STP-PT-054

CONCENTRATED SOLAR POWER (CSP) CODES AND STANDARDS GAP ANALYSIS

ASME STANDARDS TECHNOLOGY, LLC

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CONCENTRATED SOLAR POWER (CSP) CODES AND STANDARDS GAP ANALYSIS

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Date of Issuance: December 21, 2012

This report was prepared as an account of work sponsored by ASME Pressure Technologies Codes and Standards and the ASME Standards Technology, LLC (ASME ST-LLC).

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ISBN No. 978-0-7918-6866-9

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FOREWORD

The report provides an analysis of the ASME codes and standards that apply to Concentrated Solar Power (CSP) technologies to determine the gaps in the codes and standards and where there may be additional codes and standards work required to implement and commercialize CSP.

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ABSTRACT

Numerous concentrated solar power (CSP) facilities have been in successful commercial operation for the past 25 years. Recently, government incentives and advances in cost reduction have brought many new players into the field. An accelerated deployment of CSP is currently being seen worldwide. Many of the developing technologies in CSP have failure modes and effects different from those treated by existing boiler and pressure vessel codes. This study is a gap analysis to identify differences between the safety regulation needs of emerging CSP technologies and existing ASME Boiler and Pressure Vessel codes (BPV). Six leading CSP technologies are examined. The safety related failure modes of these systems are identified and compared with existing Code rules to identify gaps in code coverage. Recommendations for actions to close these gaps are proposed.

1 INTRODUCTION

Concentrated solar power (CSP) systems focus solar radiation collected from a large surface area to a smaller area to heat a medium to an elevated temperature. The collected heat is then used for process purposes or for the generation of electric power. A wide variety of heat transfer media are being explored for use in CSP systems. These media include water, steam, heat transfer oils, air or other gases, and even solid particles. This study examines a select subset of six CSP technologies being developed today with the objective of identifying gaps between the technologies and current ASME Boiler and Pressure Vessel (BPV) Codes.

This study is not a comprehensive review of the entire field of concentrated solar power. Because of the wide scope of active work in the field, only the most visible technologies are reviewed here. Although some of the advantages and disadvantages of the various systems are mentioned here, it is not the goal of this report to make any judgments about the economic viability of any of the systems. There are commercial plants that have been operating for as long as 25 years; nonetheless, this field is in its relative infancy. There are myriad researchers following a multitude of paths. The industry does not yet appear to be narrowing its technology choices. It would be premature at this point in time to try to sort the winners from the losers.

The common elements in all CSP systems are the collector system and the receiver system. The collector system consists of the mirrors, lenses, or other devices that focus and concentrate the solar radiation on the receiver. The receiver system is a heat exchanger that converts the focused solar radiation to another form of energy that can be used either for process heating or to generate electric power. This paper focuses on CSP power generation.

The CSP technologies reviewed for this study are:

- Dish systems
- Linear systems
  - Parabolic trough reflector systems
  - Linear Fresnel reflector systems
- Power towers
  - Direct steam (Rankine cycle) systems
  - Volumetric expansion (Brayton cycle) systems
  - Molten salt systems

These three categories are based on the physical architecture of the collector systems. A wide variety of receiver systems are being explored by developers. Receiver systems can be generally be coupled with a variety of different collector systems which results in a large domain of collector/receiver pairings.

Dish systems have a physical architecture employing a parabolic reflector, generally multi-faceted, as the collector. The receiver, located at the focal point of the reflector, is generally a reciprocating Stirling engine. There has been some research of dish systems employing a gas turbine as the engine. Dish receiver systems that export a heated fluid are also possible.

Linear systems consist of linear, fluid-filled receiver tubes running parallel to grade at a relatively low elevation. The collector system employs linear reflectors of parabolic shape or multi-element Fresnel arrangements in a common plane to focus sunlight on the receiver tubes. Thermal heat transfer fluids, air or molten salt can be heated in these systems. Some systems are generating steam that can directly power a turbine.

Power towers are point focus systems that consist of a collector field of flat or slightly curved mirrors with two axis pointing systems that focus the solar radiation onto a receiver located on a tall central tower. The mirrors and their pointing drives are referred to as heliostats. The receivers in power tower systems can be designed for direct steam generation, for expansion of air or gas, or to heat a mass storage medium such as molten salt. There have even been experimental systems tested that heat a fluidized curtain of falling solid pellets or spheres which could be stored for subsequent extraction of heat for process or power generation purposes.

Each of these systems is described more specifically in Section 2. The major components and their relationships are explained with emphasis placed on identifying system components that contain pressure or provide a heat transfer function. It is these components that may fall under BPV jurisdiction.

Section 3 examines the BPV Code issues related to each system. First, the code section having the system within its scope is identified. This exercise is not trivial as the definition of a boiler varies between jurisdictions. Some jurisdictions classify all of these CSP systems as boilers while others classify none of them as boilers. The confusion in definitions is largely because current regulations were written before the advent of current CSP technologies.

Section 3 then examines the safety related failure mechanisms of the systems. For each failure mechanism, two questions are posed:

1. Are these failure mechanisms adequately covered by present codes? (i.e., what are the code gaps?)
2. Are there BPV Code requirements imposed on the system that serve no safety related purpose?

Section 4 provides provisional suggestions of future BPV code development initiatives. Some judgment will be needed to choose which of the suggestions to pursue. At this time, a wide variety of technologies are being pursued. The industry has not settled on a favored or best technology yet. Some of the technologies may not prove to be economically viable and will fall out of the marketplace; developing rules to address these systems may waste limited code committee resources. However, the number of gaps between the industry's needs and the BPV codes is small, so the burden of addressing the gaps is not great.

Section 5 touches on the future in the development of PTC technologies. The ASME PTC 52 committee is developing a performance test code for concentrated solar thermal power systems. Among the technologies that will be covered by this code are linear Fresnel collectors, parabolic troughs, power towers, and thermal storage. The committee members were drawn from various countries and interest areas.

2 SYSTEM DESCRIPTIONS

2.1 Dish Systems

Figure 1 illustrates a typical dish system collector. The parabolic shaped dish can consist of a single reflector element of an array of smaller reflectors lying on a parabolic surface. The dish tracks the sun by means of a two-axis drive. Dish collectors are generally used to power an engine mounted at the reflector focal point. Stirling engines and gas turbines are being explored as receivers for dish collectors.

Many dish systems currently being explored have collector diameters of about 10 m (33 ft.). Larger collector areas are possible, but wind loads and drive actuator costs increase with dish size.

The modern Stirling engines employed in dish systems operate at pressures as high as 20 MPa (2900 psi) and gas temperatures over 700°C (1292°F). The preferred working fluid is hydrogen gas. A Stirling engine sized for a 10 m dish is about the size of an automotive engine, although it has a lower power density. The Stirling engine may include a regenerator to increase efficiency. It also has a heat exchanger for removing heat from the cooling chamber. Pressure parts in a Stirling engine include the cylinder(s), connecting passages or piping, and heat exchanges used to either receive or reject heat.

Although most dish collector systems being commercialized use Stirling engines, other types of receivers such as gas turbines are possible.

There are a number of demonstration Stirling engine dish systems, but no large scale plants have been built yet.

Figure 1 - Parabolic Dish With Stirling Engine [1]

2.2 Linear Systems

Linear systems employ ground mounted reflectors that focus radiation on an elevated horizontal tube at the focal point of the reflector. Two different types of collector are employed in these systems. The two collector systems share a common set of solutions for the thermal side. Linear collectors have reflectors oriented in a north-south direction and rotate about a single axis to track the sun.

2.2.1 Linear Parabolic Trough Systems

The parabolic trough system consists of a linear parabolic reflector with a receiver tube at its focal point. The entire mirror rotates to track the sun.

Figure 2 - Parabolic Trough Collector [2]

2.2.2 Linear Fresnel Systems

A Linear Fresnel system uses flat or slightly curved linear reflector elements that are rotated independently from each other to focus sunlight on the receiver tube. The reflector elements are generally mounted at a common height close to the ground.

2.2.3 Linear System Heat Transfer

A variety of heat transfer fluids can be heated in the receiver tubes of a linear system. The fluids include water/steam, heat transfer oils and molten salt and air. Presently there are systems in service using all of these fluids. The systems can generate steam directly from the heat transfer fluid or the heated fluid can be stored. There are systems that store hot oil and molten salt for later power generation. There are some systems which heat air that is used to heat a solid phase storage media such as gravel or concrete. To generate power, cold air is passed over the hot storage media and then passed through a heat exchanger to generate steam. Oil systems generate steam in a heat exchanger to power a steam turbine. Oil systems can also be configured to capture and store solar heat by transferring energy to a molten salt system using heat exchangers and storage tanks. The stored molten salt can then be passed through a heat exchanger to produce steam for power generation.

Steam generating, linear systems supply steam directly to a turbine for power generation. Linear steam systems are once through steam generators. The pressure containing parts found in linear systems include:

1. Receiver tubes
2. Piping connecting receiver field tubes to central generating station
3. Storage vessels
4. Heat exchangers

Presently there are linear systems using oil and steam in operation. The Solnova Power Station in Spain is also employs a synthetic oil for heat transfer. The Novatec Biosol plants (Spain) have linear Fresnel collectors and utilize water/steam as the heat transfer fluid. The Archimedes demonstration plant in Sicily is a parabolic trough system that heats molten salt. The SEGS plants in California are parabolic trough systems that heats oil. The SEGS plants have been in service since 1984. Airlight Energy of Switzerland is developing trough systems that heat air.

2.3 Power Towers

Point focus power towers place the receiver at the top of a tall tower. Towers can range from 30 m (98 ft.) to 165 m (540 ft.) in height. [3] The collector system is an array of ground mounted mirrors with two axis drives that track the sun to keep the reflected light beam focused on the receiver.

The power tower systems typically have a relatively large collector field enabling it to generate higher temperatures than dish or linear systems.

Receivers for power towers employ a wide range of technologies:

- Steam production. A solar boiler generates steam to power a conventional Rankine cycle.
- Molten salt heating. Molten salt is heated and then stored in tanks. The stored molten salt is then used to generate steam for power production.
- Air heating. The heated air powers a Brayton cycle employing a gas turbine.

2.3.1 Power Tower Rankine Cycle Receiver

Direct steam production power towers use a boiler as the receiver. Two types of boiler receivers are common, the external receiver and the cavity receiver. The external receiver has the boiler tubes placed around the perimeter of the top of the tower and exposed to ambient air. Cavity receivers have the boiler tubes lining the inside surfaces of a partially enclosed volume. An opening at the bottom of the enclosed volume admits light from the collector system. Rankine cycle receivers can be either natural circulation or of forced flow design

Pressure parts in a Rankine cycle system are the same as for a conventional boiler and consist of:

1. Economizer, boiler, superheater and reheater tubing.
2. Interconnecting piping and headers
3. Steam drum

A number of operating plants produce steam directly for power generation. Among these is the eSolar Lancaster, California plant. The BrightSource Energy Ivanpah plant under construction in the Mojave Desert south of Las Vegas will also generate steam directly. Direct steam production from CSP may be replaced in the future with molten salt systems that allow the plant to store heat and therefore generate power over a longer part of the day.

2.3.2 Molten Salt Receiver

Molten salt systems heat a high temperature molten salt mixture that can be used to generate steam for a conventional steam turbine and/or stored in insulated tanks for later power production. The main advantage of a molten salt system, as with any energy storage system, is that it can allow a facility to generate power over a longer period of time than the period of available sunlight. Molten salts can also be used at higher temperatures (565°C, 1050°F) [4] than currently available heat transfer oils (393°C, 740°F) [4].

The salts used are mixtures of primarily potassium nitrate and sodium nitrate. These mixtures typically melt at 288°C (550°F) [5] and are usable up to 565°C (1050°F). A power tower molten salt system heats the salt flowing through receiver tubes on which the solar flux is concentrated. Pumps move the salt through the circuit and store the heated salt in a hot storage tank. The cold salt storage tank provides enough salt to enable a day's worth of heat collection. The heated salt is then drawn off the hot tank and run through heat exchangers to produce steam for power production. The cooled salt is then returned to the cold salt tank for reuse on the following day. The benefit of a molten salt solar storage system is that power production can be spread out over a longer period of time and tailored to match grid demand. Molten salt systems are fairly complex because the minimum operating temperature of about 288°C (550°F) requires extensive measures to assure the salt does not freeze in the circuits. Heat tracing and drainage procedures must be carefully followed to assure freeze-ups do not occur.

Operating pressures are relatively low as the pumps need only overcome the pressure drop in the system. Molten salts do not boil or create a vapor that can expand to create high pressures like water does when it vaporizes. Hence safety issues with molten salt are different from those of a steam system.

Special long-shafted pumps are needed for molten salt to protect the drive motor from heat.

The pressure parts in a molten salt system consist of:

1. Receiver tubes
2. Collection headers and piping
3. Molten salt pumps
4. Valves
5. Molten salt/steam heat exchangers
6. Surge tanks
7. Storage tanks

Molten salt systems can be open or closed to the atmosphere.

There are molten salt CSP plants in service in Spain. The Solar Reserve Tonopah plant currently under construction is a molten salt system.

2.3.3 Power Tower Brayton Cycle Receiver

Numerous variations of the Brayton cycle are being investigated. Some heat air that has been compressed by the turbine and return it immediately to the power side of the turbine. Others heat an intermediate fluid that can be used to store heat. Air or another gas is then heated by the storage medium to power the engine. Storage media include molten salt, carbon, gravel, special concretes, ceramics and refractory materials.

Gas turbine, Brayton cycle, systems currently being explored are relatively small developmental models. If the technology is scalable to utility sized plants, fairly large engines would be used.

In a solar powered gas turbine, the compressor section pressurizes air which flows to the receiver to be heated and expanded. From there it flows to the turbine power section where it drives the turbine to provide compressor and generator set power. For large gas turbines, it is likely that the receiver section would be separated from the engine by some distance. Small, developmental gas turbines have the receiver mounted directly to the gas turbine.

Pressure parts in a gas turbine receiver would consist of:

1. Receiver heat exchanger. An array of tubes, cavities, or chambers in which the working fluid is heated
2. Connecting pipe to transfer working fluid between the compressor, heat exchanger and turbine
3. Turbine pressure shell
4. Pressure relief devices

A significant advantage of a Brayton cycle solar system is that it needs no water. Most solar rich areas are in arid regions where water is expensive and difficult to obtain. A number of Brayton cycle solar systems have been tested but efficiencies are still low because of material limitations. To obtain reasonable efficiency, developers would like to reach a heated gas temperature of at least 1000°C (1800°F). Finding materials with sufficient creep and fatigue life at this temperature is the major challenge for Brayton cycle developers.

3 BOILER AND PRESSURE VESSEL CODE ISSUES AND GAPS

The first step in examining gaps between existing codes and the emerging CSP technologies is to determine which code or codes have jurisdiction. ASME BPV Section I, Power Boilers, asserts that boilers are within its scope. However, Section I does not define what a boiler is. That task is done by the individual local jurisdictions. Definitions for the terms “boiler” and “pressure vessel” vary between jurisdictions. In some jurisdictions, all of the systems reviewed in this study could be defined as boilers and therefore fall within the scope of Section I. Close examination of the individual systems shows that this is not a desired outcome. Some solar receiver systems have entirely different failure modes than a steam boiler.

The first part of this section examines the issue of inappropriate classification of some receiver technologies as boilers. The remaining parts examine the pressure related safety risks of each technology. The set of risks for each technology is then compared to the applicable ASME BPV code to identify gaps in code coverage.

3.1 Boiler Definitions

The boiler laws and regulations of the six US states with highest CSP potential were examined to determine how the various solar receiver technologies would be classified under their rules. These six states are Arizona, California, Colorado, Nevada, New Mexico and Utah. All of the receiver technologies heat a fluid in a confined space so they have elements that are common to boilers and pressure vessels. The receiver technologies considered in this evaluation were:

- Stirling engines
- Rankine cycle systems
- Brayton cycle systems
- Molten salt systems
- Thermal fluid systems

3.1.1 Is a CSP heated device fired?

The Preamble of ASME BPV Section I states that “A pressure vessel in which steam is generated by the application of heat resulting from the combustion of fuel (solid, liquid, or gaseous) shall be classed as a fired steam boiler.” The wording can be interpreted as not including solar energy since the word “combustion” is generally understood to be an oxidation process. Solar energy is produced by a thermonuclear process that might be loosely labeled as combustion, but it is not an oxidation process. This has led to a number of disagreements over classification of solar heated devices as fired boilers. There are those who feel that they are not fired. Most state definitions for a fired boiler are broader than the Section I definition. They refer to the application of heat without specifying the source of the heat. Hence, in four of the six states surveyed for this report, solar heating constitutes “firing.” Arizona’s definition requires the applied heat to be from combustion of a fuel. The Nevada definition states “direct” application of heat. One could argue that CSP is not a direct application of heat. In Arizona, one could try to argue that a solar heated boiler is not heated from the combustion of fuel and therefore doesn’t meet the definition. In view of the precedents in neighboring jurisdictions, it is not likely the argument would stand.

The inconsistency between state definitions of “fired” and the Section I definition should be cleared up. Additionally, it would be worthwhile for states that are likely to be hosts for CSP plants to clarify their definition of heat sources.

3.1.2 Closed or Open Systems

A common qualifier in definitions of pressure vessels or boilers is that the systems are "closed." The term "closed," however is seldom defined. Some solar technologies are open to the atmosphere. Most current molten salt systems dump the heated salt into a storage tank that is open to the atmosphere. The same is true for some oil based systems. Gas turbines typically exhaust to atmosphere. The author feels that all of these systems are closed from the point of view of pressure envelope integrity. There are flow restrictions in these systems that cause a pressure drop between the inlet and outlet. At any point before the outlet, there is a safety concern that the strength of the containment envelope is adequate for the pressure at that point. However, the author's opinion is not universally shared.

The BPV codes should clarify the terms "open to atmosphere" and "closed to atmosphere" to preclude disagreements.

3.1.3 Review of State Boiler Definitions

Some of the state definitions of a boiler are so broad that nearly all solar technologies are classified as boilers. Other states have more specific definitions that capture some of the technologies and leave others outside the scope of their boiler and pressure vessel laws. All are so broad that they encompass molten salt systems in their scope as boilers. Molten salt system behavior is vastly different from that of a boiler and boiler rules are not a good fit for the potential hazards.

Table 1, quotes the definition of boiler from the statutes or regulations of the six examined states. Although there are common elements in each definition, they are all different. Table 2 compares the elements of each definition for the six states.

Table 3 to 8 compare each state's definition of a boiler to the characteristics of the five types of receiver technology. Each of these tables treats an individual state and repeats the elements of the state definition at the top. Below the definition elements, the five receiver technologies are listed and an "x" is marked if the technology matches that element. These tables indicate which technologies are considered to be boilers if the state rules are read literally.

The comparisons in Table 3 to 8 show that Stirling engine systems are not boilers. They escape classification as a boiler because they either do not produce steam or the working fluid is not used external to its self. This is consistent with long standing practice in the pressure vessel codes. Rankine cycle systems fit within the definition of a boiler, as expected. The surprises are Brayton cycle and molten salt systems. Both fit the jurisdictional definitions of a boiler in five of the six states. California is the exception.

Brayton cycle systems heat air under pressure and generally exhaust it to the atmosphere through a gas turbine engine. Thermodynamically, they are considered open systems but for purposes of this analysis they were considered closed in the mechanical sense because their construction has pressure restrictions and sizable volumes in which high pressures can be reached. However, these systems do not involve a phase change or a risk of phase change as do boilers. As will be shown in more detail later, the safety concerns with a gas turbine are very different from those of a boiler. Application of boiler rules to gas turbines is inappropriate.

Table 1- State Boiler Definitions

State	Boiler Definition
Arizona	"Boiler" means a closed vessel in which fluid is heated for use external to itself by the direct application of heat resulting from the combustion of fuel, solid, liquid, or gaseous, or by the use of electricity.
California	A boiler is "a fired or unfired pressure vessel used to generate steam pressure by the application of heat."
Colorado	A high temperature boiler is a boiler in which water or other fluid is heated and intended for operation at pressures in excess of 160 psig and temperatures in excess of 250 degrees Fahrenheit.
Nevada	"Boiler" means a closed vessel in which water is heated, steam is generated, steam is superheated, or any combination thereof, under pressure or vacuum, for use external to the boiler by the direct application of heat. The term includes a fired unit for heating or vaporizing liquids other than water if the unit is separate from the processing system and is complete within its self.
New Mexico	"Boiler" means a closed vessel in which water or other liquid is heated, steam or vapor is generated, steam is superheated, or any combination of these functions is accomplished, under pressure, for use external to itself, by the direct application of energy from the combustion of fuels or from electricity or solar energy. The term includes a fired unit for heating and vaporizing liquids other than water where the unit is separate from the processing system and is complete within itself.
Utah (relies on NBIC definition)	A power boiler is a closed vessel in which water or other liquid is heated, steam or vapor generated, steam or vapor is superheated, or any combination thereof, under pressure for use external to itself, by the direct application of energy from the combustion of fuels or from electricity or solar energy. The term boiler includes fired units for heating or vaporizing liquids other than water but does not include fired process heaters and systems. The term boiler also shall include the apparatus used to generate heat and all controls and safety devices associated with such apparatus or the closed vessel.

Molten salt systems can be open or closed to the atmosphere but their construction, like that of a gas turbine, creates a flow restriction that acts as a closure and allows high pressures to be reached. As with the gas turbine, phase change cannot occur. Molten salts do not boil because they thermally decompose before reaching a boiling point. Application of boiler safety rules to molten salt receivers is also inappropriate. There is little overlap in the failure modes of boilers and molten salt systems.

Table 2 - Elements of State Boiler Definition

	Closed vessel	Heats fluid	Fluid for external use	Direct application of heat from combustion of fuel or electricity	Direct application of heat	Fired or unfired pressure vessel	Generates steam	Application of heat	Pressure > 160 psig	Temperature > 250°F	Pressurized	Specific reference to solar heating
Arizona	x	x	x	x								
California						x	x	x				
Colorado		x							x	x		
Nevada	x	x	x		x						x	
New Mexico	x	x	x		x						x	x
Utah	x	x	x								x	x

Table 3 - Comparison of Arizona Definition to Solar Technologies

	Closed vessel	Heats fluid	Fluid for external use	Direct application of heat from combustion of fuel or electricity
Arizona	x	x	x	x
Stirling Engine	x	x		x
Rankine Cycle	x	x	x	x
Brayton Cycle	x	x	x	x
Molten salt	x	x	x	x
Thermal oils	x	x	x	x

Table 4 - Comparison of California Definition to Solar Technologies

	Fired or unfired pressure vessel	Generates steam	Application of heat
California	x	x	x
Stirling Engine	x		x
Rankine Cycle	x	x	x
Brayton Cycle	x		x
Molten salt	x		x
Thermal oils	x		x

Table 5 - Comparison of Colorado Definition to Solar Technologies

	Heats fluid	Pressure > 160 psig	Temperature > 250°F
Colorado	x	x	x
Stirling Engine	x	x	x
Rankine Cycle	x	x	x
Brayton Cycle	x	x	x
Molten salt	x	x	x
Thermal oils	x	x	x

Table 6 - Comparison of Nevada Definition to Solar Technologies

	Closed vessel	Heats fluid	Fluid for external use	Direct application of heat	Pressurized
Nevada	x	x	x	x	x
Stirling Engine	x	x		x	x
Rankine Cycle	x	x	x	x	x
Brayton Cycle	x	x	x	x	x
Molten salt	x	x	x	x	x
Thermal oil	x	x	x	x	x

Table 7 - Comparison of New Mexico Definition to Solar Technologies

	Closed vessel	Heats fluid	Fluid for external use	Direct application of heat	Pressurized	Specific reference to solar heating
New Mexico	x	x	x	x	x	x
Stirling Engine	x	x		x	x	x
Rankine Cycle	x	x	x	x	x	x
Brayton Cycle	x	x	x	x	x	x
Molten salt	x	x	x	x	x	x
Thermal oil	x	x	x	x	x	x

Table 8 - Comparison of Utah Definition to Solar Technologies

	Closed vessel	Heats fluid	Fluid for external use	Pressurized	Specific reference to solar heating
Utah	x	x	x	x	x
Stirling Engine	x	x		x	x
Rankine Cycle	x	x	x	x	x
Brayton Cycle	x	x	x	x	x
Molten salt	x	x	x	x	x
Thermal oil	x	x	x	x	x

When today's definitions of a boiler were created, the writers did not anticipate gas turbine or molten salt technologies. Jurisdictions need to review their definitions of a boiler. The definitions should be refined so that they don't bring under their scope technologies that are not appropriate for the boiler code.

Brayton cycle systems and molten salt systems are so different from boilers that it is not appropriate to define them as such. Trying to modify BPV Section I to deal with these systems would create complex provisions and lead to confusion. The Code Committee should consider developing a separate, stand-alone code for molten salt systems. Solar powered Brayton cycle systems are not likely to be commercially viable for some time; therefore, there is no pressing need to develop a Brayton cycle code at this time. Section 4 provides specific recommendations for a solar molten salt code.

A recent case involving a developer of a commercial molten salt solar system illustrates the confusion caused by molten salt falling under the definition of boiler. The developer proceeded with his design on the assumption that he would have to comply with ASME Section I, Power Boilers. The system fit within the state definition of a boiler. Considerable design work and planning had been completed. The project had proceeded to the stage of procurement for the molten salt receiver at which time the successful bidder, an ASME S-stamp certificate holder intervened. The certificate holder obtained a state ruling based on logic and common sense that Section I was inappropriate for the application. The parties agreed that ASME Section VIII, Division 1, and B31.1 Power Piping should be the codes of construction.

The state of California has issued a directive concerning molten salt and thermal fluid systems that generate steam in a heat exchanger. The directive is provided in Appendix A. The steam side of the systems is defined as Section I system of which parts are built to either Section I or Section VIII, Division 1 in accord with Code Case 1855. The directive is silent with respect to the molten salt side of the system. Presumably, California is not exercising any jurisdiction over the salt side.

3.2 Stirling Engine Receivers Gap Analysis

As shown in Section 3.1, Stirling engines do not fit the definition of a boiler so they do not fall under the scope of ASME BPV Section I. Stirling engines are outside the scope of Section VIII, because U-1(c)(2)(c) exempts reciprocating engines.

Solar Stirling engines heat a gas (hydrogen is preferred) to expand it and push a piston. The safety risks are similar to those of conventional diesel and gasoline engines. The sizes of the pressure chambers and the maximum pressures in Stirling engines are also similar to their diesel and gasoline counterparts.

While a gap analysis for Stirling engines is out of the scope of this study which focuses on the ASME BPV codes, a brief list of their safety risks and methods of mitigation is presented below in Table 9.

Table 9 - Solar Stirling Engine Risks and Mitigation

Risk	Consequences	Mitigation
Excessive pressure in containment chambers	Explosive rupture Dispersal of high velocity fragments Personal injury Property damage	Mass of gas in system is small and is held constant. Excessive heat and pressure is controlled by sizing of reflector dish for maximum solar flux (solar noon at summer solstice) or by moving dish off focus.
Explosion from ignition of leaking hydrogen working fluid	Fire Explosive shock wave Personal injury Property damage	Limited amount of hydrogen gas. High quality sealing throughout system.
Excessive engine speed.	Dispersal of high velocity fragments Personal injury Property damage	Control heat flux (fuel) by moving dish off focus. Design engine for maximum possible solar flux condition.

The ASME BPV codes, by established precedent, have excluded rotary and reciprocating engines from their scope. There are adequate standards for safe engine design available for designers. The failure modes from solar applications are similar to the failure modes from conventional gas and liquid fuels. Hence there is no need for ASME BPV development for solar Stirling engines.

3.3 Rankine Cycle Receiver Gap Analysis

Rankine-steam-cycle receivers are boilers whose source of heat is concentrated solar radiation. As explained earlier, there are two styles of tower mounted receivers, the cavity and the external receiver. There is also a linear type steam receiver that is not tower mounted.

As shown in Table 10, failure modes for a CSP boiler are similar to those of conventional fuel fired boilers. Existing Section I rules are generally adequate to deal with solar powered boilers. There is one exception. That exception is loss of feedwater supply.

Table 10 - CSP Rankine Cycle Boiler Risks and Mitigation

Risk	Consequences	Mitigation
Excessive pressure	Rupture of pressure envelope. Physical injury. Property damage.	Pressure envelope design rules. Safety factors used to establish allowable stresses. Control of materials. Provisions for safety relief valves.

Risk	Consequences	Mitigation
Excessive temperature	Reduction in material strength. Rupture of pressure envelope. Physical injury. Property damage. Physical damage to boiler. Metallurgical damage to boiler.	ASME Section I, PG-61.1, provisions for second independent source of feedwater for fuels that continue to evolve heat after fuel supply is shut off. Code Case 2635 rules for tower mounted solar boilers.
Loss of feedwater	Excess temperature. Reduction in material strength. Rupture of pressure envelope Physical injury. Property damage Physical damage to boiler. Metallurgical damage to boiler	Drum water level requirements. Control protocols for heat source.

The behavior of the fuel on shut down and the means of controlling it are different for solar fired boilers.

Section I, PG-6.11 specifies requirements for feedwater supply redundancy for solid fuels that continue to evolve heat after their feed is shut off. Gaseous, liquid and solids in suspension are exempted from the feedwater redundancy requirement. Gaseous and liquid fuels cease to evolve heat shortly after their supply is shut off. Solid fuels not in suspension, on the other hand, continue to evolve heat for some time after being shut off. To protect the boiler from metallurgical damage caused by heat evolved after shutting off the fuel feed, boilers fired by solid fuels that are not in suspension must have a second, independently powered source of feedwater. Solids in suspension, e.g. pulverized coal, are exempted from the redundancy requirement because, like liquid and gaseous fuels, they quickly cease to evolve heat after being shut off.

The rate at which heat can be removed from a solar fired boiler depends on the design of the collector system. It is slower than the action of shutting off a liquid fuel but is generally much more rapid than the action of a solid fuel after it is shut off. Heliostat designers have two options for shutting down radiation input to the receiver: moving the heliostat focus off of the receiver or blocking the heliostat beam. Blocking the beam would require a costly mechanism so designers prefer methods that move the heliostat beam off of the receiver. Heliostats, however, move slowly and need some time to move off of their target. Furthermore, for power management reasons, some systems do not operate all heliostats simultaneously. Power is supplied sequentially to individual heliostats or groups of heliostats. The sequencing of operation and the slow drive speed mean that it takes a finite amount of time to remove heat from a CSP boiler. Code Case 2635 set guidelines for removal of the heat source for tower mounted boilers. The case, however, does not apply to linear boiling water receivers which are ground mounted.

For tower mounted systems, the Code Case 2635 provisions appear to be reasonable. The code case was written narrowly to apply to natural circulation, tower mounted boilers. It ignores linear receiver systems which are once-through boilers. Developers of linear, once-through boiling water receivers need their own set of rules which achieve the same objective of preventing damage to the boiler. Rules for removing the focused solar flux from a linear system will be substantially different. First, there is no drum to provide a supply of water during the duration of the shutdown event. Secondly, the rules need to recognize the dynamics of the once-through circuit and the dynamics of the heliostats. While there is no drum in a once through system to supply water during the shutdown sequence, the tubes of the circuit contain some water that will continue to provide cooling for a short period of time. Additionally, in single boiler installations, the pressure will drop rapidly when the water supply is interrupted. This will reduce the pressure stress in the tubes allowing them to rise to a higher temperature. In this case, a small amount of tube metal temperature rise may not compromise safety.

The issue of controlling heat input from heliostats is fairly complicated and may take Section I into areas of active control design. Although there is no mandate that Section I use only passive controls to achieve safety, the Code has historically shown a preference for passive controls. CSP systems with their multitude of electrically powered heliostats will present a challenge to both system developers and code writers.

Rules governing the removal of heat from a linear system in the event of a loss of feedwater need to recognize the following factors:

- A loss of feedwater will cause a temporary increase in steam pressure as the remaining water in the evaporator section of the circuit vaporizes.
- The pressure increase from evaporation of the residual water in the tubes will be accompanied by a tube metal temperature increase due to heating and expansion of the residual steam in the system.
- Steam flow to the steam turbine will result in a decrease in steam side pressure.
- There will be an increase in tube temperatures coincident with the dry out of the system.
- De-focusing collector system mirrors takes a finite amount of time.
- It may not be possible to de-focus all collector system mirrors simultaneously.

Tower mounted steam receiver systems introduce some new questions that Section I may need to address. Do valve requirements for multiple tower systems that feed common headers need to be reviewed? Are double valves to isolate the off-line tower and boiler needed when work on the tower would not be allowed because the remainder of the solar field is on line? Do definitions of hydrotest pressures have to be modified to adjust for the high hydrostatic head? Are safety valve requirements for these systems sufficient? Is there a need for additional instrumentation to monitor temperatures?

3.4 Molten Salt CSP System Gap Analysis

As explained in Section 3.1, molten salt systems are classified as boilers when state boiler definitions are read literally. Molten salt systems have a number of properties that differentiate them from boilers.

First is the lack of a phase change when heated. The upper operating limit for molten nitrate salts is the decomposition temperature of the mixture. This temperature (570-580°C, 1058-1076°F) is reached before the mixture boils. Within its useable operating temperature range, the vapor pressure of molten salt is low. The fluid remains liquid and there is no gaseous phase that could result in rapidly rising pressures and possible pressure envelope rupture. Many of the safety rules for boilers derive from the behavior of superheated steam, a gas which will expand when heated. There is no parallel to steam in a molten salt system. (There is a possible, but not yet demonstrated, existence of a gaseous phase. This possibility is discussed in more detail below.)

Similarly, Code rules for liquid phase thermal fluid heaters are a poor match for molten salt systems. Thermal fluid heater rules assume excess temperature of the liquid will result in boiling and evolution of substantial amounts of gas.

In molten salt systems, freezing of the salt is a more important issue than dealing with overpressure from boiling induced gas evolution. The ASME BPV Codes don't address freezing. It's always been left to the owner to deal with. Molten salt does not expand, like water, when it freezes, but a frozen system must be thawed before it can be operated. Practices and methods to avoid salt freezing need some definition.

Contaminants, such as chlorides, found in commercial molten nitrate salts will corrode most metals at the upper end of the operating temperature range, so a very limited selection of Code accepted materials is available. There may be candidate materials not presently recognized by the Code that would provide better corrosion resistance.

Table 11 shows the major risks and mitigation for a molten salt system. If Section I were to add rules to cover the risks of a molten salt system, a great number of exemptions and exceptions would have to be added to the Code to avoid burdening the system with unnecessary requirements. For example, most of the rules dealing with pressure relief valves for steam are not applicable to a molten salt system. The pressure in the system will never exceed the capacity of the system pump. Limiting the pump pressure capacity would be a more economical way of preventing over-pressure.

Rules governing feedwater supply redundancy would also need revisions to address molten salt.

Table 11 - CSP Molten Salt System Risks and Mitigation

Risk	Consequences	Mitigation
Excessive pressure	Rupture of pressure envelope. Physical injury. Property damage.	System design pressures are set at a level greater than the maximum possible pump pressure. Pump size assures pressure limits are not exceeded. The molten salt mixture has no vapor phase. Creation of high pressures from heating a gaseous phase is not possible.
Excessive temperature	Reduction in material strength. Rupture of pressure envelope. Physical injury. Property damage. Physical damage to boiler. Metallurgical damage to boiler.	Heliostat controls to limit heat input. Size pumps for maximum heating day, (summer solstice).
Loss of salt flow	Excess temperature. Reduction in material strength. Rupture of pressure envelope. Physical injury. Property damage. Physical damage to boiler. Metallurgical damage to boiler	Provision of a back-up supply of molten salt to assure flow until heliostats can be off-pointed. Provide a second, independently powered pump or a storage reservoir that would supply the system by gravity or a compressed air cap
Pressure envelope corrosion	Rupture of pressure envelope. Physical injury. Property damage. Leaks, loss of working fluid.	Use materials resistant to the corrosive effects of molten salt mixture contaminants. Salt purity guidelines.

3.4.1 Molten Salt Gaseous Phase

Molten salts are eutectic mixtures primarily containing nitrate salts. The principle constituents are sodium, calcium, lithium and potassium nitrate. Other salts and constituents can be included to achieve better performance properties. For example potassium and sodium nitrate individually melt, respectively, at 334°C (633°F) and 308°C (586°F). Mixtures of these two salts with smaller amounts of other salts can lower the melting point to as low as 221°C (430°F). Maximum useable temperatures of molten salt are about 565°C (1050°F). Above the maximum useable temperature, the salts decompose. The mixtures do not boil and, therefore, do not have a phase change to a gaseous state, although some gas (O_2) is evolved in the decomposition. Some literature states that the evolution of gas is slow and spread out over a long period of time; however, no literature has been found documenting testing of decomposition rates above 600°C (1112°F). Upset conditions such as failures in heliostat control could lead to overheating of areas of the receiver heat transfer surface to well beyond 600°C. Since most chemical reactions accelerate at higher temperatures, it is likely that the evolution of gaseous decomposition products could be greater than what has been seen in the limited testing to date. Heating of these gases inside the confines of receiver tubes would lead to expansion of the gases and pressure rise in the system. There would be safety consequences from these higher pressures.

Since designers have no test data for such upset cases, accurate predictions of the consequences of receiver overheating cannot be made at this time. Nor can safety rules to deal with the event be developed. Some research into molten salt behavior at temperatures above the current limit of 600°C (1112°F) is needed.

3.5 Brayton Cycle Receiver Gap Analysis

Brayton cycle receivers employ heated, pressurized air to operate a gas turbine. The compressor section of the turbine supplies the pressurized air which is passed through a heat exchanger which uses concentrated solar radiation to heat and expand the air. The heated air then flows through the power section of the gas turbine to drive a generator. The working fluid has no liquid phase, no vaporization occurs and the gas turbine exhausts to atmosphere.

As pointed out in section 3.1, this non-boiler like system would be classified as a boiler in 5 of the 6 jurisdictions whose rules were examined for this study. Some tailoring of the definitions is required to prevent miss-classification of Brayton cycle systems as boilers.

Like the Stirling engine, the gas turbine falls outside of the scope of the ASME Boiler and Pressure Vessel Codes because of its rotating parts. However, the heat exchanger in a Brayton cycle system would likely fall within the scope of ASME BPV because it is separate from the engine. In the smaller developmental systems that are currently being deployed, the heat exchanger is integral to the turbine and would fall outside of the Code. Current developmental systems are operating at reasonably low temperatures (816°C, 1500°F) and pressures (800 kPa, 116 psig).

The goal of Brayton cycle investigators is to scale up to larger gas turbines, higher pressures, and higher temperatures. Target temperatures of 1000°C (1830°F) are being sought. Associated target pressures are 1500 kPa (217 psig).

Receiver heat exchangers for large gas turbines would be considerably larger than the engine package and be independent of the engine. Although operating pressures are relatively low, the potential for pressure boundary rupture and resulting injury and damage are equivalent to the rupture of a compressed air tank. Safety demands would dictate that these heat exchangers be designed to a safety code.

The anticipated temperatures for these heat exchangers are outside the allowable range for any materials currently allowed for ASME BPV Section VIII construction. Researchers must find materials with oxidation resistance, creep strength and fatigue strength at the extreme temperatures needed by these systems. It is likely that materials for future Brayton cycle heat exchangers will be non-metals, most probably ceramics. Code writing teams will need to include ceramics experts. New methods of testing and evaluating high temperature properties of these unknown materials will be needed.

A solar powered gas turbine, like any rotating engine, will need some means of assuring that maximum operating speeds are not exceeded. The speed control function will require a means of modulating flow. On fuel fired gas turbines, flow modulation is done by controlling the flow of fuel to the combustor with a valve. Valves can be designed to act fast enough to provide the desired over speed protection. The analogous operation for a solar fueled gas turbine would be to remove the incoming solar flux. Since heliostats operate slowly, they will likely not have a short enough response time. The designer may have to design a portion of the heliostats for rapid operation in order to achieve responsive flow modulation.

Alternatively, turbine speed modulation could be accomplished by a device that controls the system air flow rate. Control of air flow rate can be accomplished by valves. If these are placed on the cold side of the heat exchanger, existing technologies should be able to do the task. Should designers find it necessary to locate the air flow control on the hot side of the heat exchanger, all of the materials issues associated with the high gas temperature in the heat exchanger will need to be addressed by the valve designer.

Because of the limitations of existing materials, large scale implementation of CSP Brayton cycle systems is not imminent. The payoff from development of a successful Brayton cycle system is great, so continued research can be expected.

Table 12 presents some of the major failure modes expected in a solar powered gas turbine system.

Table 12 - CSP Brayton Cycle Risks and Mitigation

Risk	Consequences	Mitigation
Excessive pressure	Rupture of pressure envelope. Physical injury. Property damage.	Pressure envelope design rules. Safety factors used to establish allowable stresses. Control of materials. Control pressure by controlling air flow. Provide rupture disks.
Excessive temperature	Reduction in material strength. Rupture of pressure envelope. Physical injury. Property damage. Physical damage to heat exchanger. Metallurgical damage to heat exchanger.	Manage heat input with heliostat controls
Loss of air flow from engine mechanical failure	Excess temperature. Physical damage to heat exchanger. Metallurgical damage to heat exchanger.	Unknown
Engine over speed caused by excess heating of air or loss of generator load.	Explosive disintegration of engine. Physical injury. Property damage	De-focus heliostats. Modulate system air flow rate.

As in any system that heats a fluid to a high temperature, a loss of the cooling side fluid can result in high temperatures and heat induced damage. A delicate balance between the heating medium and the cooling medium determines the temperature of the pressure envelope. Since the air flow in a Brayton cycle system is provided by the gas turbine's compressor section, any mechanical upset that would shut down the engine will result in a loss of coolant flow to the heat exchanger. Rapid heating and metallurgical damage to the heat exchanger will result unless heat can be removed from the system fast enough. Conventional heliostats do not have operating speeds sufficient to protect the air heat exchanger. System designers will have to come up with a solution that addresses loss of coolant from engine shut downs. Assuming that these receivers would be Section VIII vessels, the control of coolant would fall outside of the Code's scope.

Should Brayton cycle CSP become commercially viable, there will be a desire by regulators to have some rules to assure public safety. It may be necessary at that time to develop a separate code to deal with the Brayton cycle system.

4 RECOMMENDATIONS

4.1 Boiler Definition

State and National Board Inspection Code (NBIC) definitions of the term boiler need revision. The definitions of a number of prime solar states and the NBIC are so broad they label Stirling engines, molten salt systems, thermal fluid systems and gas turbines as boilers. This brings these systems under Section I jurisdiction. Section I is not written to address the safety issues of engines or molten salt systems. Although thermal fluid systems can be built to Section I, there are challenges in applying Section I rules to such systems. The anticipated new Section I part dealing with liquid phase thermal fluid heaters should resolve issues with solar heated thermal fluid heaters.

4.2 Stirling Engine Systems

Stirling engines fall outside of current BPV Code jurisdiction. There is no evidence of a need for a pressure code for these engines that have safety related failure modes similar to other types of reciprocating engines.

4.3 Rankine Cycle – Tower Mounted

A tower mounted Rankine cycle boiler has the same failure modes as any other industrial boiler. There are a few gaps that the Code Committee should examine:

1. For a multi-tower system where towers feed a common header, are double valves necessary for isolation of an out of service boiler? Safety rules normally allow no access to the field when other towers are operating.
2. Due to the high hydrostatic head, is it necessary to modify rules for field hydrotests?
3. Hydrostatic head will also influence the MAWP of the boiler. Should safety valve set pressures be lowered?

4.4 Rankine Cycle - Linear Receiver Systems (Troughs and Linear Fresnel Collectors)

Linear receiver systems used to generate steam or heat a heat transfer fluid can experience a loss of feedwater or fluid flow if the supply pump fails. Failure of flow will starve the system of coolant and can lead to overheating and metallurgical damage to receiver tubes. Present rules in Section I, PG-61.1 for feedwater supply redundancy do not recognize concentrated solar power as a fuel. Code Case 2635 has closed this gap for tower mounted solar boilers. A new code case, similar to Code Case 2635 is needed to address this deficiency for linear steam producing receivers.

4.5 Molten Salt Receivers

Molten salt receivers have many similarities to liquid phase thermal heaters. However, molten salt lacks a phase change and therefore doesn't have the same level of risk of excess pressure from vaporization. The safety related failure modes for molten salt are of significantly lower risk than those of a steam system. Section VIII is generally suitable for design of molten salt receivers. Because molten salt systems have unique properties and failure modes that differentiate them from conventional boilers and pressure vessels, a separate molten salt safety and design code may be worthwhile to the industry.

A solar molten salt system code should address, at a minimum, the following factors:

1. Materials

2. Temperature limits
3. Requirements for defocusing of heliostats in the event of loss of coolant flow
4. Instrumentation
5. Valves
6. Salt/steam heat exchanger
7. Salt freeze protection
8. Determination of design pressure
9. Storage tank design – insulation requirements, expansion provisions, thermal isolation from earth.
10. Overpressure protection

Additionally, there needs to be some research to determine if overheated molten salt can decompose to its gaseous constituents fast enough to cause an over-pressure condition.

4.6 Brayton Cycle Receivers

Brayton cycle receivers are air heat exchangers. Boiler definitions need to be changed so that these systems do not get treated as boilers. The rules of Section VIII are sufficient to deal with the safety issues. This field would benefit from new materials able to contain pressure at temperatures up to 1000°C (1830°F). When researchers find suitable materials, ways to bring them into the Code will need to be developed. It is likely these unknown materials will be accompanied with limitations not seen in conventional metals used in boiler and pressure vessel design.