10
Boilers and Pressure Vessels: a Brief Look at General Safeguards

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10.1
Water

The compound composed of 2 atoms of hydrogen bound to a single atom of oxygen, though simple in structure, is truly staggering in its diversity. Essential though it may be for the very existence of life, water has many other useful properties as well. Frozen it expands with enough force to shatter rock, while flowing as a river it can slowly erode that same rock and change the face of entire country sides. Water is the most universal solvent in existence, able to transport all manner of chemicals and solids in both man-made and naturally occurring processes. Heated to 100 °C the change of state from liquid to vapor occurs, and water becomes steam. Several centuries ago, steam's ability to be used as a force multiplier was discovered, and many ingenious ways to make it do work have been developed since then.

This chapter is mainly concerned with water's unique ability to be converted to steam in boilers and pressure vessels. Specifically, a high-level survey of some of the safeguards that should be in place in modern boiler systems is undertaken. It bears mentioning that such safeguards will have a high degree of commonality whether applied to a vessel pressurized with steam or any other process commodity. Hence discussions around the safeguards required with steam production are usually transferable to other pressurized high-temperature substances, at least in broad generalities. Differences inherent in the chemical properties of a commodity under pressure and the effects of heat and pressure on the commodity itself should be accounted for during hazard and operability analysis – which should occur prior to construction!

A survey of the uses of steam in any industrialized nation will yield a lengthy list that some readers may find surprising. Hospitals utilize steam for cleaning surgical equipment and area heating; hospitality industries use steam to prepare food; it is used for heating large industrial and commercial building complexes; oil and gas facilities, pulp and paper mills, mines and airports are all steam users. Yet the largest users of steam by far (in most industrialized nations), are electrical power-generating stations.

Handbook of Loss Prevention Engineering, First Edition. Edited by J. M. Haight.

Regarding the production of electricity, one source comments:

> It is the power plant that provides this critical energy source, and in the United States approximately 90% of the electricity is produced from power plants that use steam as an energy source, with the remaining 10% of the electricity produced primarily by hydroelectric power plants.
>
> *(Woodruff, Lammers, and Lammers, 2005)*

Considering that the United States is one of the largest consumers of electrical power on Earth (China being the largest according to Woodruff, Lammers, and Lammers, 2005), that should give one an appreciation of the pervasiveness of, and dependence upon, steam in our society.

Steam is, of course, generated from water, which acts as an energy transfer medium as it absorbs the thermal energy released from a fuel, changing state from a liquid to vapor. The steam at this point is also carrying the mechanical energy expended in pressurizing the water via a pump system as it is fed to the boiler. That pressure is maintained in the steam header until steam is released to do work. The steam will either be utilized for its heating value or be converted into mechanical energy as it is allowed to act on some process.

An example of converting thermal to mechanical energy occurs with the steam turbine (Figure 10.1). A steam turbine that drives a generator to produce electricity is part of a complex series of steps involving energy transformation. The chemical energy in fuel is converted to thermal energy during combustion and heat is then absorbed by the water. The water changes state to steam and this steam is transferred at (usually) high pressure and velocity to the inlet nozzle of a turbine. The steam impinges upon and expands across turbine blades converting thermal and internal energy to mechanical energy. Finally, the turbine itself drives a generator to produce electrical energy.

The efficiency losses that must exist across each stage of energy transfer are more than made up for by electricity's versatility and the ability to distribute electrical power over a wide area in a cost-effective manner. Surely any consumer in a developed nation can point to an endless array of devices that exist to take electrical power and convert it back to mechanical or thermal energy in some fashion, and apply it to do useful work. It is therefore no overstatement that electrical power usage would be a fraction of what it is today without the use of steam. Perhaps more startling is the fact that advanced civilization, with our insatiable thirst for electricity, is impossible (or would be drastically curtailed) without the use of steam at present and for the foreseeable future.

In the light of the many volumes written about boilers and associated processes, there is no hope of ever dealing with the full complexity of the topic in a single chapter. The intention here is simply to give the loss control engineer or safety professional a glancing knowledge of some of the processes while prompting them to look at where to focus their energies for their own safeguards analysis. The reader should take heed that generally the larger the system, to greater is the complexity of control and operation, and hence the greater the array of safeguards required.

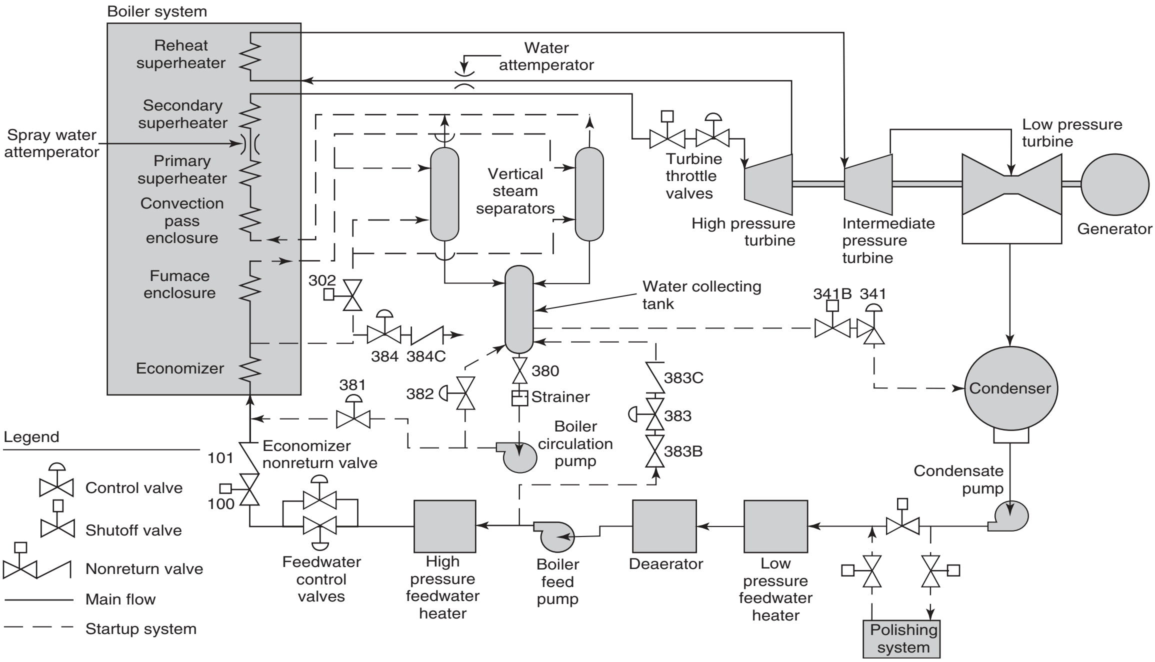

Figure 10.1 Schematic of a steam turbine power-generating system (Babcock and Wilcox).

The references cited should provide ample direction to more complete resources to aid in further research. There are many thorough treatments of boiler equipment and auxiliaries in existence due to the widespread use and long history of the technology. The author, like anyone else purporting to tackle the subject in a single chapter, is thus forced to beg forgiveness for the many missing pieces regarding specific types of processes, trusting that the reader will appreciate this chapter as a survey and not a treatise!

A further disclaimer is that you will not find specific reference to nuclear power plants in this chapter. The most significant safeguards employed in using nuclear fuel to generate steam are placed around the fuel source. The engineering and operating safeguards involved in nuclear power generation are highly specialized, as recent difficulties with Japanese reactors have highlighted. It is intriguing that for all of its advanced technology, the nuclear power plant still uses steam and provides considerable power-generating capacity in some countries. Nuclear facilities achieve economy of scale through stable fuel costs and lack of emissions control requirements compared with fossil-fueled plants. These offset the tremendous engineering, construction and operating costs associated with nuclear facilities (Kitto and Stultz, 2005).

Nuclear facilities aside, there are other special-purpose boilers such as recovery boilers used in Kraft pulp mills, heat recovery steam generators, and other fit for purpose units that are not specifically addressed in this chapter.

10.2
Safeguards

Perhaps it would be best to begin with a brief definition of what the author means by the term ‘‘safeguard.’’ The foundation of this approach is the work of Dr William Haddon Jr, who was a medical doctor in the State of New York. His pioneering approach was to study traffic accidents (a significant source of fatal injury in that State) in the same manner as one approaches a disease of the human body, seeking intervention points which he called ‘‘counter measures’’ to prevent the accident. A modern evolved version of this system is now taught worldwide by the System Improvements (SI) organization, purveyors of the root cause analysis program ‘‘TapRooT’’ (Paradies and Unger, 2008).

Building on Haddon’s work and *Barrier Analysis* by Trost and Nertney (1985), the SI group have adapted the elegantly simple approach known as ‘‘barriers to energy.’’ The safeguards are regarded as a barrier (physical or otherwise) between the worker and the hazard. To sum up, Paradies and Unger (2008) sort the safeguards into several categories. These may be physical (such as a guard on a motor); natural (using the geographical distance between a hazard and a population); human action (placing your seatbelt on before driving); and administrative control (posting a sign on a tiger’s cage). In the light of the many differing opinions and systems of hazard analysis and control, it seems best to keep this most elementary of views: a safeguard is some type of barrier to install (or utilize) between the hazard and the target, be that target human, equipment, or environment (Paradies and Unger, 2008).

Loss causation models abound and "a large percentage is difficult for many to understand and remember" (Bird, Germain, and Clark, 2003). Rather than get bogged down with a complex analysis, here a brief examination of the broad groups of hazards is undertaken, and a selection of some of the more important engineered and administrative or human action safeguards in modern boiler systems are reviewed, in the broadest of terms. This approach is taken because of the sheer breadth of the topics under discussion. Safeguards are addressed with an eye towards code requirements, and some of the systems involved in generating pressurized steam (water treatment, chemical addition, boiler systems, and fuel delivery). Along the way we touch on some operating considerations, emergency preparedness, and some of the unique hazards associated with steam and pressure vessels in the workplace. Due to its complexity, the modality of structural and mechanical failure will not be regarded in this chapter. For an expansive look at analyzing mechanical failures the reader is urged to consult the work of Heinz Bloch and Fred Geitner from the reference list (Bloch and Geitner, 1999).

10.3
Codes, Regulations, and Training

One of the oft heard maxims in the safety profession is "the codes are written in blood," an ominous reference to events that drove some of the modern legislation. The lessons learned through boiler explosions and mishaps are at best sobering and at worst downright frightening. The fearsome potential of boiler explosions became the major driver in formalizing engineering and maintenance practices for large commercial boilers, as they became more widely used. The regulations concerning boiler fabrication and operation may not often be thought of as safeguards to the casual observer owing to their latent and non-visible nature.

However, no discussion around boiler safeguards would be complete without addressing the regulatory requirements and why they have become so essential to industrial boiler applications. The construction, installation, and design of boiler and pressure vessel systems is highly specialized, governed by metallurgical properties, welding methods, construction expertise, location, and service application. There are many factors in play that will govern which design codes apply to a particular facility. Consider the differences that the type of fuel (coal, gas, oil, nuclear, etc.) would make in furnace selection and fuel delivery systems and environmental emissions management. Alternatively, the seasonal temperature variations (contrast power generation in a northern Canadian installation with a similar facility in Dubai, for example) would need to be accounted for, hence one can appreciate the diversity of engineering complexity.

Construction and design aside, it would appear the codes governing safe operation and maintenance of boilers and pressure vessels have perhaps been the most costly ones to learn. Despite a large body of information on boiler mishaps as boiler use spread, regulation was slow in coming, as evidenced by this summation provided by the American Society of Mechanical Engineers (ASME):

> Steam powered the technology of the late 19th century. Despite their power, boilers and pressure vessels were temperamental, requiring constant attention and maintenance. Although there were numerous boiler explosions throughout the 19th century, there were no legal codes for boilers in any State in the Union.
>
> *(ASME, 2011)*

On their web site, the ASME historians point to a likely trigger point for the formation of legislation surrounding boiler construction (in the United States at least). This was the explosion at the Grover Shoe Factory in Boston that killed 58 people and injured over 100 more in March 1905. That incident prompted the Governor of Massachusetts to request legal rules for boiler design and construction (ASME, 2011).

The codes governing the construction, operation, and maintenance of boiler systems may differ, depending on the country of origin. North America remains relatively consistent, having largely adopted the Boilers and Pressure Vessel Code developed by the ASME in 1915. It is a testament to the thorough nature of that work that made for adoption into law in the majority of American States and Canadian Provinces. Although a relative ‘‘latecomer’’ to the international scene as a nation, Canada’s safety record, for example, has been very good. This is likely due to the lessons learned by so many other nations in the past. According to one source:

> The Canadian jurisdictions have an excellent safety record in the area of boiler and pressure vessel operations. This is generally attributed to the standards set by the various jurisdictions for safety inspections, installation requirements, and operative certification.
>
> *(SAIT Legislation, 2000)*

Regulations and codes require careful attention and must be frequently consulted prior to construction or modification by both engineering and operations staff. Local provincial regulatory bodies (such as those in each of the Canadian Provinces) are tasked specifically with the certification, inspection, and regulation of boilers and pressure vessels. In addition to certifying equipment, regulatory authority can also oversee the requirements for the examination and certification of at least two types of personnel: the operations staff who attend to boilers and pressure vessels, and the welders who build or modify them.

Operations staff are certified as ‘‘Power Engineers’’ in Canada and elsewhere. On ocean-going vessels the term ‘‘Marine Engineer’’ is also still in use. The highest Power Engineer level would be a First Class Power Engineer, moving down through the ranks to Fifth Class (again using Canadian systems as an example). Each level allows the bearer to operate certain types of equipment under certain conditions, normally based on the heat output of the equipment. Certification is attained through a combination of academic testing and work experience in the same fashion as in any other trade.

The reader who is going to undertake any work on boiler systems will need to be familiar with the code requirements governing boiler use in the country in which they operate in order not to exceed their boundaries. Thus anyone who has the boiler and ancillaries under their direct supervision had best be fully conversant with the codes in their country.

Reviewing the history and development of codes and regulations for boiler service will point to several larger lessons learned from past operations. Perhaps the first among ''lessons learned'' in the history of boiler use is one common to every human endeavor: ''don't ignore the lessons learned!'' Trite as this may sound, the capacity of humans to rationalize and make costly, bad decisions when large production dollars, downtime, or ''shareholder value'' are placed in front of operational issues with perhaps a known history of failure is amazing. If it is not an approved method of doing something, likely it has been tried before with less than stellar results! Acclimation of deviation (successive compounding of small errors leading to larger divergence from the intended path) is an ever-present danger when dealing with equipment that has long in-service times with monotonous stability coupled with repetitive sample analysis results.

The second lesson to be learned is ''follow the codes''; they are derived from lesson one in many cases. Such a statement is not made lightly in recognition of the somewhat circular logic. The alternative is to be in an area that is at best experimental and at worst exposing one's organization, personnel, and themselves to unnecessary harm and perhaps even with legal ramifications if things go wrong in a big way.

The third lesson is to ensure that both new construction and/or changes to systems are made only through some sort of approval process (i.e., a Management of Change system) and by certified workers. In Canadian vernacular, ''code shop'' and ''non-code shop'' refer to the limits of authority that a facility has to fabricate and repair boilers and pressure vessels. Canadian code shops are authorized under ASME standards to build and repair boiler equipment and ancillaries. A non-code shop would only be allowed to build and repairs items such as storage tanks for water and other equipment not governed by pressure vessel standards (SAIT Legislation, 2000).

The point is somewhat belabored because numerous incidents have been the result of well-intentioned, poorly performed changes to a system without consulting the proper engineering authorities and experienced, knowledgeable individuals. In his classic work ''*What Went Wrong?*,'' a selective review of industrial accidents, Trevor Kletz states, ''Many accidents have occurred because changes were made in plants or processes and these changes had unseen side effects'' (Kletz, 2009).

To sum up, the codes and regulations generally establish who can construct, work on, or modify boilers, what modifications require inspection, and what type of documentation is required. Further, the various certification requirements for operations and welding personnel in each jurisdiction are also generally given in the codes.

Regulatory codes provide a safeguard that will falter if not exercised within a culture that is committed to high standards of maintenance and operation, yet when implemented will go a long way towards operational excellence, which is just one of the marks of a company committed to excellence in managing the entirety of its operation, including safety management.

10.4
Types of Boilers

A brief look at the classifications of boilers is an appropriate place to start the discussion around these systems. Here the reader is urged to consult with the venerable volume by Kitto and Stultz published with numerous revisions since the early 1900s entitled *Steam, Its Generation and Use*. In its numerous revisions (the 41st edition cited in the reference list being the most current) both boiler maintenance and operations staff have been given a vast quantity of information concerning boilers and pressure vessels. This collection of works, from initial publication, contains a fascinating overview (to the boiler enthusiast/attendant at least) of the evolution of both boiler and process to meet the ever-changing demands of modern civilization. Operationally one would be hard pressed to find a more complete work than *Steam Plant Operation*, now in its eighth edition (Woodruff, Lammers, and Lammers, 2005). An Internet search will reveal many more knowledgeable sources for boilers in their wide array of design and utilization.

Despite the lack of sophistication in the term ''boilers,'' as most are aware, they are not just an oversized kettle for heating water! Several broad classifications of boiler are best distinguished from the outset, accompanied by a very brief description of their characteristics. It is hoped that this is something that will prove helpful to those less familiar with steam generation, although it will be found woefully brief to those who have a working knowledge of these systems! The intent is merely to establish a frame of reference for those perhaps less familiar with boilers.

The boiler proper has often been classified according to how it heats the medium, the medium contained, amount of heating surface exposed to water, its fuel source, fan equipment, and a myriad of other details. The limited scope of this chapter requires that only some of the broader groupings be understood. Traditionally, boilers producing steam fell into the larger classifications of fire tube or water tube boilers. Essentially, this is a reference to where the water resides within the boiler.

At the inception of steam generation, engineers quickly became aware of the gross inefficiency of simply heating a vessel full of water with some external flame source to generate steam. Modifications ensued to increase the surface area of the water in a given vessel exposed to hot gases generated by the combustion process and to increase the circulation of the water. This was done by immersing hot flame and exhaust gas tubes in a water-filled drum. The result became known as the fire tube boiler (sometimes called a ''Scotch boiler'').

In a fire tube boiler, the water jacket surrounds the furnace and also part of the hot gas exhaust flue. A simple version is a drum-shaped vessel mostly filled with water. Flame and hot gases pass through a series of sealed ''tubes'' that are

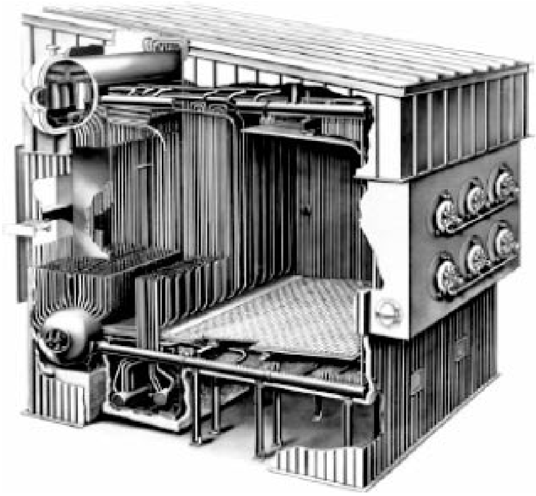

Figure 10.2 Small industrial packaged water tube boiler (Babcock and Wilcox).

immersed in the water. The level of the water will be sufficient to cover the fire tubes so they will be continuously immersed, yet allow for space for steam to form. It will immediately be apparent that the shell must be able to sustain whatever internal pressure is generated by the boiler processes. Practical limitations make this type of boiler economical in design applications with working pressures below 350 psi.

Although simple in appearance, the larger internal pressurized surface area of fire tube boilers creates a point of diminishing returns with increases in size. As industry demanded larger steam throughputs at higher pressures, the engineered strength required to maintain vessel integrity against the internal pressure required ever more complex internal bracing. The advantages of fire tube boilers are, however, that they are simple to install and operate, compact, and still find service in a wide variety of industries and applications. Their smaller size also means reduced exhaust stack height requirements and easier installation as ‘‘package’’ systems rather than *in situ* builds, greatly reducing construction time and costs. In addition, they are more forgiving with regard to boiler feed water quality, making them suitable for more rugged installations.

The disadvantages of fire tube boilers can be summed thus: ‘‘the water volume is large, the circulation poor, resulting in slow response to changes in steam demand, and the capacity, pressure, and steam temperature are limited’’ (Woodruff, Lammers, and Lammers, 2005). A different way of generating steam was required if steam output was to increase and at the same time remain economically viable.

Enter the water tube boiler, which, in contrast to the fire tube boiler, has the water inside banks or ‘‘walls’’ of smaller diameter tubes and the ‘‘fire’’ goes on the outside (Figure 10.2). This type of boiler offers many advantages and increased versatility over the older fire tube style. The water tube boiler has largely replaced the fire tube in most high-flow/high-pressure applications. In addition to allowing for construction sizes that will be staggering to the uninitiated, their versatility, economy of scale, higher pressure, and better circulation ensure that ‘‘ . . . certainly all modern turbine plants use them for main steam supply’’ (Morton, 1979).

Water tube boilers can vary in size from small, low-flow, packaged, skid-mounted boilers to units as tall as a 30-story building constructed in place, providing several million kilograms of steam per hour. Whether fire tube or water tube, the preference is for a packaged unit due to construction consistency, economical build, ease of installation, and uniformity of controls. However, when boiler demands exceed certain practical limits on the hourly steam throughput, a build-in-place unit will be the necessary option.

Water tube boilers have the ability to create a pressurized furnace to increase heat transfer and throughput. This can be achieved by welding the water tubes together with a series of fins, sealing in the furnace area, a step change that greatly increased fuel efficiency, and heat uptake.

Steam demand, type of fuel available, spacing requirements, and the process end user for the steam will all be deciding factors in the choice of fire tube over water tube boiler, and packaged over an *in situ* build. Each will have their design strengths and purposes for a particular operational window. Another boiler type, the so-called ‘‘heating boiler,’’ may or may not have the medium undergo a change of state into steam, nor is this process limited to using water. Glycol–water combinations and even certain types of oil can be utilized as a heat medium in heating boilers. These are a mainstay in heating larger commercial complexes and apartment buildings in colder climates (such as Canada). They are also common to certain industries using smaller packaged mobile units. These mobile units are a mainstay for the oil and gas industry in Alberta and part of the standard drilling rig utility system.

Increasing demands for throughput and economy have led to classifying boilers as utility and industrial boilers. Utility boilers supplying steam for large modern electrical generation and industrial boilers provide a process with steam (Kitto and Stultz, 2005).

A passing glance through any modern manual on steam boiler history and operation will show all manner of additional classification regimes involving economizers, heat exchangers, number of hot gas passes, burner locations, fan configurations, arrangement of steam and water drums, steam separators, super heaters and de-super heaters, pressurized furnace issues, fluidized bed boilers – *ad infinitum* (e.g., see Figure 10.3). Suffice to say that this discussion of operations safeguards is very broad in scope and will need to be adjusted to the specifics of the particular type of unit being considered.

10.5
Operating Considerations

The operation of boilers is an entire discipline in its own right and one that is perhaps given less credence as a trade than it deserves in industry. The boiler operator is by nature a generalist, requiring some knowledge of applied

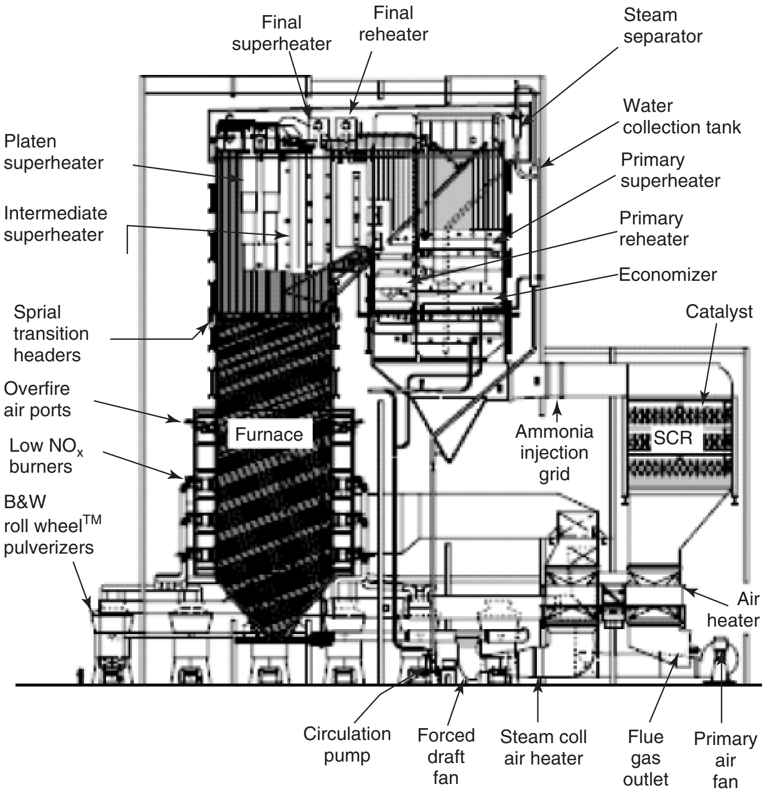

Figure 10.3 Variable-pressure 750 MW boiler for pulverized coal firing. Design pressure 26.4 MPa; 568 °C superheat and 596 °C reheat steam temperatures. Capacity 630 kg steam s^{-1} (Babcock and Wilcox).

mechanics, thermodynamics, water treatment, and electrical fundamentals. They should possess a high mechanical aptitude and will require process knowledge for the systems accompanying the boiler in use. Knowledge of laboratory and maintenance practices, shutdown procedures, emergency protocols, and ability to work largely unsupervised (during a variety of shifts on 24 h operations) make up much of the rest of the requirements. Training paradigms and educational requirements will vary from country to country depending on the type of boiler and its use, and local code requirements. One can well imagine that a high-output nuclear power-generating plant will have higher educational requirements than, say, a small, conventional power-generating station with a much lower heating surface and power output. Nonetheless, a combination of trade-specific training and on-the-job experience is a requirement in most countries for both types of facility.

The loss prevention engineer will need to grapple with process flows and day-to-day operation requirements while involving experienced operations staff in decision-making and implementation of any new practices and procedures.

If there is a chance to ‘‘shine’’ as a safety or loss control professional it is in bringing the process safety norms to these situations. This occurs through applying standard safety and occupational hygiene practices in addition to energy barrier methodologies in use throughout the world that meet local occupational health and safety (OH&S) regulations. It is here in the intersection between sound engineering practice, health and safety codes, and boiler operation that the loss control engineer or safety professional will best prove their worth and add value to the business endeavors!

Although the actual steps involved are the realm of the boiler operations group, the loss control engineer or safety professional can bring expertise to bear on:

- Input into procedures to shut down the boiler, including isolation of the fuel source, and boiler feed water – after a cooling period has been observed – in a fashion that meet local OH&S codes and boiler regulations. This will also apply to the overall training program for operations staff.
- Lock-out and isolation procedures which need to be developed prior to commissioning the boiler and related systems, while utilizing vendor expertise and manuals and again local OH&S regulations.
- Special practices for entry into the boiler and any plant confined spaces meeting local codes (and industry standards) for confined space entry and isolation of process equipment.
- Dealing with environmental challenges posed to humans, that is, work in unusually hot/cold/humid conditions under the appropriate guidelines, normal to the workplace.
- Fall protection requirements, personal protective equipment, weekly and monthly checks of safety equipment, and emergency response gear, working at heights.
- Occupational hygiene issues, personal protective equipment fit, testing for respiratory protective equipment, hearing protection and testing, detection and control of hazardous or explosive atmospheres, and naturally occurring radiation monitoring (NORM).
- Certification checks for both employees and third party contract service providers and on-site safety orientation for employees and visitors.
- New and young worker or so-called ‘‘green worker’’ programs.
- Document retention and control for completed lock-out/tag-out and confined space entry paperwork.
- Incident response and investigation guidance and practices.
- Emergency preparedness guidelines, including inventory management/ inspection of emergency response equipment and staff awareness and training.
- Drug and alcohol practices – their implementation, training, and awareness.
- Audit and inspection of practice and equipment to ensure compliance with corporate policy and local legislation (OH&S, environmental, etc.).
- Consideration should be given to practice scenarios for emergency shutdowns, large-scale fires, chemical spills, and high-angle rescue even if only in classroom settings. The more familiar operations staff become with what to do in an emergency, the higher the comfort level will be for both operations and plant management on emergency response preparedness.

- Construction and maintenance practices as they interface with operations personnel, particularly where they interleave in operating facilities.
- Ensuring Management of Change practices are adhered to.
- Ensuring engineering drawings and process flow diagrams are updated to reflect changes accurately.

This is just a partial list that the author has prepared as examples based on personal experience in several industries (in both operations and safety management) and can surely be expanded upon. The breadth and scope of boiler systems require due care and attention to detail in these matters. It cannot be stressed enough that the practices and procedures around lock-out and isolation such as the use of blinds (also called ‘‘slip plates’’ in some countries) be worked out prior to run up and commissioning or maintenance outages. The extra stress associated with sudden unplanned (and planned!) downtime is not conducive to safe and thorough development of these critical practices.

Good planning, isolation procedures, and shutdown and startup practices form the foundation of well-run shutdowns and maintenance outages. Loss control professionals sometimes need to campaign aggressively for these well ahead of time. In addition to giving operations staff a solid time window to isolate a facility properly, isolation practices will need to address the following:

- Methods of ensuring that valves are capable of being secured in the open/closed position. Some facilities use lengths of chain and locks, others use permanently crimped stainless-steel cable on each valve for quick securing with locks. This has the advantage of being permanent and negates the carrying around of dozens of lengths of heavy chains by operations staff. This is particularly advantageous since (in the author’s experience at least) many valves which look very accessible on a process flow diagram are in fact found in awkward locations, accessed only by a long climb up a caged ladder!
- Methods of positive isolation of flow through the various lines in the boiler system, including all commodities entering the boiler system (chemical, steam, water, etc.). These methods will vary with local codes, but will usually include rated and (engineer) stamped blinds and blind flanges. Even if local codes do not require blanking and blinding lines associated with vessel entry, the fatal accidents that have occurred from not following such practices are reason enough to install these practices.
- Draining water from the tubes (or shell) and possibly purging with a warm air supply and or ‘‘pigging’’ (swabbing) the lines if the boiler will be exposed to sub-zero temperatures for any length of time. Freezing in low-lying bends or between closed valves can cause piping failure when pocketed water expands, and corrosion when sitting. Laying up practices (preparing for long periods of inactivity) should be provided by the manufacturer.
- Ensuring procedures for draining vessels and boilers include steps to prevent equipment from attaining negative pressure (vacuum), which can destroy internals and drums that are constructed to withstand large positive (but not negative) pressures.

- Determining acceptable time frames for cool-down prior to vessel and furnace entry in accordance with occupational hygiene exposure limits.
- Methods for filling the boiler system (which will again require special considerations when filling the boiler system in low ambient temperatures.). The author is aware of at least one case where operations staff introduced hot water under pressure into a boiler that had been dormant in sub-zero temperatures with predictably disastrous results. It might seem logical to think that high-pressure hot water should not freeze; however, the tube runs inside large boilers are measured internally often in terms of miles, not feet, with a significant heat sink capacity. Unfortunately the thermal mass required to heat up long runs of empty sub-zero temperature water tubes cannot be carried by the inrushing water front, which will rapidly give up heat to the surrounding metal and form an ice plug.

10.6
Boiler Feed Water

The very qualities that make water so versatile, in particular its ability to dissolve many substances, become an engineering compromise when used in the modern steam generator. Water purity with respect to its use as boiler feed water is a reference to a specific set of parameters that the water must satisfy for the boiler being ‘‘fed.’’ It may be purified of some undesirable elements and yet from a true purity standpoint it would be ‘‘contaminated’’ with chemicals necessary for boiler processes. On ocean-going vessels, large distillation and demineralization plants may be used to convert the most readily available source of water – sea water – into suitable boiler feed water (Morton, 1979), requiring lower chemical loads than land-based units.

Water treatment processes vary, but large-scale water intake (fresh water) may involve contact clarifiers where contaminants can be settled out with a coagulant/polymer injection through a sludge ‘‘bed,’’ settling out larger particulates. The water may then be filtered and finally softened to remove calcium and magnesium to meet feed water requirement (Betz Laboratories, 1991). There are many compounds, metals, minerals, and biological contaminants (such as silicates, iron, and algae) that can be undesirable for boiler feed water systems. Water treatment processes will be established for peculiarities of the source water and also the process requirements. What is unacceptable in one process may be tolerable in another, hence the boiler system as a whole will likely be examined and parameters established by an engineering firm prior to startup. It may help gain an appreciation of the necessity for water treatment by briefly looking at one of the most commonly controlled parameters – hardness.

Calcium and magnesium (the ‘‘hardness’’ components of feed water) have long been the bane of boiler feed water systems and, depending on the hardness of the source water, may pose one of the greatest operating risks to a boiler water treatment system. It is the carbonates and bicarbonates of both metals that form soft, porous scales. These scales have the unfortunate property of becoming less soluble as the temperature increases, which makes them most prone to come out of solution in the worst possible place for the boiler, in the narrow channels of the water tubes where the steam–water boundary exists (Betz Laboratories, 1991).

Consider how much scale would accumulate in a household kettle using treated municipal water if it boiled constantly for a year, and then multiply that by a factor of many millions, and you will quickly grasp why these contaminants must be managed in solution! Given that 1 m^3 of water is equal to 1000 l, it follows that 1 ppm in this example will equal 1 ml. Achieving a target hardness of much less than 1 ppm is common in many feed waters. If we take 1 ppm as the target for this example, a boiler system using 1000 m^3 per hour of boiler feed water, it would yield 1000 × 1 mL or 1 Liter of scale per hour. After a 1000 h run time, the boiler would have the chance to accumulate 1000 l of scale. Hence even the seemingly low level of 1 ppm would be unacceptable in a high-volume boiler without other means of control. The scale deposits will slowly insulate the tube metal from the cooling effect of the water and make heat transfer inefficient at best, or turn the tube into molten slag at worst. Typically, chemicals will be added to keep the mineral salts in solution so they do not flash off with the steam and the boiler blow down will be adjusted to keep the solids and hardness in the solution side of the steam generator at target levels.

Blow down is the removal of concentrated mineral and undesirable solids mixed in the steam drum of the boiler. The steam flashing off in a boiler is distilled and fairly ‘‘pure’’ from a mineral content standpoint, as the impurities travel in the liquid. The liquid left behind will thus slowly increase its concentration of impurities, requiring the removal of a certain percentage of the liquid which is at boiler pressure, hence the term ‘‘blow down.’’ Some systems are automated for this, others are managed remotely, and still others by slowly opening a series of valves in a special sequence by the boiler operator.

The monitoring regimes for feed water quality vary with the complexity of the process, volume of steam generated, and heating surface of the boiler. High-throughput marine steam generators may require distilled water with lower chemical demands, others systems may have continuous real-time computer analysis of feed water contaminants and follow a program of aggressive chemical treatment to manage impurities.

Calcium and magnesium tests will form part of the daily regime of testing that is normally borne by operations and laboratory staff. Even where automated, the testing may be done to back up or calibrate the online measuring equipment. Silica testing may be required, although research has shown that silica will not likely be a problem below 0.02 ppm (Betz Laboratories, 1991). Testing has long been part of the monotony of boiler operation, and varies with each facility, yet it is critical to catch an upward trend in contaminants in the feed water. In large-scale systems, there may well be real-time continuous analysis of the major parameters, with a control loop to chemical feed pumps. This will be integrated with a plant distributed control system (DCS). The operations testing load is reduced to verification of the process instrumentation readings. Automation can be a boon to large systems in particular, since the reaction time between sampling, results, and making changes can already allow significant process upsets in the case of high-feed water rates.

Feed water treatment varies with the source of the water, but all large-scale processes will require water make-up, with throughput being a function of the process on site. Water itself may present some hazards depending on the treatment facilities on location. Apart from engulfment hazards when working inside water treatment vessels for maintenance, the pressure and temperature of the water are key safety concerns while the plant is running, as are the type and location of equipment. Depending on the source and surge/treatment capacity, some or all of the following might be worthy of hazard analysis to verify that adequate safeguards are in place:

- Stable guard rails (of the appropriate dimensions) around open water areas must be in place.
- Consideration should be given to lifesaving equipment and the appropriateness of areas where lifejackets are mandatory or at least readily available.
- Pumps and rotating equipment must be properly guarded and securely mounted.
- Chemical injection quills and lines must be monitored for corrosion and leaking gaskets, and regularly inspected, where they enter water systems.
- Chemical pump areas are often given heightened respect for eye protection. Some facilities will have a ‘‘goggles only’’ area for chemical storage and pump facilities, even to walk in the vicinity (due to potential misting of chemicals due to leaks, etc.).
- All confined space entry into vessels containing water during maintenance outages must adhere to local codes and at the least include documented lock-out and tag-out and should utilize a blanking/blinding of inlet points to the vessel being entered.
- Plant permit to work systems will take into consideration the special nature of chemical hazards and mitigation protocols flowing out of effective hazard assessment.
- Redundant systems (i.e., dual or ‘‘twin’’ pumps) that are in critical process streams need to be function tested or rotated into service periodically to ensure that they are functional when needed.
- Leaks in packing and gaskets should be reported immediately and guarded or barricaded while the decision to ‘‘repair or run’’ is made. Temperature, pressure, and chemical hazards are the prime consideration when adding barriers. It is possible to run for extended periods with minor leaks in certain areas if they are monitored and guarded adequately, particularly if equipment isolation is problematic without a large-scale shut down. It is equally possible for metal flanges to wear through given the right combination of steam and water escaping! Experience and hazard assessment will be the necessary guide here.
- High-pressure system leaks must be physically cordoned off if there is some higher requirement in play to maintain operation and allow the leak to continue if emergency shutdown is not warranted.
- High-temperature water/steam lines that are in areas of human contact must be insulated or guarded in an acceptable fashion.
- One of the greatest reductions in long-term confusion and aggravation for operations staff is the labeling (or lack thereof) of piping. Although best done

before commissioning a plant, this can be done at any time and the long-term payoff is incalculable. Professional quality pipe labeling systems will pay for themselves within hours of the first maintenance shutdown. There may be local requirements to meet such as WHMIS (Workplace Hazardous Materials Information System) labeling or the new Globally Harmonized System in place in some countries. There is, however, a danger in relying too much on labeling that may not have been accurately applied, hence labeling cannot replace an operator's thorough knowledge of the work area. Other factors to consider are long-term degradation of labeling and inability to apply directly to high-temperature lines. Many an incident has been traced to poor labeling protocols in process facilities through the years (Kletz, 2009, p 98).

- Practices must be in place to prevent thermal shocking of equipment and lines, allowing temperature increases and expansion to occur according to the manufacturer's specification. This means that entire piping streams and systems may be at the mercy of the most sensitive piece of equipment in the chain during startup and shutdown. requiring extra diligence during these periods.
- Vessels must be grounded or ''earthed'' to the plant grounding grid in order to avoid a potential difference that could result in personnel becoming the path for electricity to earth. This is often missed during short-term chemical trials, temporary storage requirements, or replacements due to failures, process outages, and other non-permanent situations.
- The above represent a small sample of the types of mitigation practice that will flow out of proper hazard analysis and risk assessment programs which form the vital foundation of safe work practices.

No discussion about boiler feed water is complete without at least a passing reference to that most important of historical safeguards – the low-water cutoff. Whereas the safety relief valve discussed later is the main guard against overpressure, the low-water cutoff provides the most important barrier to overheating. No doubt a boiler could be constructed with metals exotic enough to withstand the heat from a full fire without water in the tubes taking the heat away, but it would never be able to recoup the cost of construction over the service lifetime. The low-water cutoff reacts to cut fuel supply to a boiler in the event of loss of circulation. The larger a system becomes, the higher the thermal mass that must dissipate, hence the low-water condition will have more than one system in place to mitigate (e.g., emergency pumps and fans). Certainly in smaller systems and in heating boilers in particular, the low-water condition is the most common cause of failure (ABSA, 2006).

10.7
Chemical Handling

Water must be treated with chemicals in order to ensure a consistent, pure, quality product, and to prevent corrosion of piping and equipment. Certain sections of the process may require antimicrobial treatment to prevent fouling of the pipelines and equipment. The chemicals in use must be given respect, in terms of both handling them and their impact on the boiler system at large.

Target ranges exist, verified by testing for either residuals of the chemical added or the presence of the variable that the chemical is required to control. Therefore, storage and on-site inventory management will be a matter of water throughput, add rates, and function of the chemical. It follows that the larger the percentage of recycled water in a closed process, the lower the chemical demand should be; although fresh water make-up will be part of any boiler process, the amount varies depending on the type and size of the steam generator. A large unit with several million kilograms of steam produced and recycled will have considerable make-up after all losses are taken into consideration. Commonality exists in philosophy, if not specific chemicals, across a wide range of boilers, but local preferences based on experience, availability, and process compatibility make it impossible to speak in any but the widest of terms.

Even a feed water source providing water at the ‘‘design’’ pH will likely require both an acidic and caustic chemical capacity in order to manage ‘‘swings’’ in the pH. Depending on the process, it may be desirable to have the pH in different ranges in various parts of the process path. In some systems, add rates of caustic chemical or neutralizing amines will be injected in steam headers to maintain the pH in the 9.0+ range for equipment downstream of the boiler in certain feed water programs. The reason for this is that ‘‘the corrosion rate of carbon steel approaches a minimum rate in the pH range 9.2–9.6’’ (Betz Laboratories, 1991).

Corrosion is an ever present danger in any piping system that must be controlled, as it is an unseen enemy that can pose unnecessary risks to personnel and equipment. Usually the corrosion will take place in an oxidative environment. Therefore, in addition to pH or alkalinity monitoring, the use of chemical oxygen scavengers will be a necessity in most systems. Often a sodium sulfite or a hydrazine solution is injected in the deaerator (air reduction portion of the boiler feed water system) immediately upstream of boiler feed water pumps. Many factors, such as pressure, temperature, and metal composition, will be involved in selecting the oxygen scavenger, but the intent is the same. Reducing the free oxygen in the water/steam flows reduces the ability to form oxides of various metals and corrode boiler system internals (Betz Laboratories, 1991).

Chemical addition, then, is a crucial part of modern steam generation to prevent corrosion and manage impurities in the feed water. It should be obvious that a chemical addition program must involve bulk chemical storage, and this is a prudent place to review several safeguards and best practices:

- Proper storage and handling of bulk chemicals must occur with manufacturers’ recommended practices. Drip trays, bulk offloading facilities, piping, valves, and ancillary controls must be carefully planned out. Material Safety Data Sheets (or Safety Data Sheets if operating under the new Globally Harmonized System for chemical classification) should be available and current for each chemical on-site.
- Compatibility of piping, gaskets, and materials with the chemicals involved must be assured and verified against design mandates. Such information, if carefully

catalogued, will make the job of the maintenance personnel markedly easier when it comes to replacing gaskets or pump internals on chemical feed systems!

- Fugitive emission monitoring or leak monitoring processes must be used where practical. Tell-tales such as litmus paper windows on flange blankets may be needed for bolted flanges on lines with highly caustic or acidic chemicals.
- Personal protective equipment must be verified as compatible with the chemical from which they are expected to protect the worker. This includes gloves, protective suits, and canister-type respirators where employed. Where possible, protective equipment should be sought that will provide universal protection against all chemicals stored at a particular location. Otherwise, particular care must be exercised in allocating and labeling protective equipment to provide sufficient barriers to the chemical in use.
- It is never enough simply to have the protective equipment available. Personnel must be trained and monitored in the use of protective equipment.
- Emergency response plans must incorporate responses to bulk chemical spills. Use of local emergency services (where available), reactivity with other chemicals on-site, and suppression techniques must be understood by response team members. Response practices for larger scale spills are essential and often overlooked owing to the low-frequency (albeit high-consequence) nature of these events.
- Emergency showers and eyewashes are mandatory for modern chemical supply areas. Regular testing and flushing of the systems will ensure that they work if needed and will not make matters worse by contaminating burns or exposed areas. Where overhead water supply lines to the safety showers are utilized, full-spectrum temperature tests are strongly recommended. (Initial flush tests will only verify the first few feet of line.) Supply lines running through the ceiling pipe racks of hot process buildings can create very dangerous temperature levels, but these will not be apparent until after a moment or two of flow. Scalding hot water on a chemical burn would cause serious, possibly irreversible, damage and incredible pain. In addition, emergency shower water must be clean and readily accessible.
- Laboratories must be fitted out with proper personal protective equipment and functioning fume hoods for chemicals that pose a respiratory hazard.
- Inventory control for laboratories (or any other chemicals) should include physical distancing of chemicals that can create violent reactions, even in small quantities. In certain instances, this may require the addition of post-supplier warning labels.
- Chemical storage tanks may require non-destructive testing of wall thicknesses over long time periods and these should be part of a maintenance regime.
- Chemical storage tanks should be clearly labeled with appropriate warning signs, and equipped with bonding cables to eliminate potential difference between offloading vehicles and the storage tank.
- Dikes, berms, drains, and piping equipment should be examined for chemical compatibility, and it must be ensured that incompatible chemicals will not mix (otherwise this will be a startling revelation at the first drain and flush that occurs in maintenance turnarounds!)

- All containers and hoses used for temporary storage should be ‘‘triple rinsed’’ (if water is an acceptable rinse agent for the chemical) and prepared for reuse or disposal according to the manufacturer’s recommendations.

The author has witnessed at first hand a number of compatibility issues such as the wrong style of pump being set up on a portable chemical tote, corrosion from hoses and containers not properly rinsed, and leaks developing in hazardous chemical storage containers hastily piped into place. The common denominator in many cases was temporary or provisional nature of short term installations either for trials or to bypass unserviceable equipment. The loss control engineer should take a higher level of interest/supervision in observing and making recommendations in these situations, as diligence can easily regress during such ‘‘non-permanent’’ scenarios.

Process issues involving chemical attack can go unnoticed for long periods of time due to the inability to observe it, or in some cases the lack of a perceived necessity for non-destructive testing. It is worth noting that chemical attack on piping and ancillaries can be aggressive and immediate, or longer term and slow. The author once observed an overhead stainless-steel chemical injection line containing a fairly innocuous water treatment coagulant start to deteriorate rapidly over a 1 week time frame. The interesting part is that it occurred almost 13 months after the installation of that particular line! An examination of the Material Safety Data Sheet revealed an unexpectedly high level of a certain chemical in the coagulant that was aggressive to stainless-steel piping over the long term (unfortunately, none of us could beg ignorance of the fact that the incompatibility existed; had we scrutinized the chemical data more thoroughly, it would have been obvious). The resulting chemical sprinkler was fortunately more of a nuisance than a serious hazard, but it was certainly a memorable lesson learned.

One area of chemical handling that can be neglected due to familiarity and perhaps perceived lack of consequence is the so-called ‘‘field laboratory’’ or operators’ test laboratory. Typically small and confined, these areas serve as a location to perform water quality and numerous other process-dependent tests in an environment less conducive to the higher accuracy required in quality controlled laboratories. It is the urgent test that often seems to outweigh judgment on matters as simple as wearing rubber gloves or goggles, this when dealing with chemicals that can have long-term health impacts.

Chemical quantities are small inside the laboratory compared with the large volumes used in the field, and there is a subconscious equation of volume to impact. While this may be true to a certain extent with acute exposure, it does little to offset the side effects of long-term chronic exposure. Added to this is the largely unsupervised nature of laboratory testing, and that personal protective equipment is often not the subject of field laboratory attention.

It is ever the battle of the industrial hygienist to institute practices and educate workers about safeguards to protect against long-term (chronic) exposure hazards. Certainly people are easy to convince about the veracity of a barrier to visible sources of energy, but the less acute and immediate the impact and the more subtle and long-term the effects, the more management diligence is required to maintain safeguards. Chronic skin conditions, respiratory problems and even certain types of cancer can result from long-term minor exposure to small amounts of certain laboratory chemicals.

Chemical handling and worker protection are not new topics. As early as the sixteenth century, the physician Agricola was documenting chemical exposure in miners and practicing primitive industrial hygiene – that branch of science that deals with the anticipation, recognition, evaluation and control of workplace hazards (Nims, 1999). This is important to frontline workers since boilers have a long established history of chemical use with substances such as potash (caustic) having been used as industrial scale removers for centuries. In fact, as far back as the late nineteenth century Egbert Watson wrote:

> In handling caustic potash the utmost care must be used. It is truly caustic or burning, and if a portion gets in the eyes it will cause serious trouble. Handle it with gloves; treat it very respectfully.
>
> *(Watson, 1892)*

Having witnessed at first hand the ‘‘troubles’’ that chemicals can cause when not treated respectfully (from serious burns to minor irritations), the author adds his caution to heed Watson’s words and instill a healthy respect for chemicals amongst operations and maintenance staff alike. Caustic, for example, a chemical frequently found in water treatment for boiler feed water, will burn subcutaneously and requires considerable time to cool the skin to limit thermal damage to fat and basal skin layers. It is important to be familiar with and follow manufacturers’ emergency response protocols to counter exposure effectively and not make it worse.

Chemical supply manufacturers are more than willing to send educational materials (and often ‘‘educators’’ as well) to the end user’s facility. The loss control or safety professional will do well to make use of this resource for educating operations and maintenance workers on the hazards of the particular chemical they supply. Chemical suppliers can also provide a wealth of experience and knowledge for troubleshooting process issues. They will have a wider view of the particular issues you encounter as the supplier usually provides to a wide customer base and other facilities may have learned lessons that can be applied.

Chemistry is like electricity, not thought about until it escapes containment and acts in unexpected ways, hence the best practices for safety professionals and loss control engineers will include in equal parts preventative medicine and emergency preparedness.

10.8
Steam

At this point the reader may be wondering, ‘‘what makes steam so special?’’ The cost and complexity of water acquisition and treatment combined with all the extra equipment in place to make steam certainly appears to be a lot of effort expended

Figure 10.4 A typical steam drum being lifted into place in a boiler during construction (Babcock and Wilcox).

in order to make a turbine shaft spin to generate power. Why not just take the fuel source and figure a way to drive the generator with a motor of some sort and eliminate a step? On the surface, it seems logical and in some cases, where boilers cannot be utilized either due to the sporadic nature of the demand or geographical challenges and lack of availability of cheap, reliable fuel sources, a direct drive internal combustion system may be chosen to turn a generator shaft. It is inefficient, however, and in the case of coal-fired units not currently feasible since ''The overwhelmingly dominant fossil fuel used in modern U.S. power plants is coal, since it is the energy source for over 50% of the electrical power produced'' (Woodruff, Lammers, and Lammers, 2005). That equates to about 1800 billion kWh from coal-fired units alone. Given the high level of complexity in mining coal, pulverizing and conveying it to be burned in the boiler furnace, ash and slag handling systems, and extensive pollution control monitoring, not to mention the overall plant footprint, staffing, and maintenance, the reader is justified in asking how this can possibly be efficient! (Figure 10.4 gives an idea of the scale of a large boiler under construction).

Most high school students learn in science class how inefficient the internal combustion engine is for propulsion, and how very good it is at generating heat (that is, because hydrocarbon fuels release a tremendous amount of heat during combustion, and that heat is actually a ''bother'' to deal with in the engine – winter in northern Canada excluded!). The modern steam generator is capable of capturing a much higher percentage of the energy released from the fuel – the economic efficiency for a fossil fuel plant is around 40% and for a nuclear plant 33% (Woodruff, Lammers, and Lammers, 2005). Not only that, boilers are more versatile and can be equipped to use coal, natural gas, oil, and even nuclear fuels. Efficiency is a slippery concept with many variables in play, but thermal efficiency can be often be twice the above figures according to Woodruff, Lammers, and Lammers (2005).

A unique property of steam is that the higher the pressure at which it operates, the more heat it can absorb, which means the more work it can do at the end point. At higher heat inputs, steam also follows more closely the so-called ‘‘perfect gas laws.’’ The amount of energy entrained in steam is called enthalpy and is measured in megajoules per kilogram (mJ kg^{-1}) in the metric system (Embleton and Jackson, 1991). The enthalpy of steam at various pressures and temperature is well documented and the earliest stages of education for power or marine engineers involve familiarity with this information. The temperature at which water will produce steam is dependent on the pressure on the surface of the boiling water and is called the ‘‘saturation’’ temperature. The saturation temperature of steam at each particular pressure has long been known and accurately measured. These temperature–pressure points and the enthalpy of the steam are itemized in charts known as ‘‘steam tables.’’

Given this property of steam to hold tremendous quantities of heat, and the ability to convert that heat to mechanical energy as it expands across steam turbine blades (for example) and begins to condense, it was a natural process of innovation and creativity to bring about ever-increasing levels of efficiency in the steam cycles. Means have been established to increase the amount of heat that steam can carry (and thus plant efficiency) above its saturation temperature via a process called ‘‘superheating.’’ There have also been many approaches to capture and reuse as much energy as possible before sending the excess steam and condensed water back to the boiler. This too is part of increasing the overall efficiency of the boiler system, extracting as much useful work as possible from each kilogram of fuel burned in the boiler furnace. That cycle is another part of the attraction, in some cases, of using boilers. In closed-loop systems, steam – the heat/energy carrier – can be recycled, when it condenses back to water, after small losses in leaking pumps and seals are accounted for by fresh water make-up. (see Figure 10.1 and follow the path of condensing steam that occurs after the turbine).

Understanding even this brief overview of the steam-generation process will help the uninitiated reader acknowledge the need for caution during certain phases of boiler activity such as startup, shutdown, blow down, and other activities.

Steam ‘‘quality’’ in power engineer terms is a reference to how much ‘‘dry steam’’ exists compared with the amount of liquid water either in droplet or microdroplet form. A steam quality of 80% is thus 80% dry steam and 20% water. Normative for some processes this ratio would be unacceptable for a large steam turbine. It is normally desirable to have as little water as possible enter the turbine steam to prevent erosion and mineral build up internally. It is not possible to eliminate all water droplet carryover into the steam lines, and when the carryover becomes excessive the entrained solids in the water begin to deposit on turbine blades. Steam separators are used to achieve the desired steam quality and exist in a variety of forms, depending on the desired end point.

Hence control of the water content in the steam is crucial and a variety of devices are employed to manage the steam-to-water ratio required for the particular process involved. Even so, there will always be some condensate in the bottom of steam lines that must be removed at different points, often through the use of devices called condensate traps. These are specialized units that utilize any number of different physical processes to remove condensate from steam lines.

There is another reason why the steam and water mix is critical, and this is where we pick up the safeguards discussion once more. Certainly everyone has likely heard water pipes rattle and move about when taps are opened or closed quickly. The sudden pressure changes that cause minor shock waves inside the piping system are known as "water hammer." Water hammer is possible in steam lines carrying any condensed water or in water lines that mix with and engulf pockets of steam. It can cause lines to rupture, valves to break apart, and even steam piping to fail over large areas. It happens most frequently when a surge of hot water traps pockets of steam. The steam instantly condenses and water fills the void, collapsing in a shock wave. Given that "High pressure systems that provide steam for turbines are designed for velocities of 8000–15 000 ft min^{-1}" (Woodruff, Lammers, and Lammers, 2005), situations that can cause water hammer must be avoided.

One incident that highlights the effects of water hammer occurred in a remote area of north-eastern Alberta in May 2007. A large 24 inch steam line several kilometers long was steam flooded with apparently inadequate condensate removal procedures in place. The resulting debris had to be searched for by helicopter, on foot, and with all-terrain vehicles. The investigation report stated:

> The failure of the 24-inch steam pipeline and the ensuing pipe whip and energy release damaged portions of the adjacent lift gas and production pipelines, as well as trees, support structures, and a small metal building.
>
> *(ERCB, 2008)*

The Energy and Resources Control Board (ERCB) is Alberta's oil and gas regulatory authority. Their investigation of the above incident details a lapse in both engineering and administrative safeguards. This is highlighted by the fact that the stakes are high with water hammer. Since at least some of the controls are administrative (you cannot be sure a human will not open the wrong valve too quickly), the new boiler operator will learn early in their career that the most common causes of water hammer are (i) opening and closing valves rapidly, (ii) increasing steam flow too quickly when bringing boilers on-line from cold starts, and (iii) sudden stop/starts of pumps or motor-operated valves (SAIT, 2000).

To prevent water hammer, bypass lines of much smaller diameter than the main line are installed around critical water and steam flow valves. These are used to provide a low volume of fluid to bring lines and equipment slowly up to the operating temperature, preventing rapid condensation of steam that could create a disastrous steam–water mix at full steam flow. In this process, provision must be made to drain off the slowly condensing steam while the lines warm up (either automatically with condensate traps or manually opening drains). Best practices must be established and followed to ensure that the use of warm-up lines and drainage is not circumvented regardless of the need to bring a system on-line.

On a final note, anyone who has worked with steam over a long enough time span learns to respect and even fear its destructive potential. Extra diligence is required during manual valve adjustments, sampling, and opening up of lines and vessels. A sudden release of a rapidly expanding, high thermal mass substance is not a situation in which anyone wants to find themselves.

10.9
Special Considerations for Pressure Vessels

One of the major protection sources for pressure vessels, and boilers in particular, is the pressure safety valve (PSV), also known as a safety relief valve. According to the Alberta Boiler Safety Association, ‘‘The safety relief valve is the most important fitting on a boiler’’ (ABSA, 2006). One can imagine the level of engineering difficulty and cost that would be involved in designing all vessels to contain all pressures to which they might possibly be exposed, rather than a maximum allowable working pressure (MAWP). The PSV operating strategy is to open at a certain level above the MAWP and close when within a certain percentage of the MAWP, discharging the overpressure commodity to a safe location. For this reason, PSV servicing maintenance and replacement are in a tightly controlled program. In some industrial settings, such as the sour gas processing plants in which the author has worked, this (PSV service) time frame will be the main factor in determining the frequency of plant shutdowns.

Fortunately, according to one engineer who researches industrial accidents and their causes:

> Failures of pressure vessels are very rare. Many of those that have been reported occurred during pressure test or were cracks (*sic*) detected during routine examination. Major failures leading to serious leaks are hard to find.
> *(Kletz, 2009)*

which is comforting news from one who scours the world looking for incidents to report on! Ironically, it is low-pressure storage tanks and vessels that are more at risk of collapsing under negative pressure (vacuum). There are numerous reports of vessel collapse after cleaning or painting due to ‘‘gagging of atmospheric vents or disconnected pressure relief valve openings with plastic bags’’ (Kletz, 2009). It is difficult to conceptualize a large metal tank succumbing to internal vacuum because of a plastic bag left on a vent! Yet sometimes all that is required is a very hot day followed by a cool evening, which allows the air density to collapse and put the tank on vacuum that it was never constructed to withstand. Low-pressure storage tanks can withstand only the smallest amounts of negative pressure.

This is an embarrassingly simple incident to prevent and all tank or vessel draining practices should make allowances for vacuum breakers (i.e., opening

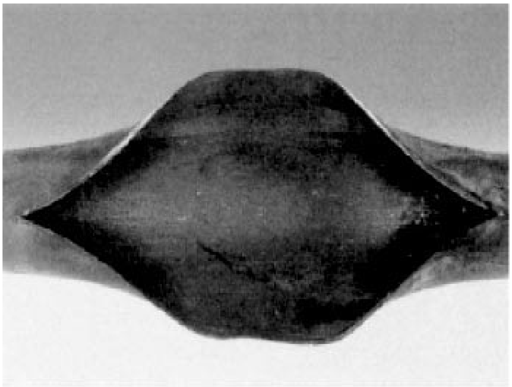

Figure 10.5 Short-term overheat thin edge failure (Babcock and Wilcox).

vents or man ways) when draining and servicing tanks, boilers, and pressure vessels. It is also a risk for steam drums and boiler internals because of the considerable temperature difference between operating and ambient conditions. The rapid drop in temperature during a shutdown coupled with evacuating liquids can create surprisingly abrupt negative pressure conditions inside the vessels, which have been engineered primarily to withstand high internal *positive* rather than negative pressures!

The addition of PSVs to a given system also brings certain risks that must be guarded against and ASME codes, for example, are fairly detailed in their construction and application of relief valves in Section 10.11 (ASME, 2004). Pressure relief systems are critical and the author has been party to several investigations involving them. One such had disastrous consequences. Particular care must be given to testing, recertification and structural support of pressure relief systems. The sudden release of a commodity via the PSV at high pressures can generate enormous reaction forces on the piping proper that must be adequately restrained.

Attention to detail and rigorous maintenance requirements have been in play for PSVs in many countries for some time. One result of these efforts has been that in modern water tube boiler systems, tube failures are more common from overheating due to poor circulation of water or scaling internal surfaces than from overpressure (Figure 10.5 depicts damage that can occur from even brief overheat conditions).

10.10
Fire Detection and Control

Boiler systems, like most modern equipment, will undergo large blocks of time where they are unattended by people, although their systems are monitored remotely via the plant DCS. Practical considerations and also many insurance regulations will require automatic fire detection and suppression systems at key areas. Given that combustion is part of the process of steam generation, fire detection and suppression systems will differ widely in type, as will the extinguishing media (unlike many facilities, there are monitoring systems also to ensure the fire is still going – but these are generally inside the boiler!). While this topic is covered in greater depth elsewhere in this volume, there are several key considerations with respect to boiler systems and pressure vessels that are worth special consideration here.

Pressure vessels suffer from a two-pronged attack during a fire, with flame or hot gas impingement on the vessel: (i) the metal tensile strength begins to decrease as the temperature increases and (ii) the pressure within the vessel will increase as the temperature rises. The result is an undesirable combination of internal pressure increasing while the container strength decreases until fracture occurs. During a fire, metal fatigue will occur in areas above the liquid line at a faster rate than below (Kletz, 2009). An explosion in such a scenario is commonly referred to as a BLEVE (boiling liquid expanding vapor explosion) and is unique to pressure vessels or any sealed container with fluid in it. These are the topic of many firefighting courses and much has been written about responding to potential BLEVEs due to the enormous destructive power unleashed when one occurs.

Fire system maintenance and testing are thus critical for ensuring deployment when it is needed and also for meeting insurance requirements in many cases. It is worth noting that fire crews and firefighting training become more important the further a given facility is from assistance by municipal fire crews. Fire preparedness and training are important, but the knowledge and experience to know what a crew should be running towards or what they should be running away from is equally important!

10.11
Incident Investigation

Elsewhere in this volume, the topic of incident investigation is covered much more competently than can be expressed here. However, some comments are appropriate in terms of utilizing incident investigations to combat better the recurrence of any near-miss or actual events.

In the case of rupture or fugitive emissions, the damage that can be incurred by human exposure to steam is staggering. Carrying high thermal value in vapor form means that it follows gas laws when released and attempts to fill the whole volume in the area of dispersion. The higher the steam pressure prior to release, the faster it wants to fill that volume and the more violent the aftermath of any catastrophic failure of equipment.

The value gained from learning from near miss and actual incidents cannot be overstressed. Value will not happen if reporting is negatively rewarded. This has the side effect of driving reporting underground should management react negatively and haphazardly to incident and near-miss reporting. There is perhaps some value from a high-level report standpoint in that you never have to show ‘‘bad things,’’ the aptly termed ‘‘ostrich effect.’’ The immaturity of this response path will lead to a culture of hiding bad news at every level (why be a messenger if you will just be kicked for it . . .). This approach ‘‘works’’ until a significant event occurs that could have been prevented by more timely reporting. Then all the compounded events hidden by the culture of silence will come home to roost.

In addition, if a major event occurs and it does not result in preventive action then there is no trust in management from the line worker, and obviously a serious lack of ethics on the part of the management team. Incident reports should generate reasonable corrective actions that are implemented judiciously and methodically or else reasons must be given for why the event can be considered a tolerable failure. The author would adamantly maintain that tolerable failure is not a suitable option if people have been seriously injured or worse. This is certainly not a defensible position in an accident investigation.

10.12
Closing Thoughts

The author’s intention in this short chapter was to give a brief overview of the complexity and inter-relatedness of the many systems involved in managing modern steam generators and pressure vessels. In the case of a survey such as this, the author’s standpoint was to try to provide enough information to provoke some thoughts, but not too much to dictate methods of application (and not expose his lack of specialization in any single area!). Considering that the combined page count of just two of the steam generation sources referenced above runs into the thousands, it is obvious that the proverbial surface on the topic has only been scuffed here and not even scratched! The various references cited provide a wealth of information in their related fields and will prove a rich resource for the new recruit and experienced worker alike. The reader will take away at the very least the fact that this topic cannot be entombed in a single chapter or even an entire book. Much is dependent on local individual commitment to excellence in managing the complex interplay of the various systems, personnel, and processes.

As boiler systems have increased in scale, they contain enormous amounts of energy. Given the tremendous potential harm from a high-consequence event, be it ever so infrequent, the task of the loss control professional has never been more complex. Years of research and development into increasing steam generator output and efficiency has led to building ever larger and more complex systems. (See Figure 10.6 for large boiler under construction). Yet it is a mistake to think that ‘‘modern’’ processes will remove the potential for significant loss, for ‘‘Many of the mishaps we prefer to regard as impossible aren’t impossible at all – they just take longer’’ (Chiles, 2002).

Loss control is analogous to looking for those areas where control can be lost – usually in failures with controls and equipment or with operational errors, the unintended results impacting people, environment, assets, or production in

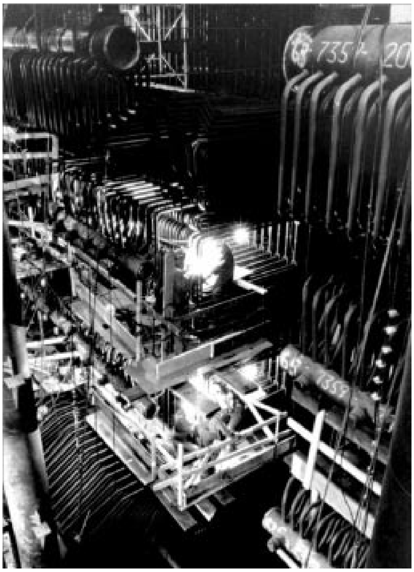

Figure 10.6 Super heater installation on a coal fired utility boiler (Babcock and Wilcox).

a negative manner. The best management systems put plans in place to identify the potential instead of reacting to the event. As such, the effort becomes a multifaceted endeavor requiring interface between engineers, construction firms, maintenance teams, operations, and suppliers, under the umbrella of maintaining a cost-effective program that is able to provide a return on investment when finally assembled and running!

It is true that vigilance is necessary, but it must be wielded by experienced and knowledgeable people at every point in the energy conversion chain. That remains as much a challenge now as it has through history. Perhaps an individual who invested years specializing in the investigation of major losses should have the final say: ‘‘Those who want to spend more money to make a plant safer and those who think enough has been spent share a false premise: they both assume more safety will cost more money’’ (Kletz, 2009).

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