the tube length being determined afterwards.

Maximum tube lengths for convection sections or for horizontal radiant sections should be limited to about 100 ft (30 m), because of the difficulty in handling longer tubes. Maximum lengths of vertical tubes should be limited to 45 ft (13.7 m) (preferably shorter), because the vertical maldistribution of heat input is excessive in longer tubes.

NUMBER OF RADIANT SECTION TUBES N_r

$$N_r = \frac{A_r}{A_o L_r} \qquad \text{Eq. (9)}$$

where: N_r = Number of tubes in the radiant section

A_o = Tube outside surface, $ft^2/ft = 0.262\ D_o$ ($m^2/m = \pi\ D_o \times 10^{-3}$)(see Table 2)

D_o = Tube outside diameter, in. (mm)

L_r = Radiant tube effective length, ft (m). This is the exposed tube length for heat transfer and does not include return bends. While return bends located inside the firebox will actually absorb some heat, EMRE practice is not to count bends in the effective heat transfer surface of process heaters. Note that for tubes with return bends located in header boxes, the actual length of the tubes will be longer than the effective length.

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LAYOUT OF RADIANT SECTION (Cont)

This calculated number of tubes should be adjusted so that there are an equal number in each pass. Each pass must also have a number of tubes consistent with the type of heater being designed, as well as with the locations of inlets and outlets (e.g., a top inlet and bottom outlet from the radiant section requires an odd number of tubes per pass). Note that in special cases, it may be desirable to use an unequal number of tubes per pass in order to compensate for a severe maldistribution of heat input to the passes. Consideration must be given to flow control in such cases, since pressure drops in the passes will be unequal.

For heater designs where the number of tubes is known, based on layout, etc. (e.g., vertical tube box), Eq. (9) is used to determine tube lengths.

Burner Clearances - Listed below are minimum clearances that should be provided.

1. **Natural Draft**

For natural draft operation with burners firing vertically or horizontally, the following minimum clearances shall be provided:

	DISTANCE IN ft (mm)			
Maximum Heat Release Per Burner MBtu/hr (MW)	**A Burner Exit to Centerline of Roof Tubes or Refractory (Vertical Firing Only)**	**B Burner Centerline to Centerline ofTubes**	**C Burner Centerline to Unshielded Refractory**	**D Between Opposing Burners (Horizontal Firing Only)**
OIL 4 (1.2)	12 ft (3650 mm)	3 ft, 3 in. (1000 mm)	2 ft, 0 in. (600 mm)	16 ft (4900 mm)
6 (1.8)	16 ft (4900 mm)	3 ft, 9 in. (1150 mm)	2 ft, 6 in. (800 mm)	22 ft (6700 mm)
8 (2.3)	20 ft (6100 mm)	4 ft, 3 in. (1300 mm)	3 ft, 0 in. (900 mm)	28 ft (8550 mm)
10 (2.9)	24 ft (7300 mm)	4 ft, 9 in. (1450 mm)	3 ft, 6 in. (1100 mm)	32 ft (9800 mm)
12 (3.5)	28 ft (8550 mm)	5 ft, 3 in. (1600 mm)	4 ft, 0 in. (1250 mm)	36 ft (11000 mm)
GAS **(*)** 2 (0.6)	9 ft, 1 in. (2800 mm)	2 ft, 3 in. (700 mm)	1 ft, 6 in. (500 mm)	12 ft (3650 mm)
4 (1.2)	13 ft, 0 in. (3950 mm)	2 ft, 9 in. (850 mm)	2 ft, 0 in. (600 mm)	18 ft (5500 mm)
6 (1.8)	16 ft, 11 in. (5150 mm)	3 ft, 3 in. (1000 mm)	2 ft, 6 in. (800 mm)	24 ft (7300 mm)
8 (2.3)	20 ft, 9 in. (6350 mm)	3 ft, 9 in. (1150 mm)	3 ft, 0 in. (900 mm)	30 ft (9150 mm)
10 (2.9)	24 ft, 8 in. (7500 mm)	4 ft, 3 in. (1300 mm)	3 ft, 6 in. (1100 mm)	36 ft (11000 mm)
12 (3.5)	28 ft, 7 in. (8700 mm)	4 ft, 9 in. (1450 mm)	4 ft, 0 in. (1250 mm)	39 ft (11900 mm)

Notes:

(*) Minimum clearances for gas firing above are for Low NOx burners. For conventional burners firing fuel gas only, a decrease in longitudinal clearances (ie. columns A and D) may be allowed. However, absolute minimum clearance permitted will be the result of multiplying dimensions in column A by 0.77 and dimensions in column D by 0.67

(1) For horizontal firing, the distance between the burner centerline and the closest roof or sloped arch tube centerline or refractory shall be 50 percent greater than the distances in Column B.

(2) For combination liquid and gas burners, the clearances will be based on liquid fuel firing, except when liquid fuel is used for start-up only.

(3) This table applies to burners capable of natural draft operation, even though they may often operate with a small forced and/or induced draft.

(4) Clearances for liquid fuel service govern for combination gas/oil services, or where provisions are made for future oil firing.

(5) No minimum burner-to-burner clearances are set. Allow at least 1 in. (25 mm) between adjacent burners. If a plenum chamber is to be used for muffling combustion noise (the usual case), increased spacing is required mainly to ensure proper air distribution around the burner. See Section VIII-F, *Burners*.

(6) For intermediate firing rates, linear interpolation can be used for estimating minimum clearances.

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LAYOUT OF RADIANT SECTION (Cont)

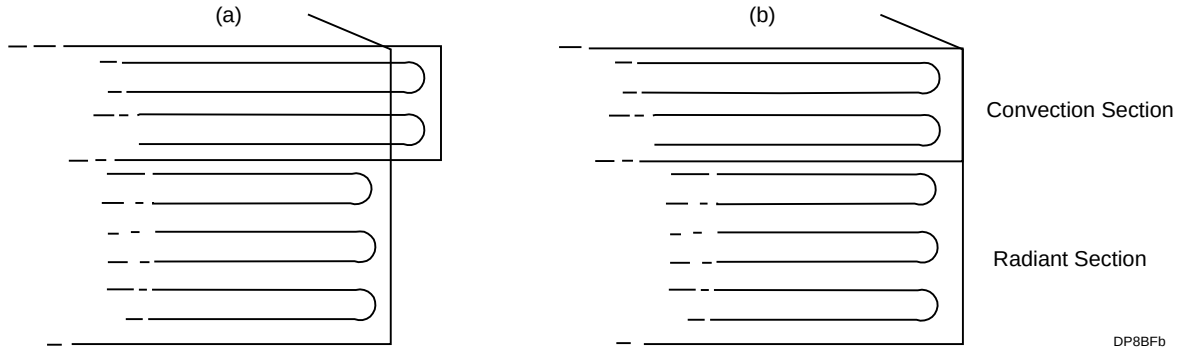
2. **Forced Draft Upfiring**
   a. The following clearances are required for typical large, forced-draft burners (fuel gas or fuel oil or combination fired).

BURNER HEAT RELEASE	MINIMUM DISTANCE FROM BURNER CENTERLINE FOR BOTH GAS AND OIL FIRING TO:		
MBtu/hr (MW)	Centerline of Radiant Tubes	Unshielded Refractory Walls	Centerline of Adjacent Burners
20 (5.9)	4 ft, 6 in. (1400 mm)	3 ft, 6 in. (1100 mm)	4 ft, 6 in. (1400 mm)
30 (8.8)	5 ft, 0 in. (1550 mm)	4 ft, 0 in. (1250 mm)	5 ft, 0 in. (1550 mm)
40 (11.7)	5 ft, 8 in. (1750 mm)	4 ft, 8 in. (1450 mm)	5 ft, 8 in. (1750 mm)

   b. Provide vertical clearances between burner and refractory, tubes, stack entrance, etc. in line of the burner throw. Consult burner manufacturer for clearances of a particular burner model. Provisions are made for future oil firing.

HORIZONTAL TUBE CABIN HEATER

1. **Number of Passes and Arrangements**
   a. Typical pass arrangements are shown in Figure 7. Combinations of these arrangements can be used for more than 4 passes (Figures 7A and 7D).
   b. Use Figure 7C for severe coking services (vacuum pipestill heaters), rather than Figure 7A. The use of jump-over return fittings are very expensive and should not be used unless they are necessary.
2. **Tube Length** - Figure 8 may be used as a guide in choosing approximate radiant tube effective length for the typical horizontal tube cabin heaters shown in Figure 7. This approximate length may require adjustment, based on the number of tubes and passes, burner clearances, etc. For most applications, the actual length used can be expected to be 80 to 100% of this approximate length.
3. **Heater Length** - The locations of return bends will affect the actual length of radiant and convection tubes. The possible arrangements are shown below:



   a. Sketch (a) is preferred. The effective length of the convection tubes is approximately 3 ft (0.9 m) longer than that of the radiant tubes. Clearance for thermal expansion must be provided between radiant section return bends and the end wall. Clearances must also be provided between convection section return bends and the header box, but this affects only the detailed mechanical design.
   b. Sketch (b) should be used when radiant section return bends with removable plugs (plug headers) are used. Radiant and convection tubes have the same effective length in this case.
   c. Convection section return bends should always be located in header boxes to prevent flue gas by passing around the end of the convection section.
4. **Radiant Section and Burner Layout**
   a. Assume a single row of burners (one row in each cell for Figure 7D).
   b. Select burner to tube clearances as previously stated. For the preliminary layout, assume a burner to tube center-to-center spacing of 51 in. (1300 mm) for natural draft and 60 in. (1520 mm) for forced draft.

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LAYOUT OF RADIANT SECTION (Cont)

c. Leave a 1 ft (300 mm) clearance between the outside diameter of the lowest radiant wall tube and the floor.

d. Space tubes (center-to-center) on two nominal diameters (2 times IPS).

e. Hip sections (transition between radiant and convection sections) should be assumed to be at a 45-degree angle.

f. Determine the number of burners required, based on the minimum clearances previously stated. Determine if burners can be physically laid out in a single row as assumed. If burners cannot be placed in single row:

   i. For natural draft, use a staggered row (triangular pitch) or double row of burners and increase the width of the radiant sections accordingly.

   ii. For forced draft, revise the layout to fit.

g. The height/width ratio of the radiant section in general should not exceed 3.5:1 unless necessary to comply with plot space or specific burner flame length requirements. Height should be taken as the distance between the floor and the centerline of the uppermost tube in the vertical wall section. Width should be taken as the tube centerline spacing across the firebox.

VERTICAL-CYLINDRICAL HEATER

1. **General** - Most vertical-cylindrical heaters will be designed with horizontal tube convection sections. Heaters should not be designed with integral convection sections. (See Section VIII-A, Figure 1B.)

2. **Number of Passes and Arrangement** - Any number of passes can be used in vertical-cylindrical furnaces, since the radiant section layout is always symmetrical. However, certain number of passes (1, 2, 4 or 8) tend to result in simpler outlet piping. Other arrangements may require an expensive ring manifold, not otherwise required, to collect the heater outlets and should be avoided unless process considerations dictate their use.

3. **Radiant Tube Length** - Figure 9 may be used to determine the approximate range of possible tube lengths. Consistent with the criteria listed below, economical radiant tube lengths are usually the longest possible. The final length will only rarely fall below the indicated range (L_r / D_t < 1.6). To avoid excessive longitudinal maldistribution of heat input, maximum tube length should normally be 35 to 40 ft (10.7 to 12.2 m). In no case should tubes longer than 45 ft (13.7 m) be used.

4. **Radiant Section Layout**

   a. The circumference of the tube circle is determined by multiplying the number of tubes by the center-to-center tube spacing.

   b. The ratio of tube length to tube circle diameter (L_r / D_t) should be no greater than 2.6 and no smaller than 1.2.

   c. Check burner clearances as developed below.

   d. If necessary, the radiant layout can be revised by the following:

      i. Increase the number of tubes. This decreases L_r and increases D_t. Thus, L_r / D_t is reduced, and burner-to-tube clearances are increased. However, clearance in line of burner throw is also reduced and may in turn require smaller burners.

      ii. Increase the spacing between radiant tube passes. This reduces L_r / D_t and increases burner-to-tube clearances, but does not decrease burner throw clearance. Since this approach causes a far greater increase in heater cost than that from increasing the number of tubes, it **should not be used** until these possibilities are exhausted.

   e. The welded return bends are normally located inside the firebox and the overall height of the box must allow for thermal expansion of the coil.

   f. The radiant coil may be either top-supported and guided at the bottom or bottom-supported and guided at the top. With an even number of radiant tubes per pass, the outlet will be at the top of the radiant section (since the inlet from the convection section is at the top). In this case, the radiant coil should usually be hung to eliminate vertical growth at the heater outlet nozzle. Conversely, with an odd number of radiant tubes per pass, the coil should normally be supported from floor level, since the outlet nozzle is at the bottom of the heater.

      Convection to radiant crossover designs is less difficult with top supported coils, since the crossover requires much less flexibility. However, both arrangements are routinely done successfully. Consideration should be given to the likely arrangement of the outlet manifold and transfer line since these are also affected by locations of supports and tube outlets.

   g. Crossovers should normally be located outside the heater rather than inside. This permits better support and permits increased flexibility, thereby avoiding potential mechanical problems. This also provides a place for temperature indicators between the radiant and convection sections.

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LAYOUT OF RADIANT SECTION (Cont)

BURNER ARRANGEMENT

a. Select the number and size of burners. The minimum clearances specified above must be maintained. When possible, the number of burners should also be a multiple of the number of passes to provide symmetry.

b. Avoid using two burners in a vertical-cylindrical heater. The use of two burners produces unsymmetrical heat patterns and may result in poor operations.

c. The use of only one burner requires that the heater be shut down every time the burner must be cleaned or otherwise maintained. Therefore, the use of three small burners is preferable to one large burner in heaters in continuous services.

d. The burners are normally laid out in one burner circle.

6. **Convection Section Layout** - In addition to the general section on convection section design, the following are specific to the vertical-cylindrical heater (see Figure 10):

a. The convection section length L_c and width W_c depend upon the radiant tube circle diameter. Therefore, they must be worked out in conjunction (trial and error) with the radiant layout.

b. For the preliminary layout, assume $L_c = 0.9\ D_t$. Final design lengths will usually fall in the range of $0.8\ D_t$ to $1.0\ D_t$.

c. The convection section box is supported by the radiant section cylindrical shell and supporting structure. The inside four corners of the convection section refractory should be located just above the inside of the radiant section refractory wall. This then sets the convection tube effective length as well as convection section width, since the combination of both is a function of radiant section diameter.

d. The convection section header boxes usually extend beyond the radiant shell.

e. In the rare case where the radiant tubes have cleanout plugs, the convection tubes (including headers and header boxes) cannot extend beyond the radiant tube circle diameter, since access must be provided for cleaning of the radiant tubes.

7. **All-Radiant Heaters**

a. For an all-radiant type heater, no means are provided for cooling flue gases leaving the radiant section. The stack temperature is the bridgewall temperature. Stack temperature and efficiency depend solely on the choice of radiant heat density.

b. Radiant surface is obtained directly by dividing the heater duty by the heat density.

c. All-radiant vertical tube heaters usually have an even number of tubes per pass, with the coil bottom-supported.

8. **Very Small Heaters** - Meeting normal established design criteria is often difficult with the design of very small heaters [less than about 10 MBtu/hr (3 MW) heat duty]. The following should be considered:

a. These heaters are usually all-radiant. However, a convection section may be economical, particularly with only gas fuel.

b. Higher-than-normal allowances should be provided for radiation and other heat losses. Multiply the net fuel by 1.03 to determine the gross fuel required.

c. The minimum height of the radiant section should be about 15 ft (4.6 m).

d. Minimum burner-to-tube clearances should be maintained.

e. Increase the spacing between passes (as previously discussed) and/or decrease the heat density, as necessary. Since the heater shell dimensions will largely be determined by minimum burner clearances, decreasing heat density has the added benefit of increasing heater efficiency.

f. Helical coils are sometimes used in small heaters, instead of the usual serpentine coil.

i. The coil is supported at three points on each turn. Each support usually consists of a high alloy pipe extending the entire height of the radiant section, with the coil supported from this pipe by means of U-bolts.

ii. No return bends are required for the coil, reducing heater cost. Pressure drop through the coil is also reduced by the elimination of return bends. Pressure drop is approximately 150% of that of a straight tube of the same length.

iii. A maximum of two tube passes should be used.

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LAYOUT OF RADIANT SECTION (Cont)

9. **Multi-Service Vertical-Cylindrical (V.C.) Heaters** - The radiant section of V.C. heaters can be divided into two or three separate, but compatible, services. However, when possible, this arrangement should be avoided.
   a. A refractory brick wall can be used to divide the radiant section into separate zones. Although each zone has its own firing controls, the heat input is influenced to some extent by the other zones. Since the maximum height of the free standing interior walls is about 25 ft (7.6 m), this influence will be substantial in tall heaters. See the discussion on **HOOP-TUBE CABIN HEATERS** for more details on the dividing wall.
   b. Separate services can also be installed in the same radiant section, but without the interior wall. However, this arrangement can be used only in special cases, since there is no way of varying the relative heat input to the individual services once the amount of surface in each service has been selected.

VERTICAL TUBE BOX HEATER

Note: The vertical tube box heater is an ExxonMobil proprietary design and has substantial advantages over the design of our competitors. To protect this proprietary technology, care must be taken to ensure that only contractors and heater vendors who have signed appropriate confidentiality agreements are given information on the vertical tube box heater.

1. **General**
   a. Vertical tube box heaters use a combination of one-side fired tubes along the end and side walls of the radiant box, plus two-side fired tubes in rows across the box. The two-side fired (or center) tubes divide the box into a number of cells.
   b. Since equal heat input per pass is desired, each pass must contain the same number of one-side fired tubes and of two-side fired tubes.
2. **Typical Arrangements** - Figure 11 shows sketches of a number of generalized arrangements, with various pass and cell configurations. This group of arrangements is not intended to cover all possible combinations. Other arrangements may be used to meet special requirements.
   a. Figures 11a to 11c show the most commonly used arrangements. Similar arrangements can be used for 4 and 10 passes. This type arrangement should be used as first preference. As shown, the outlet tubes should be located at the sides of the heater, which is the region of less than average heat density. This layout tends to reduce the coking rate of the hottest tubes.
   b. Figures 11d and 11e show other arrangements that have been used. However, some variations in heat input per pass can be expected because of the non-symmetrical layout of the two-side fired tubes. Also, the heaters tend to be wider than shown in Figures 11a to 11c, leading to a short, wide convection section (perhaps too wide). Similar arrangements can be made for 9 passes (4 cells) and 12 passes (4 or 5 cells).
   c. Figure 11h shows the use of only high heat density two-side fired tubes, which minimize coil length at the expense of a larger box. This arrangement should be considered when very expensive tubes are required (e.g., stainless steel) or where conditions require a short residence time or uniform radiant heat density around the tube. Note that heat release in the end cells is one-half of that in the center cells. Figure 4 presents bridgewall temperature curves for this type heater. Some variations in the layout procedures described below are required for heaters with only two-side fired tubes, since these procedures were primarily developed for combinations of one- and two-side fired tubes.
3. **Layout Considerations** - The following considerations should be kept in mind when the vertical box layout is being developed. In special cases, the guidelines should be modified as required.
   a. Most heaters will have a top inlet to the radiant section (from the convection section) and a bottom outlet. Therefore, an odd number of tubes per pass is normally required.
   b. Jumpovers (i.e., between wall tubes and center tubes) may be located at the top or bottom of the radiant section, although they are most commonly located at the bottom. They are usually located outside the firebox.
   c. Tubes are bottom-supported and guided at the top. Wall tubes over 35 ft (10.7 m) long should also have a midpoint guide to restrict tube bowing caused by peripheral maldistribution of heat input.
   d. Center tubes under the convection section must be about 3 ft (0.9 m) longer than the other tubes to accommodate the top tube guide system. See Figure 12 for typical guide details.
   e. The location of center tubes relative to the convection section side walls will determine the type of tube guide required. Care must be exercised in locating these tubes to ensure that they can be adequately guided. The use of 1 or 2 long radius U-bends may be required for proper locations of these tubes. See Figure 12 for details of typical center tube guides.
   f. Allow a clear path for access and tube replacement through the end walls and from cell to cell. This is usually located down to the center of the furnace between outlet tubes of adjacent passes. Allow a 24 in. (610 mm) tube center-to-center spacing for 6 in. (150 mm) or smaller tubes [17 in. (430 mm) minimum clear access].

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LAYOUT OF RADIANT SECTION (Cont)

g. Location of the transfer line will depend upon heater and burner arrangement. Typically, one transfer line will run along each side of the heater, as shown in Figure 11f. Should this arrangement not be possible, a less desirable arrangement with outlet tubes in the center and a single transfer line may be used, as shown in Figure 11g.

h. As nearly as possible, the number of end wall tubes and center tubes per row should be equal, to take full advantage of available space for tubes. Since the design will not always permit this, it is preferable to use fewer tubes on the end walls and maximize the use of center tubes. If this results in wide spaces on the end walls, a few long radius U-bends should be used to spread out the end wall tubes.

i. While all cells should be the same size, it is acceptable to make the center cell (or two) slightly wider than the others to accommodate one or two extra wall tubes if these tubes are necessary to obtain an equal number of wall tubes per pass.

   Conversely, it is also acceptable to leave a wall tube out of one or more cells if necessary. However, cell size should not be reduced since this is probably set by minimum burner clearances.

j. A minimum of one long radius return bend (or equivalent space) should be provided in each side of each cell. These should be located at diagonally opposite corners of the cells. These larger spaces are necessary for peepholes which permit viewing of tubes and burners (see Figure 13).

4. **Radiant Section Design**

a. Determine the proposed arrangement from typical arrangements shown in Figure 11, as previously discussed.

b. Determine the number of burners. The heat release, number and size of burners will be identical in each cell (except for Figure 11h, where heat release in end cells is one-half that of the other cells).

c. Determine the minimum tube envelope surrounding the burners, based on previously stated minimum burner-to-tube and burner-to-burner clearances. Keep in mind that additional clearance between burners may be required at the center of the heater if the transfer line arrangement shown in Figure 11f is used.

d. The preliminary layout should be based upon the minimum tube envelope surrounding the burners, unless experience indicates that a larger envelope should be used for the specific case. In many designs, this minimum envelope has been used in the final layout with virtually no modifications.

e. Determine the approximately number of tubes. The following method can be used as a short-cut aid in the trial-and-error procedure for determining the proper number of radiant section tubes. See Figure 13. The following nomenclature is used in this method:

B	=	Cell width (tube center-to-tube center), ft (m)
B'	=	Preliminary approximate width, based on minimum tube envelope.
L_t	=	Heater length (tube center-to-tube center), ft (m)
L_t	=	ΣB
L_i	=	Heater radiant section overall length, inside refractory, ft (m)
L_i	=	L_t + 3 times tube size (IPS)
W_t	=	Heater width (tube center-to-center), ft (m)
W_t'	=	Preliminary approximate width, based on minimum tube envelope
W_i	=	Heater radiant section overall width, inside refractory, ft (m)
W_i	=	W_t + 3 times tube size (IPS)
a	=	Number of wall tubes at one end of heater
a'	=	Preliminary approximate number of wall tubes at one end of heater
b	=	Number of wall tubes at one side of one cell
c	=	Tube center-to-center spacing, ft (m)
e	=	Number of center tubes between adjacent cells
n	=	Number of cells
p	=	Number of passes
x	=	Number of wall tubes (one-side fired) per pass
y	=	Number of center tubes (two-side fired) per pass

a', b', e', x', y' are first approximations based on the following equations. These equations assume that the corner tubes of each cell are arranged at a 45° angle, and one long radius return bend is included in each side of each cell.

i. **End wall tubes**

$$a' = \frac{W_t' - 2}{c} + 0.586 \qquad \text{(Customary)} \qquad \text{Eq. (10)}$$

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LAYOUT OF RADIANT SECTION (Cont)

$$\left[a' = \frac{W_t' - 0.610}{c} + 0.586\right] \quad \text{(Metric)} \qquad \text{Eq. (10)M}$$

Let a = whole even number based on a′

Determine: (a′ – a)c

If this is positive, this is the increase in center access clearance above 2 ft (0.6 m).

If it is negative, this is the increase in tube envelope over the minimum.

ii. **Side wall tubes**

$$b' = \frac{B'}{c} - 0.957 \qquad \text{Eq. (11)}$$

Let b = next higher whole number greater than b′

iii. **One-side fired tubes per pass**

$$x' = \frac{2a + 2nb}{p} \qquad \text{Eq. (12)}$$

Since x must be a whole number, some adjustments may be required:

- Decrease (a) by 2 or 4 tubes. Long radius U-bends should be used as necessary to spread out the remaining tubes.
- Add to (a). Note that this also will require addition to (e).
- Add to (b) in each cell.
- Add or subtract from (b) 1 or 2 tubes in only the center cell(s). If subtracting tubes, leave the resulting space blank and don't decrease the cell size.

iv. **Two-side fired tubes per pass**

$$e = a \quad \text{(approximately)} \qquad \text{Eq. (13a)}$$

$$y = \frac{e}{2} \quad \text{(usually, when there are 2 pass outlets per row of center tubes)} \qquad \text{Eq (13b)}$$

or

$$y = \frac{e\,(n - 1)}{p} \quad \text{(adjust as required to obtain whole number)} \qquad \text{Eq. (13c)}$$

v. **Total tubes per pass** - The total number of tubes per pass (x + y) should be an odd number for most arrangements. Make slight adjustments to the number of tubes to modify this total as required.

f. Determine the radiant surface. Eq. (8) is used to determine the amount of radiant tube surface required. However, this equation must be modified for the vertical tube box heater arrangement, because of the usage of both one-side and two-side fire tubes.

The amount of equivalent surface required based on one-side firing can be determined. Since for standard tube-to-tube spacings (2 IPS) the average heat density on two-side fire tubes ($\phi_{2\text{-side}}$) is 1.5 times the average heat density for one-side fire tubes ($\phi_{1\text{-side}}$) the heat absorbed by each two-side fire tube used in the layout will be equivalent to that of 1.5 one-side fire tubes.

$$A_{1\text{–side}} = \frac{Q_r}{\phi_{1\text{–side}}} \qquad \text{Eq. (8a)}$$

where: $A_{1\text{-side}}$ = Equivalent radiant section tube surface, based on one-side fired heat density, ft² (m²)

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LAYOUT OF RADIANT SECTION (Cont)

The bridgewall temperature used for this calculation depends on the radiant section height, so a trial-and-error solution must be made to determine the final bridgewall temperature. However, for the initial approximation of radiant tube length, assume no height correction of bridgewall temperature. The convection section layout and shield duty are estimated based upon the radiant layout developed up to this point.

g. Determine the radiant tube length L_r.

$$L_r = \frac{A_{1\text{–side}}}{p\ (x + 1.5\,y)\ A_o} \qquad \text{Eq. (14)}$$

Radiant tube length L_r should be within the range of 30 to 40 ft (9.1 to 12.2 m), with the optimum length being 35 to 40 ft (10.7 to 12.2 m). It should not exceed 45 ft (13.7 m).

If L_r > 40 ft (12.2 m), consider adding to the number of tubes (x & y) to reduce L_r. Heater width should be increased first, then length.

If L_r < 30 ft (9.1 m), review the design basis, since this is an unusual case and may possibly be uneconomical.

As discussed above, the final L_r must be used in determining the final bridgewall temperature.

5. **Multi-Service Box Furnaces** - The vertical tube box heater can be used for two services by splitting the radiant section; one end of the heater in one service and the other end in a second service. The convection section may be in one service over the entire radiant section or in two services, one above each radiant section.

   The two services must operate together at similar heat densities.

HOOP TUBE CABIN HEATER (SEE SECTION VIII-A, FIGURES 4C AND 4D)

1. **General** - The double hoop arrangement shown in Figure 4D of Section VIII-A is customarily used for POWERFORMING heaters but can also be used for other all-vapor services. These heaters are usually multi-service, with each radiant zone separated from the others by free standing brick walls.

   The single hoop arrangement shown in Figure 4C of Section VIII-A can be used for two separate duties, one in each of the radiant hoop sections. A free standing brick wall should be placed between the two hoops to permit a turndown of one of the sections. Additional zones can be provided in the radiant section by joining this brick wall with another running to the heater side wall.

2. **Typical Arrangement** - A typical arrangement of double hoop tube cabin heater is shown in Figure 14. This arrangement shows three separate radiant zones. Note that vertical sections of tubes in center rows are on a staggered pitch and are connected by standard U-bends. These tubes are considered to be one-side fired, the same as if they were backed by a refractory wall. The hoops are also counted as equivalent to one-side fire tubes.

   Although Figure 14 shows inlet and outlet manifolds parallel to the convection section, manifolds can also be arranged normal to the convection section. Whatever manifolds arrangement is used, the goal is to reduce pressure drop by simplifying piping between the heater and the reactors. Refer also to Section VIII-J for additional details on manifold layout and design.

3. **Number of Passes, Tube Size and Length** - Special considerations are required for selecting the number of parallel passes and tube size, since tube length per pass must also be considered. (Note that all references are to Figure 14).

   a. Various combinations of tube size and number of passes should be considered. Since each tube size has a different ratio of tube surface to flow area, each combination will result in a different tube length requirement.

   b. Choice of coil length is relatively limited, when compared to other designs.

      i. Minimum height H_t is based upon required burner clearances discussed earlier.

      ii. Maximum height is based upon maintaining uniform heat transfer, as well as mechanical considerations. Height should be limited to straight tube length L_s of:

         - 30 ft for 5 in. IPS (9.1 m for 125 mm NPS) and larger tube diameter.
         - 25 ft for 4 in. IPS (7.6 m for 100 mm NPS) and smaller.

      iii. Cell width between tubes (B) is based on minimum burner-to-tube clearances. However, minimum cell width should be 10 ft, 0 in. (3.05 m) tube center to tube center.

   c. Although it is desirable to use the same tube size in all zones, this is not necessary; and in practice, different tube sizes can be used in the individual cells.

   d. Coil length can be increased by a factor of two by increasing the number of series passes through the zone. This is done by providing blinds, or baffles, in the manifolds. Zones A and C are shown with one series pass, while Zone B has two series passes. Any number of additional series passes can be used, if necessary.

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LAYOUT OF RADIANT SECTION (Cont)

4. **Convection Section Length** - The convection section extends the entire length of the heater, across all radiant zones. The convection section length is equal to the sum of the lengths of all radiant zones, plus the width of the internal dividing walls.
5. **Radiant Section Duty** - As in other heater designs, overall radiant section duty can be determined from heat available charts, given the net fuel rate and bridgewall temperature. Each radiant zone has its own bridgewall temperature. Average bridgewall temperature is based on the combined flue gas streams leaving each radiant section. Convection section design is based on this average bridgewall temperature.

   For services which are composed evenly of all-radiant duty, bridgewall temperature is a function of radiant heat density and tube metal temperature. The complete design of these zones in straightforward. Bridgewall temperature is determined from Figure 5. Heat transfer to the hoop has been included in this curve.

   For services which combine radiant and convection duties, the radiant duty must be determined by subtracting the other, all-radiant duties from the overall radiant duty. Before this radiant duty can be determined, the heater layout must be estimated (and later corrected as required), so that the shield radiant duty can be calculated.

   Each radiant zone will contribute to the total shield section radiant duty. This contribution will depend on the radiant section heat density of each zone and on the portion of the convection section located over each radiant zone. The calculation procedure for shield section radiant duty is given in Section VIII-C.

   Variations in relative duties over the run length must be considered in selecting design radiant heat densities for each zone. For example, in the typical POWERFORMER heater (Figure 14), Zones A and C are all-radiant reheat services, while Zone B and the convection section are in preheat service. Since A and C contribute a smaller amount of cooler flue gas to the convection section during operations when these reheat duties are reduced, Zone B must be fired harder to make up for this reduced convection heat input. Therefore, Zone B may have to be increased in the size to avoid high radiant heat densities during the periods when Zones A and C operate at low rate.
6. **Burner Layout** - Burners should be located to give uniform heat distribution to the tubes, consistent with minimum burner-to-wall clearances. The burners should be located so that the burner-to-wall distance is approximately half the burner-to-burner distance.

   Adequate burner space is not always available in hoop tube heaters and additional clearances are occasionally required. For natural draft burners, these may be obtained through use of a double row of burners (Zone A). In other heaters, it may be necessary to provide a longer cell length than otherwise required.
7. **Dividing Walls** - Free standing refractory brick walls divide the radiant zones. These walls should be 2 ft, 3 in. (690 mm) wide at the base [three 9 in. (230 mm) bricks], with a stepped construction and a maximum height of about 25 ft (7.6 m).

   The radiant section layout should provide for a minimum clearance between this interior wall and the adjacent hoop tubes of 1.5 times the tube size, the same as between the tubes and the exterior walls.
8. **Radiant Section Manifolds** - These manifolds are located below each radiant zone, at each side of the heater. Various methods of sealing the heater in this area are used: an external header box to enclose the manifold, a sliding seal plate arrangement or a foil seal around each individual tube connection to the manifold. The latter method is not always possible, particularly in designs with small tubes, where manifold thermal expansion is greater than the space between adjacent tubes (Figure 15). The sealing arrangement used must also ensure that the manifold is not directly exposed to radiant heat transfer.

PRESSURE DROP THROUGH THE COIL

Computer Program No. 3660 can be used to calculate heater coil pressure drop for both single and two-phase flow conditions. This program initially calculates thermodynamic property information for the heater feed stream and then using this data calculates the pressure drop for the coil geometry submitted.

Heater pressure drop can be calculated by hand using the procedures and equations presented in Section XIV which covers fluid flow. For all-liquid and all-vapor systems, pressure drops can be easily and quickly calculated by hand since specific volume changes through the coil are small. To facilitate this calculation, the Fluid Flow Module of the Pegasys computer program can be used for single-phase pressure drop calculations. However, with two-phase systems the pressure drop per unit length of coil changes continuously with changes in gas-liquid ratio. Calculation of pressure drop is, therefore, a complex point-to-point trial-and-error calculation. As a result, hand calculation of two-phase pressure drop is very time-consuming and is best done by using a computer program such as 3660.

The internal diameter of the tube used in pressure drop calculations should be the average instead of the minimum tube wall thickness. [Minimum wall thickness = 0.875 (average wall thickness).] Since the tube diameter greatly affects pressure drop ($1 / \Delta P$ varies approximately as the 2.5 power of tube diameter in vaporizing services), it is important that any anticipated coke buildup be allowed for, when the internal diameter of the tube is figured for pressure drop calculations. The following are

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PRESSURE DROP THROUGH THE COIL (CONT)

suggested thicknesses of coke to be used in the radiant section (no coking is assumed in the convection section, unless reverse decoking facilities are also provided):

- 1/8 in. (3 mm) for light coking services (atmospheric pipestills, etc.).
- 1/4 in. (6 mm) for heavy coking services (vacuum pipestills, etc.).

In addition, the designer may have to estimate the pressure drop through the transfer line downstream of the radiant section. In this case, refer to Section VIII-J for sonic velocity considerations.

TUBE DESIGN

MATERIALS

The primary considerations are the required strength, resistance to corrosion (or erosion), and oxidation (or reduction) characteristics. Bearing upon these characteristics are the temperature level, the heater atmosphere, and corrosive constituents of the process fluid or the fuel.

The most commonly used materials are carbon steel, C-1/2 Mo, 1-1/4 Cr-1/2 Mo, 2-1/4 Cr-1 Mo, 5 Cr-1/2 Mo, 9 Cr-1 Mo, 18 Cr-8 Ni and 25 Cr-20 Ni. For selecting the proper materials, as well as for establishing corrosion rates, see the Refinery Construction Materials Manual (RCMM) or consult the Materials Engineering Section of EETD.

For process heaters, the following tube materials are most commonly selected, based on internal and external conditions:

Internal Conditions - Largely based on sulfur corrosion.

1. **Pipestills** - See RCMM Corrosion Design Curve Nos. 1-A to 1-J for APS and 4-A to 4-J for VPS.
   a. Carbon Steel (CS) is used at low tube metal temperatures [approximately 700 to 900°F (270 to 480°C)], until the corrosion rate becomes excessive.
   b. 5% Cr is used for high temperatures. It is generally good up to 1200°F (650°C) tube metal temperature (TMT).
   c. 9% Cr is occasionally used where the crude is extremely corrosive and/or the operating conditions result in high tube metal temperatures.
   d. 18 Cr-8 Ni is rarely used due to concern over polythionic stress-corrosion cracking (PSCC) during downtimes.
2. **Reboilers, Hydrofiners, etc.** - See RCMM Corrosion Design Curves Nos. 2 and 3, A through J. The corrosion rate may be significantly higher than in pipestills. See also RCMM Corrosion Design Curve 5 for hydrocarbon streams containing H_2S and H_2.
   a. CS is used for low temperatures.
   b. 5% Cr is used for moderate temperatures (no increased corrosion resistance over CS for H_2S / H_2 service).
   c. 18 Cr-8 Ni is used for higher temperatures or high H_2S partial pressure in the feed.
3. **POWERFORMERS** - Tube selection depends mainly upon resistance to H_2 attack (RCMM Corrosion Design Curve No. 6) and material strength. There is relatively little corrosion.
   a. C-1/2 Mo should not be used in hydrogen service even at low temperatures.
   b. 1-1/4 Cr-1/2 Mo is used at low temperatures as would be typical for convection section tubes.
   c. 2-1/4 Cr or 5 Cr is used for higher temperatures. 5 Cr is used if external oxidation becomes limiting.
   d. For very high temperature cases, modified 9 Cr-1 Mo material can be used to provide required strength and resistance to external oxidation.

   External Oxidation - This normally plays a relatively minor role in tube selection or corrosion allowance, but is the principal concern in the location and selection of materials for convection section extended surface. For high-temperature oxidation rates, see CMM Corrosion Design Curve No. 8.

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TUBE DESIGN (Cont)

DESIGN TEMPERATURE

Unless otherwise indicated, the design temperature is the maximum calculated outside tube metal temperature. Calculation of radiant section tube metal temperature is described below. Calculation of convection section tube temperatures is described in Section VIII-C.

$$T_m = T_b + \Delta T_f + \Delta T_c + \Delta T_m; \qquad \text{Eq. (17)}$$

with:

$$\Delta T_f = \left(\frac{1}{h_i}\right)\left(\frac{D_o}{D_i}\right)(\phi_r)_{max} \qquad \text{Eq. (17a)}$$

$$\Delta T_c = \left(\frac{t_c}{k_c}\right)\left(\frac{2\ D_o}{D_i + D_i'}\right)(\phi_r)_{max} \qquad \text{(Customary)} \qquad \text{Eq. (17b)}$$

$$\Delta T_c = 10^{-3} \times \left(\frac{t_c}{k_c}\right)\left(\frac{2\ D_o}{D_i + D_i'}\right)(\phi_r)_{max} \qquad \text{(Metric)} \qquad \text{Eq. (17b)M}$$

$$\Delta T_m = \left(\frac{t_a}{k_m}\right)\left(\frac{2\ D_o}{D_o + D_i}\right)(\phi_r)_{max} \qquad \text{(Customary)} \qquad \text{Eq. (17c)}$$

$$\Delta T_m = 10^{-3} \times \left(\frac{t_a}{k_m}\right)\left(\frac{2\ D_o}{D_o + D_i}\right)(\phi_r)_{max} \qquad \text{(Metric)} \qquad \text{Eq. (17c)M}$$

where:
- T_m = Maximum tube metal temperature, °F (°C)
- T_b = Temperature of bulk fluid at the point of calculation, °F (°C) (coil outlet or peak temperature is usually used for T_b)
- ΔT_f = Temperature rise across inside oil film, °F (°C)
- ΔT_c = Temperature rise across coke layer (fouling service), °F (°C)
- ΔT_m = Temperature rise across tube wall, °F (°C)
- D_o = Outside tube diameter, in. (mm)
- D_i = Inside tube diameter, based on average tube wall thickness, in. (mm) = $D_o - 2\ t_a$
- D_i' = Inside diameter of coke layer, in. (mm) = $D_i - 2\ t_c$
- t_a = Average tube wall thickness, in. (mm)
- t_c = Design coke thickness, in.
  - = 1/8 in. (3 mm) for light coking service (atmospheric pipestill, etc.)
  - = 1/4 in. (6 mm) for heavy coking service (vacuum pipestills, visbreakers, etc.)
- h_i = Inside oil film coefficient, Btu/hr ft^2 °F (W/m^2 • °C). See Section VIII-C for recommended calculation procedures.
- k_c = Thermal conductivity of coke, $\frac{\text{Btu / hr ft}^2}{\text{°F / in.}}$ (W/m • °C), as follows:

FILM TEMP. °F	500	1000	1500	FILM TEMP. °C	260	500	800
k_c $\frac{\text{Btu / hr ft}^2}{\text{°F / in.}}$	38	34	30	k_c $\frac{\text{W}}{\text{m • °C}}$	5.5	5.0	4.4

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TUBE DESIGN (Cont)

k_m = Thermal conductivity of tube metal temperature at mean wall thickness, $\frac{\text{Btu / hr ft}^2}{\text{°F / in.}}$ (W/m • °C). See Figure 16.

$(\phi_r)_{max}$ = Maximum point heat density, based on outside tube diameter and corrected for longitudinal and peripheral maldistribution of heat and flame luminosity, Btu/hr ft^2 (W/m^2)

$$(\phi_r)_{max} = C_1 \; C_2 \; C_3 \; \phi_r \qquad \text{Eq. (17d)}$$

where: C_1 = Dimensionless correction factor for peripheral maldistribution around tube
= 1.77 for one-side fired tubes
= 1.18 for two-side fired tubes
(These factors are good for process heaters with t_a < 0.5 in. (13 mm), and tube center to center of 2 x IPS. For other applications, see Figure 3 in Section VIII-E. Multiply factor from this figure by 1.5 for one-side fired tubes.)

C_2 = Dimensionless correction factor for vertical maldistribution, as follows:

FURNACE RADIANT SECTION HEIGHT, ft	FURNACE RADIANT SECTION HEIGHT, m	C_2 FACTOR
Up to 25	Up to 7.6	1.20
30	9.0	1.23
35	10.7	1.28
40	12.2	1.33
45	13.7	1.40

(Vertical maldistribution depends upon heater geometry. This factor should be used for all heaters previously described. For unusual applications, consult the Heat Transfer Equipment Section of EETD.)

C_3 = Dimensionless correction factor for luminosity, which depends upon the type of flame:
= 1.0 for non-luminous flames (gas)
= 1.08 for luminous flames (oil, combination gas/oil)

ϕ_r = Radiant section average heat density, Btu/hr ft^2 (W/m^2)

DESIGN PRESSURE

The pressure used for the design of fired heater tubes will be one or both of following.

Elastic Design Pressure (P_e) - This pressure is the maximum pressure the heater coil could be exposed to for short periods of time. The value of this pressure is generally related to a safety valve setting and must be determined by the individual responsible for the overall unit process design. This pressure is used in an elastic design equation to prevent excessive elastic stresses in the tube when at its maximum pressure.

Rupture Design Pressure (P_r) - This pressure is the normal operating pressure the tube must sustain over long periods of operation. If the operating pressure changes during an operating run, the highest pressure should be used. The rupture design pressure is used in a creep design equation to ensure that any creep damage accumulated under the action of the operating pressure (stress) does not result in a tube failure.

In most situations, both elastic and rupture design pressures vary depending upon the section of the total heater coil under consideration. However for low pressure and/or low pressure drop heaters it is common practice to use a constant elastic and rupture design pressure for the whole coil. For high pressure and/or high pressure drop heaters, consideration should be given to establishing different elastic and rupture design pressures for various sections of the heater coil since considerable investment savings on tubes can often be realized.

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TUBE DESIGN (Cont)

TUBE WALL THICKNESS

Calculation of heater tube wall thicknesses is based upon the procedures and stress data outlined in API RP-530. When calculating the minimum tube wall thickness required, three different design bases will generally have to be considered. The most conservative basis will set the minimum required tube wall thickness for the heater. The relevant equations for each case are summarized below.

1. **Elastic Design Basis** - Preventing failure by bursting during a maximum, short term pressure condition near the end of the design life when the corrosion allowance has been used up.

$$t_m = \frac{D_o\ P_e}{2\,S_e + P_e} + TCA \qquad \text{(Customary)} \qquad \text{Eq. (19)}$$

$$t_m = \frac{D_o\ P_e}{2000\,S_e + P_e} + TCA \qquad \text{(Metric)} \qquad \text{Eq. (19)M}$$

where: t_m = Minimum tube wall thickness, in. (mm)
D_o = Tube outside diameter, in. (mm)
P_e = Elastic design pressure, psig (kPa, gage)
S_e = Allowable elastic design stress [psi (MPa)] at the design tube metal temperature (based on two-thirds of minimum yield strength for ferritic steels and 90% of yield strength for austenitic steels). Table 3 presents stress values for typical materials used in heater design. Refer to API STD-530 for other materials.
TCA = Total corrosion allowance, in. (mm)
= Nominal annual corrosion rate (in. or mm per year) times 5. (Heater tubes are normally placed in the 5 yr corrosion design category.) Nominal annual corrosion rate (including both inside and outside corrosion) is evaluated at the design tube metal temperature using the curves contained in the EMRE *Refinery Construction Materials Manual* (RCMM).

Note: The corrosion data in the RCMM is considered to be conservative, so a 5 year design life normally results in a much longer actual life. If more accurate, measured corrosion rate data is available and used for design, the life should be increased to 10 years.

2. **Rupture Design Basis** - Preventing failure by creep rupture during the design life.

$$t_m = \frac{D_o\ P_r}{2\,S_r + P_r} + f\ TCA \qquad \text{(Customary)} \qquad \text{Eq. (20)}$$

$$t_m = \frac{D_o\ P_r}{2000\,S_r + P_r} + f\ TCA \qquad \text{(Metric)} \qquad \text{Eq. (20)M}$$

where: t_m = Minimum tube wall thickness, in. (mm)
D_o = Tube outside diameter, in. (mm)
P_r = Rupture design pressure, psig (kPa, gage)
S_r = Allowable creep rupture design stress (psi [MPa]), based on 100% of the minimum stress to produce rupture at the design life and the design tube metal temperature. Design life is to be 100,000 hrs unless otherwise specified. Table 3 presents stress values for 100,000 hours design life for typical materials used in heater design. Refer to API RP-530 for other materials.
f = Corrosion fraction, dimensionless. Determined from Figures 18 and 19. This factor is applied to take credit for the reduction in stress which results with the addition of the corrosion allowance.
TCA = Total corrosion allowance, in. (mm). Determined exactly the same as for elastic designs, see Item 1 above.

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TUBE DESIGN (Cont)

S 3. **Minimum Wall Design Basis** - Ensures that a tube near the end of the corrosion life will have sufficient mechanical rigidity to resist sagging and/or damage from external forces or abuse.

t_m = 0.125 in. (3.17 mm) + TCA for radiant, shield, and convection tubes. Eq. (21a)

t_m = 0.22 in. (5.59 mm) for studded tubes to provide mechanical rigidity required for the studding operation. Eq. (21b)

Tubes in Steam Superheating or Generating Service - Fired heater tubes in these services should be designed according to the procedures outlined above unless local statutes or ordinances specifically require ASME or some other design basis.

Thermal Stress Checks for High Pressure or High Temperature Tubes - The tube design equations discussed previously assume that the thermal stress induced by the radial temperature gradient across the tube wall is negligible. However, for high pressure or high temperature heaters, tube wall thicknesses and temperature gradients may be large enough to result in significant thermal stresses. Therefore, tubes designed for these type heaters should be checked to ensure that the thermal stresses are indeed negligible. If thermal stresses are found to be excessive, the tube material can be upgraded or the heat flux decreased to reduce the tube wall thickness and thermal stress to acceptable levels.

The equations given below can be used to determine whether thermal stresses are within acceptable limits for tubes operating in the "elastic" region. However no simplified formulas have been developed for checking thermal stresses when tubes operate in the "creep" region. Therefore, any tube designs in the creep range which has a temperature difference across the tube wall of 150°F (80°C) or greater should be submitted to the Mechanical Engineering Section of EETD for review.

The maximum thermal stress for a tube is given by the following equation:

$$S_{th} = \left[\frac{\alpha\ E\ \Delta T}{2\ (1-\nu)\ \ln Y}\right]\left[\left(\frac{2\ Y^2}{Y^2-1}\right)\ \ln(Y) - 1\right] \qquad \text{Eq. (22)}$$

where: S_{th} = Maximum thermal stress, psig.

Y = D_o / D_i, ratio of outside to inside tube diameter (D_i based on average tube wall thickness).

α = Coefficient of thermal expansion at mean tube wall temperature, $°F^{-1}$ ($°C^{-1}$). Table 4 contains thermal expansion data for the commonly used materials.

= Modulus of elasticity of mean tube wall temperature, psi (MPa). Table 5 contains values of E for the commonly used materials.

ν = Poisson's ratio, dimensionless. Equal to 0.3 for steels.

T = Design temperature difference across average tube wall thickness, °F (°C).

For the elastic region, the calculated thermal stress should meet the following criteria:

- For ferritic steels:
  $S_{th} \leq (2.0 - 0.67\ Y)\ Sy$ and
  $S_{th} \leq 1.33\ Sy$
- For austenitic steels:
  $S_{th}\ (2.7 - 0.90\ Y)\ Sy$ and
  $S_{th} \leq 1.8\ Sy$

where: Sy = Minimum yield strength, psi (MPa). Yield strengths for common materials are presented in Table 6.

External Piping - Heater piping external to the firebox and header boxes, such as external crossovers, should be designed per the Piping Code, ASME B31.3. For most applications, crossovers are made the same thickness and of the material as the tubes they connect (the upstream material if a change of materials occurs).

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INSTRUMENTATION

The following instrumentation should be provided for process heaters. This is usually shown on the design specification flow plan. Instruments requiring connections on the heater itself should also be shown on the heater sketch, so that these connections can be properly located. Additional instrumentation may be required in individual situations.

No distinction has been made here between indicators and recorders, the choice depending upon the requirements of the individual situation.

See Section XII for details of control schemes.

PROCESS FLUID

FLOW

1. Flow measurement and control for each pass in liquid and vaporizing services.
2. Protection from low flow (or flow stoppage) should be provided in accordance with Section XV-B.

TEMPERATURE

1. Coil Inlet - Average temperature into the fired heater. Also, individual pass indicators if flashing occurs across a control valve.
2. Crossovers - Temperature of each pass (or of common header) between radiant and convection sections.
3. Coil Outlet Temperature (COT) of each pass, plus combined temperature in transfer line. Because of the large number of passes in hoop tube type heaters (with nearly uniform outlet temperatures), coil outlet temperatures on individual passes are not normally measured. At most, COTs from a few representative passes should be measured.

PRESSURE

1. Coil Inlet - Pressure of each pass, downstream of control valve. Pressure in feed line if valves are not used to control flow to individual passes.
2. Coil Outlet - Overall pressure in transfer line.

TUBE METAL TEMPERATURE

Thermocouples for monitoring tube metal temperatures should normally be provided. The exact number and location of the TIs will vary depending upon the type of heater being designed. As a minimum, the general philosophy should be to provide one TMT thermocouple per pass located at the coil outlet and at an elevation above the heater floor coincident with that of the peak heat density. Refer to **GP 15-2-1** for guidelines on using TMT thermocouples.

FLUE GAS

Temperature (Instruments and connections required by **GP 15-1-1**.)

1. In stack below the damper.
2. At the bridgewall. When possible, the thermocouples shall be placed in the arch out of view of the shield tubes.
3. Between different services in the convection section.

Draft Gages (Required by **GP 15-1-1**.)

1. At the bridgewall.
2. Downstream of stack or duct control dampers.
3. Upstream of stack or duct control dampers.
4. In the sidewall at the heater floor.

Other Pressure Instruments - A high-pressure alarm (and under certain conditions, a cut-out) at the top of the radiant section is also required for all heaters, per **GP 15-1-1**.

Oxygen/Combustibles Analyzers - One shall be provided to permit continuous analysis of the flue gas in the stack, per **GP 15-1-1**.

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INSTRUMENTATION (Cont)

FORCED-DRAFT SYSTEM

PRESSURE INDICATORS

1. Main air duct.
2. At each burner, downstream of the shut-off damper.

Controls & Safety System - As required by **GP 15-1-1**.

Air Flow Measurement - This can normally be justified when it is planned to regulate the fuel/air ratio by computer control.

FUEL SYSTEM

Control & Safety System - Pressure indicators, alarms, cutouts, as required by **GP 15-1-1**.

Atomizing Steam - Provide a pressure indicator on the header, downstream of the control valve.

Fuel Oil - Reference off-site DP on Fuel System. Provide a temperature indicator near the end of dead-ended headers, and at the inlet and outlet of return loop headers.

STEAM-AIR DECOKING SYSTEM

See Section VIII-I.

SOOTBLOWERS

Pressure Indicator on steam header.

Flow Indicator on steam header for low-pressure systems (< 250 psi, < 1725 kPa).

MECHANICAL SPECIFICATION

HOW THE REQUIREMENTS ARE COVERED

Global Practices - **GP 7-1-1, 7-4-1** and **7-5-1** cover minimum requirements governing the design, fabrication, and inspection of process heaters. Although minimum process requirements are included for application to vendor-designed heaters (duty spec.), the GPs are largely concerned with the common mechanical design requirements that apply to most of our heaters. These requirements are updated periodically, based on our latest experiences and developments.

Design Specification - The design specification gives the information shown in the checklist (Table 1) in Section VIII-A. A sketch showing the general heater arrangement is necessary. Special mechanical features for the particular heater are also included in the design specification. Up-to-date details of these mechanical features are available from the Heat Transfer Equipment Section of EETD.

TUBE GUIDES AND SUPPORTS

Corrosive Compounds in Fuel - If the fuel contains significant amounts of vanadium and sodium, special consideration must be given to metal parts (mainly tube supports) operating at temperatures above 1200°F (650°C). The tube support operating temperature is assumed to be the same as the flue gas temperature. Above 1200°F (650°C), molten ash deposits on the supports and fluxes them. The common tube support and guide materials of 25/20 and 18/8 Cr-Ni alloys rapidly deteriorate under these conditions. The following means of reducing this problem must be included in the specification, where applicable:

1. The designer must specify the quantities of vanadium and sodium in the fuel, so that the appropriate requirements of **GP 7-1-1** are invoked. Among these are protective refractory coatings or the use of high chromium-nickel (50 Cr, 50 Ni, and Nb) alloy for the tube supports.
2. Where practical, heater components can be designed to minimize exposure to hot flue gases. Examples are locating tube supports and guides outside the firebox and behind tubes. Also, convection section intermediate tube sheets can sometimes be eliminated in the case of V.C. heaters by making the convention section shorter and wider.
3. The vulnerable components can also be made easily removable for replacement during turnarounds. This is practical for the radiant section supports and guides. **GP 7-1-1** requires supports for horizontal radiant section tubes to be replaceable without removing the tubes.

   Making convection section tube supports replaceable without removing the tubes requires substantial extra investment and is rarely done. Sometimes the owner wishes the radiant tube supports to be made replaceable without even shutting down the heater. However, this is normally very expensive and seldom justified. Neither of these two features should be specified unless specifically requested by the owner.

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