The Rankine Cycle:
Workhorse of the Coal-fired Utility Industry

By Steve Voss, P.E., and Greg Gould, P.E.

The steam cycle in a power plant is characterized by the maximum operating pressure of the cycle. The typical steam turbine power plant operates on the Rankine cycle, the workhorse of the coal-fired utility industry.

Subcritical Rankine Cycle

The main feature of the Rankine cycle is the compression or pumping that occurs when the working fluid, water, is in the liquid phase. The amount of energy available for extraction by the working fluid is dependent on the operating temperature and pressure of the fluid. Raising the steam pressure or steam temperature improves efficiency.

Why is it desirable to raise pressures and temperatures? Figure 1 represents the Rankine cycle. The upper line represents the steam temperature and pressure generated by the boiler. The lower line represents the condensing portion of the steam cycle. The difference between the upper and lower lines determines how much energy can be extracted by the steam turbine, and thus the efficiency of the cycle. The condenser operates at a temperature and pressure dictated by external conditions such as the temperature of the atmosphere or the cooling water temperature. It is not feasible to substantially lower this line. The only way to improve the cycle efficiency is by pushing the upper line higher.

In a typical coal-fired steam cycle power plant the operating pressure is 2400 psi. Steam temperature is typically 1000 or 1050 degrees F. Steam temperature is limited by available materials that can survive at elevated temperatures. Most larger units have a reheat cycle (shown as line from point 2 to 3 in figure 1), where the steam is produced in the boiler, passes through a portion of the turbine, is "reheated" in the boiler and then goes through the remainder of the turbine. This increases the efficiency of the cycle without increasing the maximum steam temperatures.

The operating pressure of conventional coal-fired power plants can be classified as subcritical or supercritical. The critical point is where the temperature and pressure are such that the fluid is no longer classified exclusively as liquid or gas. It is thought of as a fluid above the critical point. The critical point for water is slightly above 3200 psi. Figure 1 shows a typical 2400 psi subcritical Rankine cycle with single reheat. The critical point is shown slightly above the cycle shown. Figure 2 shows a similar single reheat cycle, but operating at 3500 psi, or in the supercritical range. Increased efficiency is represented by the increase in area under the curve, approximately as shown in Figure 3.

Increasing the steam pressure improves cycle efficiency. It also provides the opportunity to go to a "double reheat" cycle, which allows even more improvement in overall efficiency. The overall net efficiency for a typical subcritical coal-fired unit is about 10,000 Btu / kWh. Increasing the initial steam pressure to 3500 psi from 2400 psi improves the heat rate by about 1.5%. The efficiency of a unit with 3500 psi initial steam pressure and double reheat is about 4% better than a typical subcritical unit. For a 600 MW unit burning $1.20 per million Btu fuel with an 80% annual capacity factor, this represents an annual cost savings of about $2 million.

Existing subcritical units in the United States typically have a steam drum where the working fluid circulates through the water walls either by heat transfer and gravity in the case of nat-

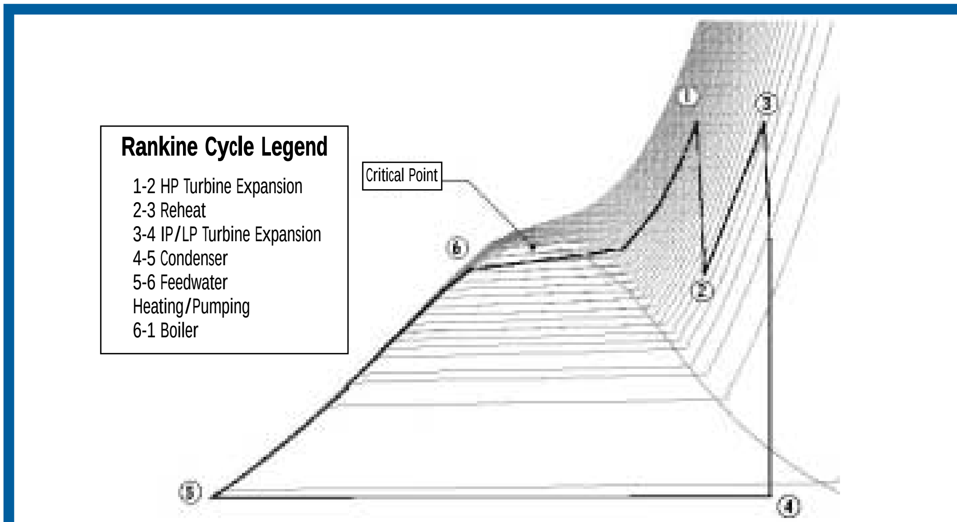

Figure 1
Temperature Entropy Diagram
Subcritical Rankine Cycle

ural circulation, or with the addition of pumps in the case of forced circulation.

Supercritical Benson Cycle

Supercritical units use a once-through design, also referred to as the Benson cycle. In a once-through boiler the fluid passes through the unit one time, and there is no recirculation as takes place in the water walls of a typical drum-type boiler. Since there is no thick-walled steam drum, the startup time and ramp rates for a once-through unit can be significantly reduced from that required for a drum-type unit.

Why Aren't There More Supercritical Units?

So if supercritical units are more efficient and have better startup and ramp rate characteristics, why isn't supercritical the right answer for any new coal-fired unit?

First, there is history. Most coal-fired plants in the United States are subcritical. The first commercial power plant using a supercritical steam cycle was placed into service in 1957. By the mid-1960s, about half of all U.S. units being ordered were supercritical. The purchase of supercritical units in the United States dropped off dramatically in the 1970s, primarily because of the onset of base-loaded nuclear power stations. Plants designed to burn fossil fuels during this time period were built to follow load, and the subcritical cycle was selected because experience with cycling supercritical units (which were all originally designed for base load operation) was minimal. Also, supercritical units that had been built in the United States up to that point suffered from a variety of problems.

Second, typical U.S. supercritical units suffered more from the rapid increase in unit size than from technology. Most of the supercritical units in the United States were designed for coal firing. More than half had pressurized furnaces and one-quarter of the supercritical units were equipped with double reheat sections. During development of the supercritical unit in the 1960s, the average fossil unit grew in size from 247 MW to 500 MW.
While the U.S. generally quit building large coal-fired units in the 1980s, they continued to be constructed in Europe, Japan, and elsewhere around the world. There have been considerable advances in design and operation of supercritical units. Units now have improved bypass systems, which simplify startup. New units are also designed to operate with sliding pressure, which improves load change characteristics. Many of the "supercritical-related" problems with the early supercritical units have been resolved with new designs.

Third, since the once-through design does not have a place for blowdown from the system, the water entering the boiler must be of a much better quality than in drum-type units. A condensate polishing system and closer attention to system water quality are both necessary to successfully operate a supercritical unit.
Supercritical units are also more susceptible to water induction than drum-type units.

Fourth, controllability of a once-through unit is tougher than a drum unit. Once-through design requires faster responding controls and adaptive tuning over the entire load range. This is much easier to accomplish with today's Distributed Control Systems (DCSs) than with the old discrete component electronic control systems. The need for better control systems was known back in the 1960s, but the advancement of Direct Digital Control (DDC) proved unsuccessful

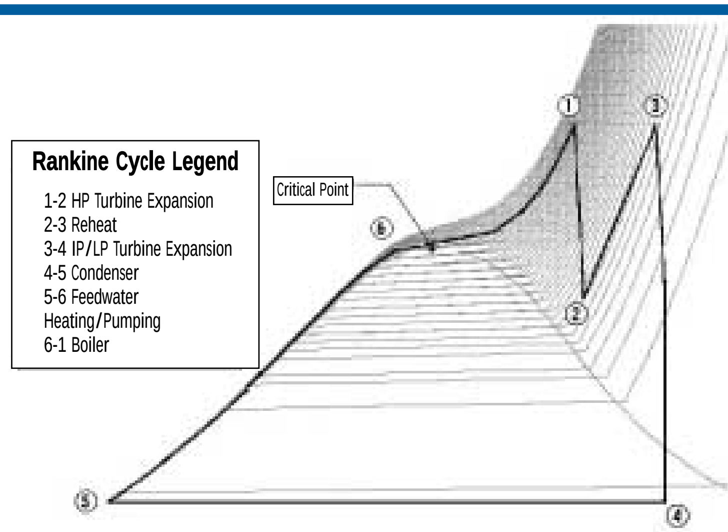

Figure 2
Temperature Entropy Diagram
Supercritical Rankine Cycle

because it required the use of redundant mainframe computers, which did not provide the reliable control required for power plants.

Lastly, there is the higher capital cost. The added capital cost of a supercritical unit over a drum-type unit ranges from no change to 3-5% depending on the source of the information.

Where Is All This Headed?

The last big hurdle is overcoming a technology that is decades old. The latest developments are aimed at even higher thermal efficiencies: 4500 psi with temperatures of 1500° F results in as much as 20% better thermal efficiency than conventional drum-type units. The limiting factors are the materials of construction that can withstand extreme conditions and what advances in metallurgy and ceramics can solve the problems.

The construction of coal-fired base-load power has been all but non-existent in the United States for the last 20 years. A few projects have been completed here and there, but the majority of the technological advances have taken place overseas, where the market for coal-fired boilers has been better. Since 1997, over 22,000 MW of coal-fired generation has been built in Europe. In that same time, less than 10% of that number has been built in the United States. An interesting trend to note is that over 80% of the overseas units are supercritical. There are approximately 360 supercritical units worldwide.

What About Unit Availability?

The availability of supercritical units built since 1990 is every bit as high as the subcritical units. The early supercritical unit population in the U.S. has a dark cloud that followed it around due to availability problems. Some of the problems can be attributed to the supercritical cycle, but just as many can be attributed to the fact that the supercritical units are on the average newer units that were built to tighter emission control standards and have had more control equipment. As any statistician or maintenance person can confirm, a system with more moving parts has a higher potential for failure than a simple system.

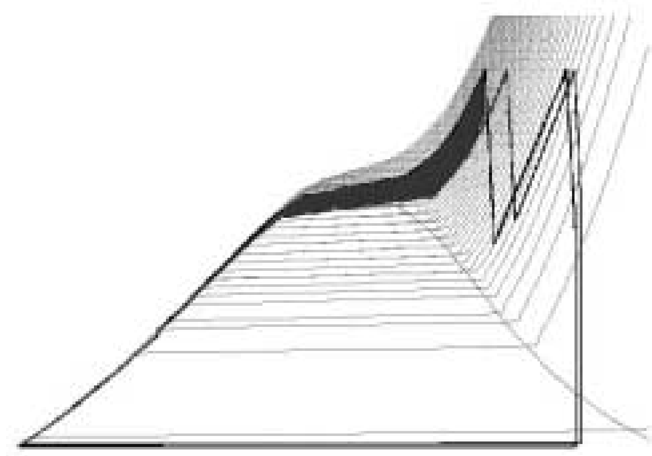

Figure 3
Temperature Entropy Diagram
Super vs. Subcritical Rankine Cycle

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