Technical Publication

# The Supercritical Recirculation Boiler

*by*

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## INTRODUCTION

Supercritical boilers have been operating in this country for a number of years, but the Riley Stoker Corporation is a relative newcomer in this area. Before I go into detail of our present offerings in this field, I would like to give you an idea of our background and our philosophy in approaching the supercritical boiler. To do this, I'll have to go back to our sub-critical experience.

Figure 1 is a diagrammatic arrangement of the circuitry in a sub-critical natural circulation boiler. Note that the economizer and superheater are once-through, as would be a reheater which is not shown. In the furnace, however, recirculation is employed. Where there is a boiler bank or convection wall, recirculation would also be used. This type of unit employs a natural pumping effect by utilizing the density differential between the water in the unheated downcomer and the water-steam mixture in the heated tubes to produce circulation in the furnace walls.

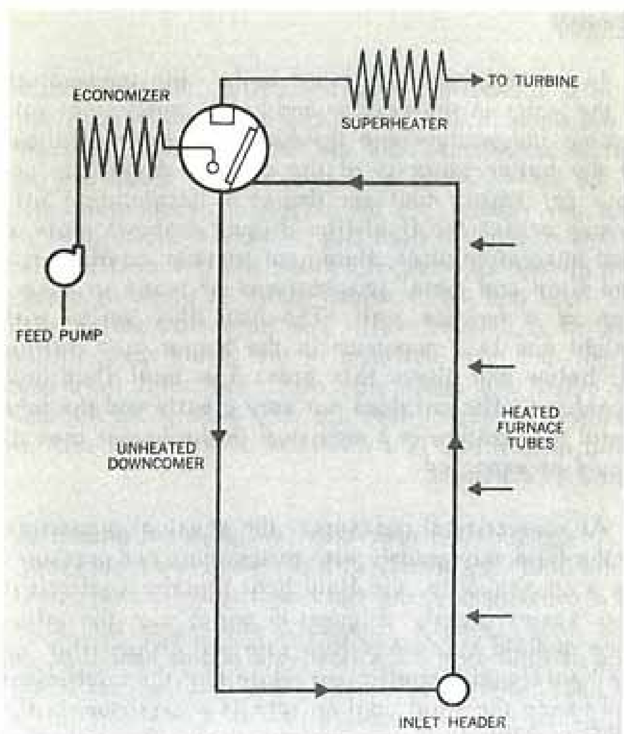


Figure 1 Natural Circulation System

It was natural, therefore, that when designers of the early supercritical units approached the problem of furnace circuitry, they were faced with a single phase fluid in the furnace, and they designed the circuit as once-through. Our early designs of ten years ago also followed this approach as illustrated in Figure 2.

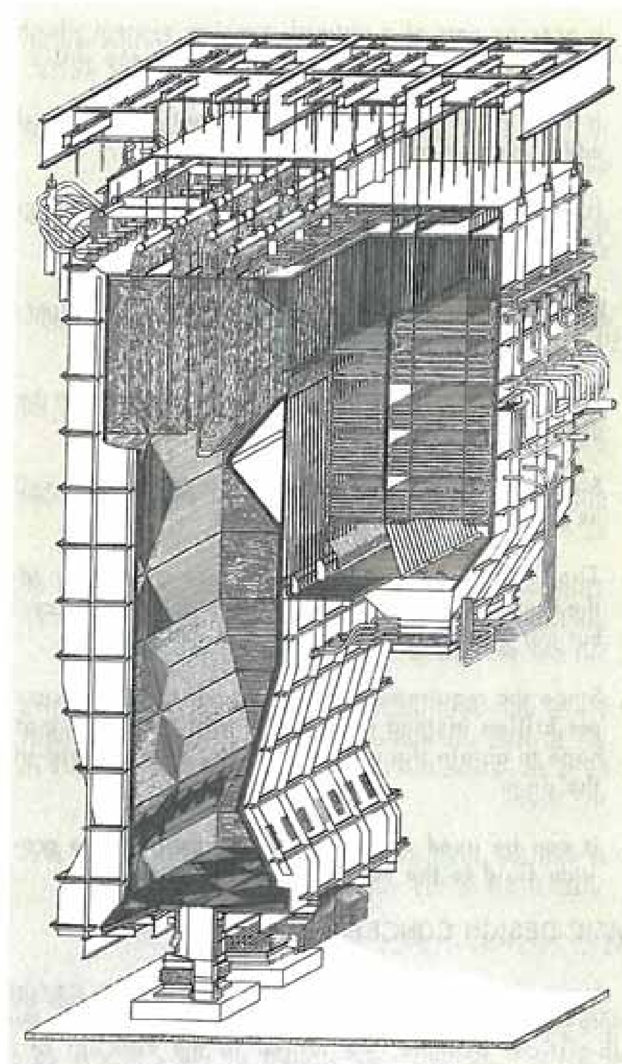

Figure 2 Early Riley Once-Through Design with Turbo Furnace

About that time, several competitive supercritical units became operational and, as with most pioneering designs, problems developed. Having the advantage of others' experience with once-through supercritical design, Riley decided to look at other approaches to the supercritical boiler.

Going back to our sub-critical designs, several differences were apparent. First, of course, there was the drum; second, all furnace tubes were in parallel; third, all tubes were upflow; fourth, the furnace tubes were protected by recirculated flow.

When we lock at the basic function of the steam drum, we find the following:

1. It acts as a mixing chamber for the fluid from the economizer and the heated fluid from the furnace tubes.

2. It provides for steam separation.

3. It acts as part of a natural pumping system which provides recirculation flow to the furnace walls.

4. It is a point of feedwater treatment by chemical additives and by blowdown.

5. It acts as a distributing manifold, to supply steam to the superheater.

When we apply these drum functions to a supercritical design, we discover that:

1. It can be used for a mixing chamber and can be greatly reduced in size.

2. Since the fluid is single phase, it cannot be used as a separator.

3. That there is a sizeable difference in density of the fluids in the hot and cold legs of the furnace, but not enough to sustain natural recirculation.

4. Since the requirements for water purity are in parts per billion instead of parts per million, we cannot hope to obtain the required quality by treatment in the drum.

5. It can be used as a distributing manifold to provide fluid to the superheater.

## BASIC DESIGN CONCEPT

Since the reliability of the furnace circuit can be improved by recirculating additional fluid, as in our sub-critical designs, we turned to the concept of a pump to assist the natural circulation tendency of the design. By replacing the drum with a small mixing chamber and a separate distributing manifold and by adding a recirculating pump, we arrive at the basic supercritical recirculation boiler circuitry shown in Figure 3.

In addition, we now make all tubes upflow and the addition of the recirculation flow also permits all furnace tubes to be in parallel. The basic circuit of our new concept is now remarkably similar to that of our sub-critical design shown in Figure 1.

With this new design concept, we went back to our studies to develop an actual operating design.

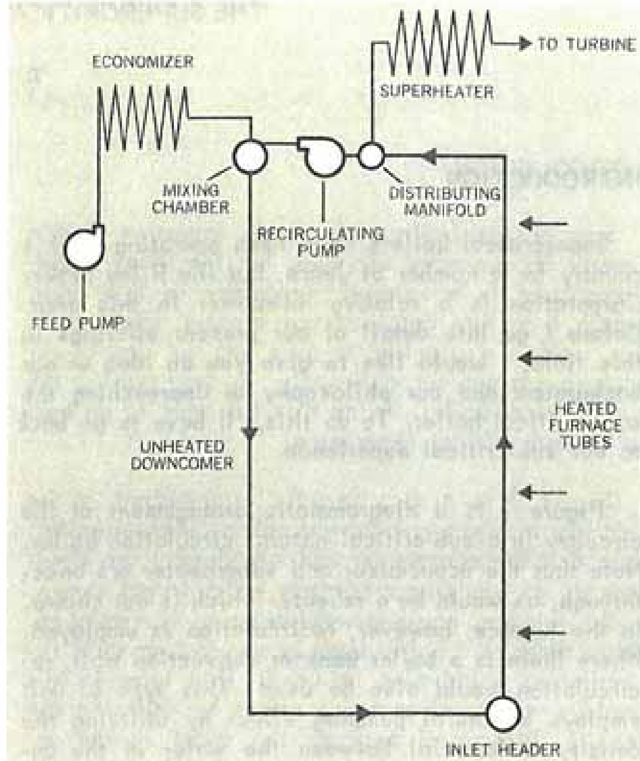


Figure 3 Supercritical Recirculation Boiler

## DESIGN

In a sub-critical pressure boiler, the temperature of the water in the furnace and boiler walls is at saturation temperature and the heat transfer coefficient of the boiler water is of the order of 5,000 Btu per hour per square foot per degree F temperature difference across the fluid film. Figure 4 shows plots of heat absorption rates, fluid heat transfer coefficients, and fluid and metal temperatures of tubes in a section of a furnace wall. The heat flux varies with height and is a maximum in the burner area, falling off below and above this area. The total fluid heat transfer coefficient does not vary greatly and the tube metal temperature is a maximum in the burner area as would be expected.

At supercritical pressures, the physical properties of the fluid vary greatly with temperature and pressure. As a consequence, the fluid heat transfer coefficient also varies greatly. Figures 5 and 6 plot the influence of fluid side mass flow rate and of heat flux, on the heat transfer coefficient. Note that the coefficient and hence the fluid cooling rate is a maximum in the 700F to 730F fluid temperature range. Also note that the fluid cooling rate increases with increased fluid mass flow and with reduced heat flux. Figure 7 is a plot similar to Figure 4, except for a furnace wall at supercritical pressure. Note that the fluid temperature increases with furnace height and that while the metal temperature is high in the burner area and falls off

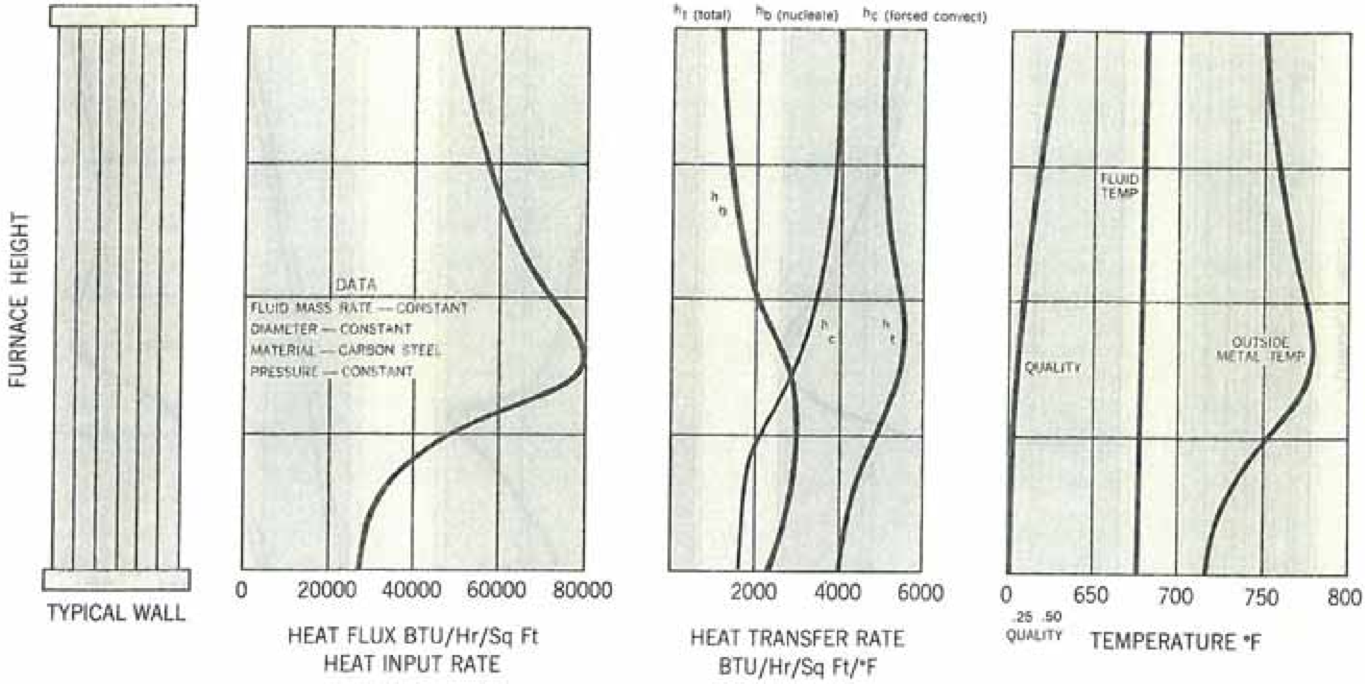


Figure 4 Furnace Tube Metal Temperature - Sub-critical Pressure

just above this area, it again rises because of the influence of the higher fluid temperature.

The effect of recirculation on fluid flow and temperature rise in the furnace walls is shown in Figure 8. Recirculation increases the flow rate and permits either greater cooling rate or an increased internal flow area for the same cooling rate or both. Further, recirculation reduces the fluid temperature rise in the tubes.

In the Riley Supercritical Recirculation Boiler, the furnace wall tubes are all in parallel flow relationship. The recirculation pump increases the cooling flow for

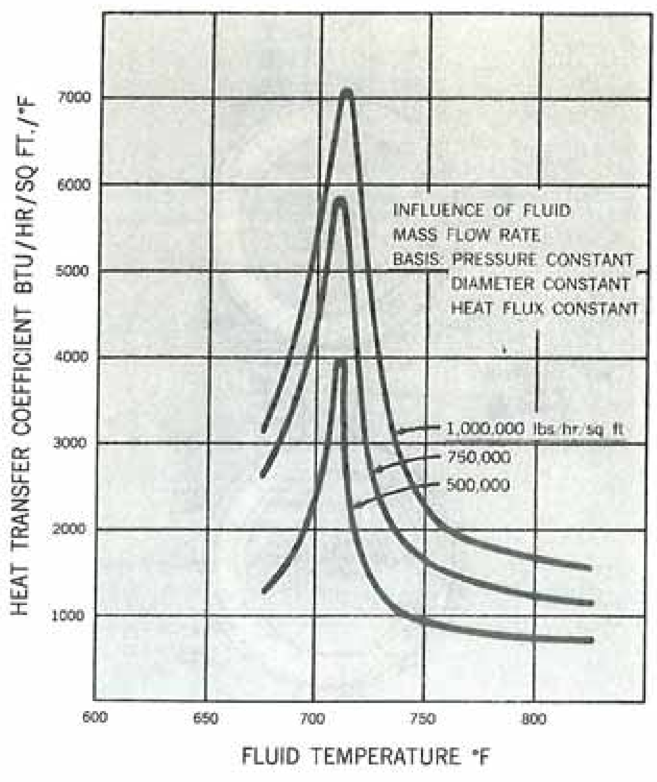


Figure 5
Supercritical Fluid Heat Transfer Coefficient

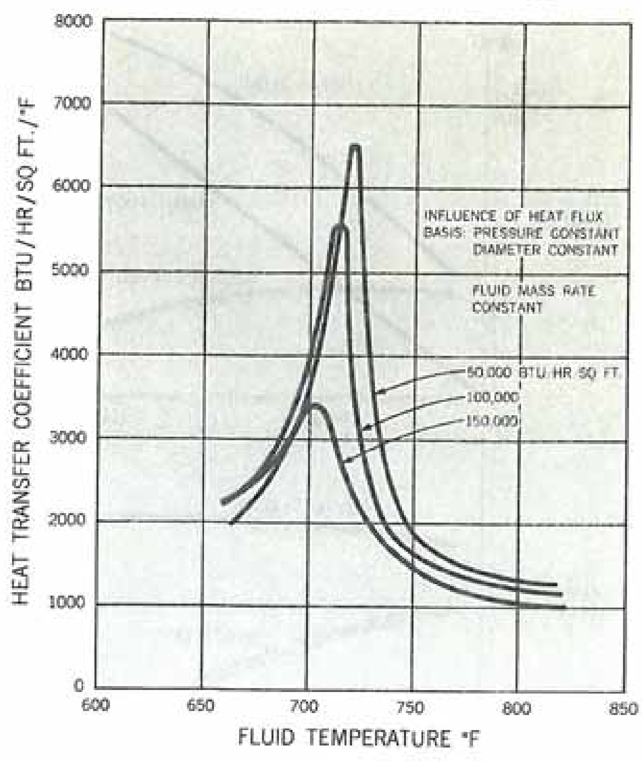


Figure 6
Supercritical Fluid Heat Transfer Coefficient

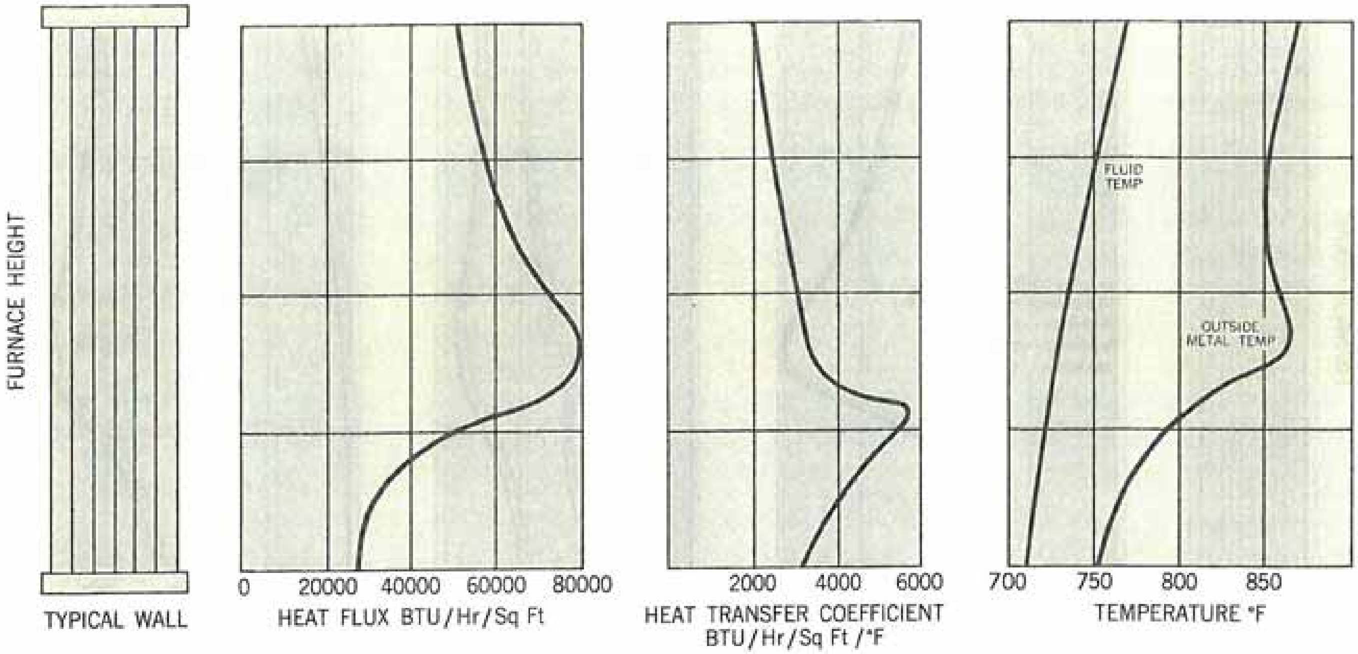


Figure 7 Furnace Tube Metal Temperature - Supercritical Pressure

protection of the walls at all loads. In modern design, furnace walls consist of tubes and spacer bars welded together to form an integral gas-tight wall. The welded wall is subject to thermal stresses which are a result of several factors. Figure 9 is a cross-section of a welded wall showing isothermal lines reflecting the temperature gradients in the tubes and bars which receive heat and are cooled by fluid flowing through the tubes. In the case illustrated, the maximum furnace face temperature of the tube at 882F is only slightly greater than that of the bar at about 875F. When the fluid temperature and the flow rates in the adjacent

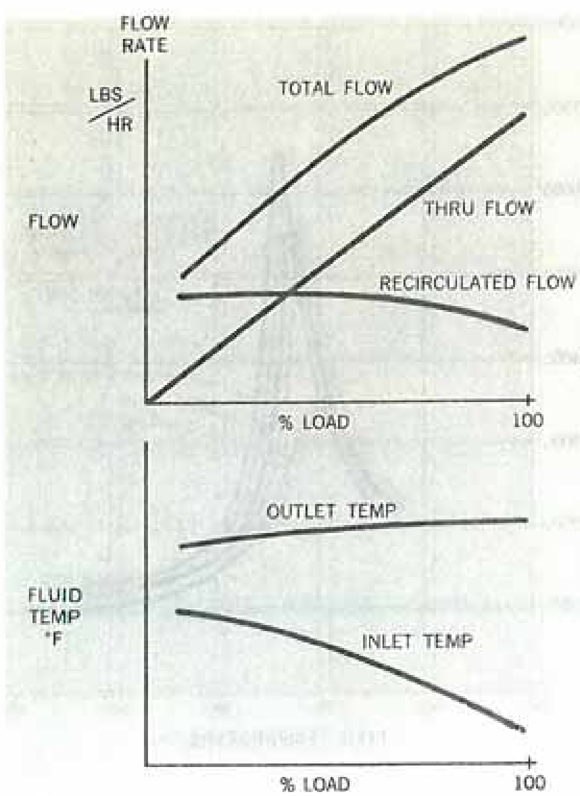


Figure 8
Furnace Fluid Flows and Temperatures

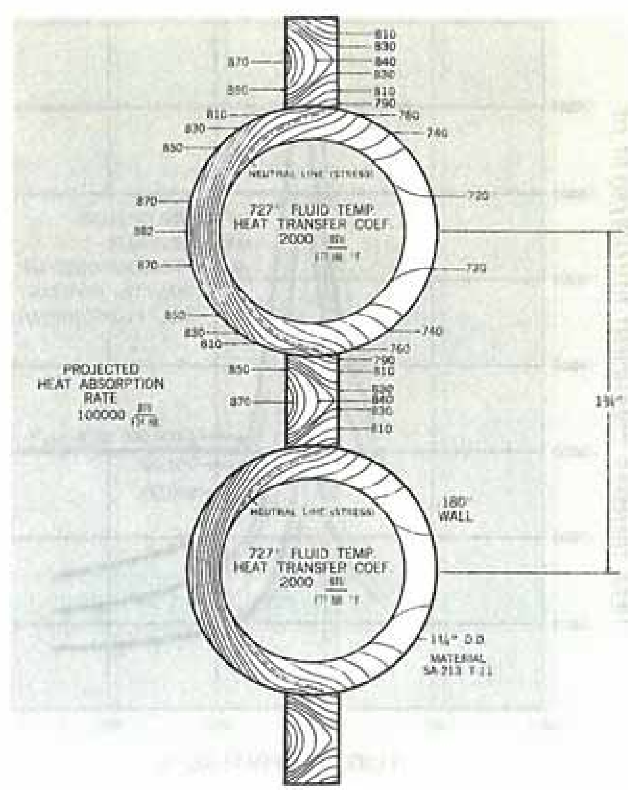


Figure 9
Furnace Wall Metal Temperature Distribution

tubes are equal, the thermal stresses are a minimum. Where there are several fluid flow passes in series in a wall, obviously the fluid temperature of the various passes will be different and the stresses will be greater where tubes in different passes are adjacent to each other. Therefore, thermal stresses are introduced in a design by using series fluid flow in a wall, in addition to the stresses normally expected as a result of variations in heat input and fluid flow in furnace tubes.

As mentioned above, one effect of recirculation is to reduce the fluid temperature rise. For example, if the fluid flow in a wall is doubled, the heat pickup per pound of fluid is halved. Therefore, the use of recirculation at all loads reduces the temperature rise in the walls at all loads and thereby reduces the temperature variation across a wall and from the floor to the roof of the furnace at all loads. As a consequence, recirculation reduces the thermal stresses in a wall, particularly in a welded wall.

While it is not possible to sustain natural circulation at supercritical pressures, it should be noted that there is still a sizeable density differential between the cooler fluid in the unheated downcomer and the hotter fluid in the furnace walls. This is illustrated in a plot of density versus temperature for various supercritical pressures as shown in Figure 10. Note the marked reduction in density particularly between 700F and 750F in which range the reduction is between 2 to 1 and 3.5 to 1. The Supercritical Recirculation Boiler takes full advantage of this density differential by locating the recirculating pumps at an elevated position. The recirculating pump is operated in parallel with the feed pump which means that the pump handles only recirculated fluid rather than a combination of through flow and recirculated fluid as would be required by a series located pump. The two features of low static head and low pumping capacity allow the pumps to be of moderate size and permit recirculation at all loads with a nominal power expenditure. For instance, the power input to a pump for a 500 MW unit would be no greater than 100 kW at full load. However, because of the low specific volume of the fluid during a cold start as compared with the specific volume at the normal operating temperature, the pump motor must be sized for the cold start condition or about six times the power required for normal operating conditions.

Because of pump recirculation, the full load pressure drop in furnace circuitry is considerably less than required for a once-through boiler which must be designed for adequate cooling at the minimum allowable load and hence must suffer from high pressure drop at full load. Consequently, the full load feed pump power requirement of a once-through boiler is considerably greater than on a recirculation boiler and the difference in power requirements is over 4 times the power supplied to the recirculation pump.

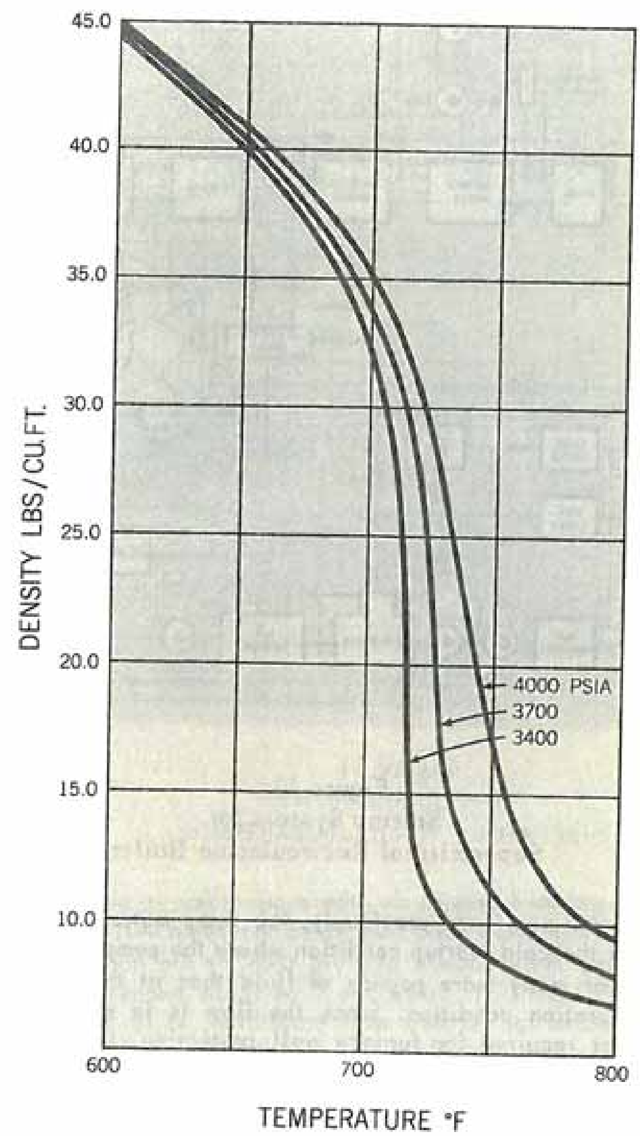


Figure 10
Density of Fluid at Supercritical Pressure

## STARTUP SYSTEM

The startup of a supercritical pressure boiler has been a difficult problem partly because of the fact that large flows have been required to protect the furnace walls, and these flows necessitate high firing rates in order to match turbine requirements. The combination of high flow and high firing rate requirements result in a large bypass system and extensive heat recovery connections.

On a recirculation boiler, the problem of furnace protection is divorced from the problem of matching turbine requirements and the startup procedures and equipment are simplified.

Figure 11 illustrates, schematically, a typical Supercritical Recirculation Boiler installation.

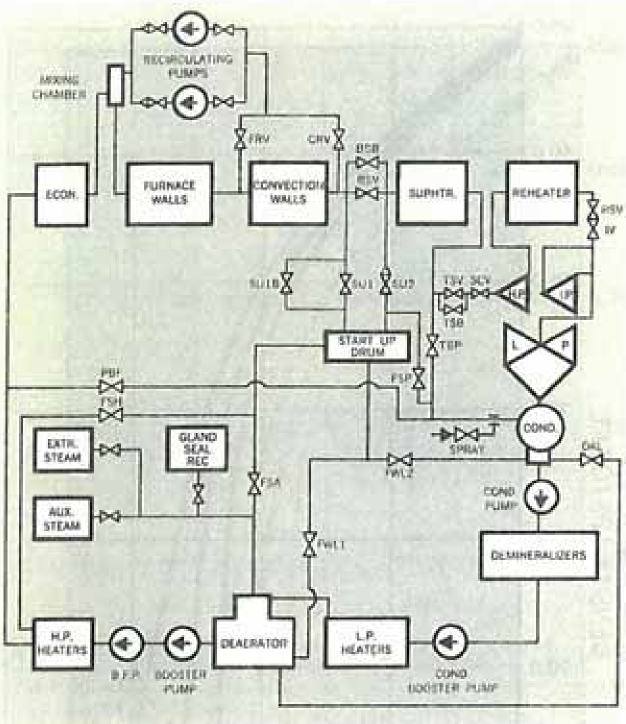


Figure 11
Startup System for
Supercritical Recirculation Boiler

As mentioned previously, the pump motor is sized for the cold startup condition where the pump will deliver many more pounds of fluid than at the normal operation condition. Since the flow is in excess of that required for furnace wall protection, it is possible therefore, to place the convection walls in series with the furnace walls by opening the convection recirculating valve (CRV) and closing the furnace recirculating valve (FRV). The added resistance of the convection walls reduces the flow somewhat, but it is still well in excess of that required for protection. The series arrangement permits maintaining a high velocity for flushing out the convection and furnace walls during hot cleanup. After the hot cleanup, the valve positions are reversed to give maximum protection to the furnace walls as the temperature increases.

The recirculating pumps also provide a convenient method for raising the temperature of the fluid prior to starting flow through the bypass system. By increasing the fluid temperature, we eliminate the problem of cold water cavitation in the pressure reducing valve (SUI). A small valve (SUIB) is used to relieve the pressure buildup during the period that the temperature is being increased.

Since the furnace walls are protected by recirculation, the flow through the bypass system is limited to that required for startup which is in the order of 10% of full load flow. The firing rate for this flow is approximately 5% of the full load rate which is considerably less than required on a once-through unit. It can be appreciated that with this firing rate, the protection of the superheater and reheater is no greater problem than encountered on a sub-critical natural circulation boiler. With the relatively small energy expenditure during the startup period, the need for heat recovery interconnections are minimized.

The start-up drum in the bypass system is designed for operating pressures up to 2000 psig. This permits maintaining the furnace walls at a conservative level of 755F and transferring from the bypass system with a minimum upset in superheater temperature. By maintaining a conservative furnace fluid outlet temperature and by limiting the Btu pick-up per pound of fluid by means of recirculation, the thermal stresses in the tubes are minimized.

## SUPERCRITICAL DESIGNS

Figure 12 illustrates our first Supercritical Recirculation Boiler being furnished to South Carolina Electric and Gas Company as Unit No. 1, for their new Wateree Station. This unit is presently under construction and is scheduled for operation in the spring of 1970. The unit is coal-fired, reheat unit, at the peak capacity of 405 MW, the boiler will generate 2,846,000 lbs of steam per hour at 3735 psig at superheater outlet and temperatures of 1005/1005F.

Reheat temperature is controlled by damper adjustment of gas flow over the reheat surface and primary steam temperature is controlled by firing rate. Two canned recirculation pumps are provided, each capable of supplying the full recirculation requirements of the unit. Heated water leaving the economizer is mixed in the mixing chamber with heated fluid pumped from the furnace wall outlet to this chamber, and the mixture flows down the large downcomers and through feeder tubes to the various sections of the waterwalls. During operation, one pump is in service while the other is on hot standby.

Figure 13 illustrates a recent offering for a 750 MW gas-fired unit. The design is basically similar to the South Carolina Electric and Gas Company boiler with the exception of higher heat releases, flat floor in furnace and finned tube economizer, which are permitted with gas-firing. Superheater and reheater temperatures are controlled as on the Wateree unit.

Figure 14 illustrates a recent design study for another 750 MW gas-fired unit. This design offers a number of inovations. The unit is a stack type boiler with the lower or furnace section in the shape of an octagon. This shape approaches the circle, which offers the optimum method of equalizing heat absorption in furnace tubes. The superheater and reheater are located in parallel passes in the upper portion of the unit. Reheat temperature is again controlled by regulating gas flow over the reheat surface, while superheater temperature is controlled by

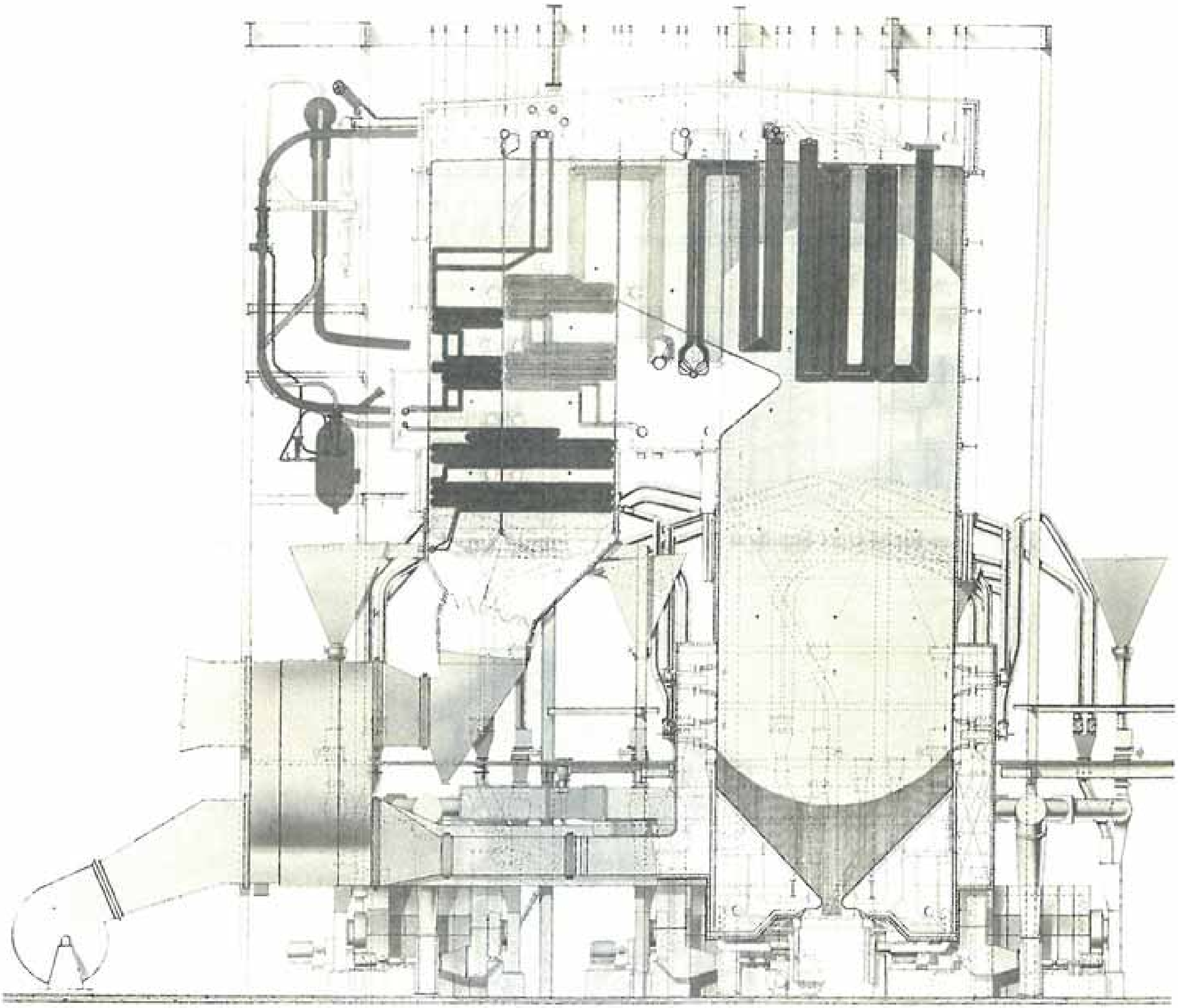

Figure 12
Wateree Station, Unit No. 1, South Carolina Electric and Gas Company
Wateree, South Carolina

firing rate. On this unit, the reheat control range is extended by means of positioning the flame in the furnace with the Riley Directional Flame Burner.

The regenerative airheater has been replaced with a closed loop heat exchanger system. The system consists of a gas cooler placed on top of the unit; an airheater located under the furnace and a recirculation pump. This system eliminates practically all breeching and expansion joints. On a normal regenerative airheater, the leakage amounts to about 5% of all air needed for combustion with an associated kilowatt consumption. Fans on this unit deliver only air required for combustion. This type design offers appreciable savings over the unit illustrated in Figure 13.

SUMMARY

The Supercritical Recirculation Boiler is characterized by provisions for recirculation in the furnace walls at all loads. One obvious disadvantage is the addition of recirculation pumps, plus the complexity and cost of the necessary piping and valves.

For this disadvantage there are a number of advantages. Since the through flow circulation is augmented by recirculation, there is sufficient cooling flow at all loads to permit a design having all the furnace wall tubes in parallel flow relationship, receiving fluid at the same temperature. Additionally, the temperature rise in the walls is reduced by recirculation and, therefore, the temperature variation

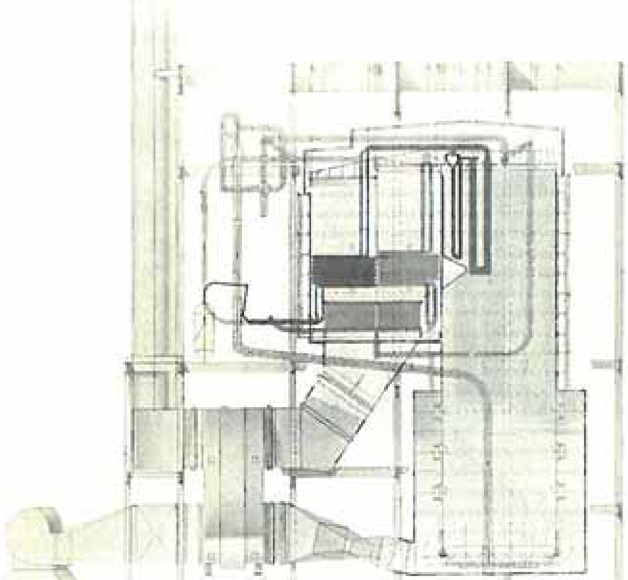

Figure 13 750 MW Gas-Fired Unit Standard Design

of the fluid and of the tubes in these walls is reduced. As a result, the thermal stress levels in the walls can be kept to a minimum, the factor of safety is greater, and under conditions of upset, the chances of failure are reduced.

Because of the recirculation feature, the startup system is relatively simple and the through flow required at minimum load is a maximum of 10%.

The pressure drop across the boiler is less than for any once-through unit and the difference in feed pump requirements is over 4 times the power input to the recirculation pump.

The intent of the design of the Riley Supercritical Recirculation Boiler was to develop uncomplicated construction having simple operating procedures and increased factors of safety. Such a design will permit operation with greater protection against failure and with increased flexibility of operation under all conditions.

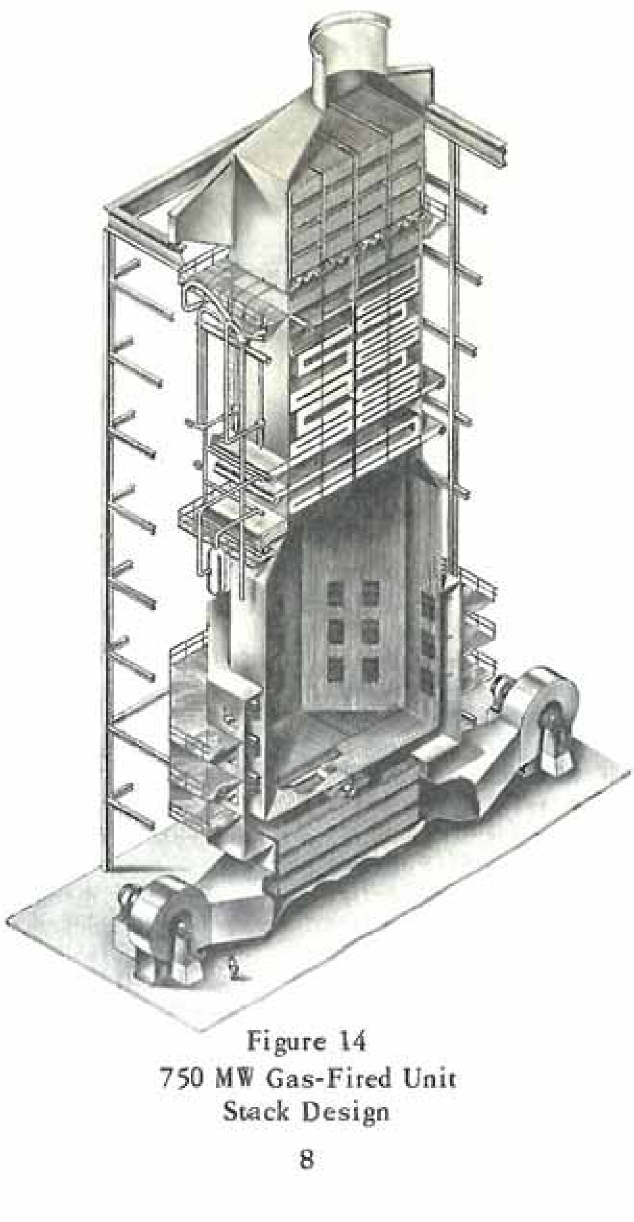

Figure 14
750 MW Gas-Fired Unit
Stack Design