Westinghouse Small Modular Reactor

Passive Safety System Response to Postulated Events

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Abstract – The Westinghouse Small Modular Reactor (SMR) is an 800 MWt (>225 MWe) integral pressurized water reactor. This paper is part of a series of four describing the design and safety features of the Westinghouse SMR. This paper focuses in particular upon the passive safety features and the safety system response of the Westinghouse SMR.

The Westinghouse SMR design incorporates many features to minimize the effects of, and in some cases eliminates the possibility of, postulated accidents. The small size of the reactor and the low power density limits the potential consequences of an accident relative to a large plant. The integral design eliminates large loop piping, which significantly reduces the flow area of postulated loss of coolant accidents (LOCAs). The Westinghouse SMR containment is a high-pressure, compact design that normally operates at a partial vacuum. This facilitates heat removal from the containment during LOCA events. The containment is submerged in water which also aids the heat removal and provides an additional radionuclide filter.

The Westinghouse SMR safety system design is passive, is based largely on the passive safety systems used in the AP1000® reactor, and provides mitigation of all design basis accidents without the need for AC electrical power for a period of seven days. Frequent faults, such as reactivity insertion events and loss of power events, are protected by first shutting down the nuclear reaction by inserting control rods, then providing cold, borated water through a passive, buoyancy-driven flow. Decay heat removal is provided using a layered approach that includes the passive removal of heat by the steam drum and independent passive heat removal system that transfers heat from the primary system to the environment.

Less frequent faults such as loss of coolant accidents are mitigated by passive injection of a large quantity of water that is readily available inside containment. An automatic depressurization system is used to reduce the reactor pressure in a controlled manner to facilitate the passive injection. Long-term decay heat removal is accomplished using the passive heat removal systems augmented by heat transfer through the containment vessel to the environment. The passive injection systems are designed so that the fuel remains covered and effectively cooled throughout the event. Like during the frequent faults, the passive systems provide effective cooling without the need for ac power for seven days following the accident. Connections are available to add additional water to indefinitely cool the plant.

The response of the safety systems of the Westinghouse SMR to various initiating faults has been examined. Among them, two accidents; an extended station blackout event, and a LOCA event have been evaluated to demonstrate how the plant will remain safe in the unlikely event that either should occur.
I. INTRODUCTION

This paper is the final paper in a series of four papers designed to introduce the design and functionality of the Westinghouse SMR. This paper focuses on the functionality of the passive safety systems related to postulated events.

The design of the Westinghouse SMR enables inherently safe power operation while also allowing for a safe transition from normal operating conditions to a passive shutdown condition. The design includes the three main barriers of protection of traditional PWRs (fuel cladding, reactor coolant system (RCS) pressure boundary and containment) with the added benefit of an external pool of water to filter out radionuclides that might escape from the containment pressure vessel. Additionally, the plant’s underground placement reduces the likelihood of external events affecting the safety of the plant.

The integral design of the RCS contains no large bore piping, which significantly reduces the flow area of postulated loss of coolant accidents. The use of control rod drive mechanisms (CRDMs) internal to the pressure boundary eliminates the possibility that the ejection of a control rod will occur. The pump driven RCS flow during power operation results in a large thermal margin of safety that is predictable to a high level of confidence. The vertical arrangement of the plant allows for a safe transition to natural circulation in the event of a disruption to the forced reactor coolant flow. Also, the vertical arrangement of the plant inherently places the majority of the RCS water directly above the core for use in cooling of the reactor during an event. These design features set the stage for and augment the passive safety features of the plant.

The Westinghouse SMR is equipped with passive safety features that draw heavily from the AP1000 plant design that is certified by the US NRC (Ref. 1). Specifically, these systems are designed to safely shut down the nuclear reaction, remove decay heat following shutdown, assure that the reactor core remains covered with water to maintain effective cooling, and provide long-term cooling and shutdown.

The key components of the passive core cooling systems are four core makeup tanks (CMTs), an in-containment pool (ICP) and associated ICP tanks, an automatic depressurization system (ADS), an outside containment pool (OCP) and two ultimate heat sink (UHS) tanks. Integrated into the CMTs are passive residual heat removal heat exchangers. The Westinghouse SMR reactor coolant and passive core cooling systems are shown in Figure 1. Combined, these components provide the protection required to mitigate the various initiating faults required to be examined for PWRs. Among them, two accidents; an extended station blackout event, and a LOCA event have been evaluated to demonstrate how the plant will respond in the unlikely event that either should occur.

II. REACTOR CONTROL

During an event, the Westinghouse SMR relies on the natural forces of gravity and convection to shutdown and maintains the plant in a safe condition. The protection system of the Westinghouse SMR will diagnose that reactor protection is necessary and send a signal to de-energize latches holding the control rods out of the core. A loss of power to these latches will also de-energize them. The control rods are then free to fall by gravity to rapidly shut down the nuclear reaction. In the unlikely event that the control rods do not fall into the core or an event occurs while at a shutdown condition, diverse shutdown will be performed through the gravity-fed injection of highly borated water from the CMTs. The borated CMT water also provides long-term reactivity control of the plant. Both of these short-term and long-term reactivity control strategies for the Westinghouse SMR are similar to those of the AP1000 plant.
III. DECAY HEAT REMOVAL

Like the AP1000 plant, the preferred source of decay heat removal of the Westinghouse SMR is through the steam generator. The unique configuration associated with the Westinghouse SMR steam generator tubes with external steam drum allows for the large water inventory of the steam drum to be automatically available for decay heat removal during most accident scenarios but also for isolation of the steam generator tubes and containment from the drum during break scenarios. If available, natural circulation from the steam drum to the steam generator tubes and back again to the steam drum provides residual heat removal via steam dump. The capability to add additional inventory to the steam drum and the capability to pump flow to the steam generator tubes are also available should AC power be available. However, neither is required to demonstrate that a safe shutdown condition is achieved for all design basis scenarios.

Similar to the AP1000 plant, the Westinghouse SMR utilizes a heat exchanger to provide safety-grade passive decay heat removal. In the case of the Westinghouse SMR, the heat exchanger has been integrated into each of the four CMTs. The top of each CMT is attached to the reactor coolant system via a balance line pipe connected to the upper internals region of the reactor vessel. The bottom of each CMT is connected to the reactor vessel through direct vessel injection (DVI) lines into the vessel downcomer. During normal operation, valves in these lines prevent flow from circulating through the CMTs. A heat exchanger within the CMTs allows for heat transfer to a secondary loop of cooling water. As a result of this heat exchanger, the CMT cooling water is initially much cooler than the RCS water. Upon opening of the valves, the cold water falls into the RCS beginning a natural circulation cooling loop.

The secondary side of each CMT is connected through a closed loop of piping to a heat exchanger that sits in one of two UHS tanks. The water in the secondary CMT piping is pressurized to ensure liquid water is available to remove heat. Each UHS tank is sized to accommodate decay heat removal from the core and spent fuel pool for at least 72 hours. When combined with the water in the OCP, seven days of decay heat removal capability is available. The two UHS tanks are physically separated to inhibit an external event from compromising both tanks. Connections to each UHS tank allow for the addition of water to extend the decay heat removal indefinitely.

The SMR containment is not pressurized during many frequent fault scenarios.

IV. INVENTORY ADDITION

Along with their role in reactor control and decay heat removal, the four CMTs of the Westinghouse SMR provide the first safety-related inventory addition to the RCS. The CMTs contain a large volume of water that is automatically delivered to the RCS as the water level in the reactor vessel drops below the CMT balance lines. Additional water, which is borated and relatively cold, is available in the ICP tanks for injection to the RCS. These two additional inventory sources, along with the RCS volume, are sufficient to maintain effective core cooling and provide the elevation head required to transition to long-term recirculation cooling. This strategy is analogous to that of the AP1000 plant which uses two CMTs and an in-containment refueling water storage tank (iRWST) for inventory addition.

In addition to the safety-related methods of inventory addition, the chemical and volume control system (if available) is capable of providing additional make up water to the reactor coolant system should AC power be available.

V. LONG-TERM COOLING

A vent path for the energy in the RCS to the containment is established by the ADS. As the temperature in containment rises from the energy exiting the RCS through the ADS, steam will condense on the relatively cool inside wall of containment. Heat will be transferred to the wall and through the wall to the OCP as the condensation occurs. The condensed water will collect in the containment sump. With sufficient head, the water in the sump will overcome the pressure differential into the reactor vessel and flow will be established. The flow will pass from the sump through check valves as it enters the ICP. Once in the ICP, the flow will pass through a screen to filter any debris and another check valve just before entering the reactor vessel. Heat is transferred from the containment external surface via free convection and boiling. This process will continue indefinitely as long as there is water in the OCP.

As the water boils, the level in the pool will drop. Float valves, which are in lines connecting the OCP to the UHS tanks, will automatically open allowing water from the UHS to refill the OCP. Connections to each UHS tank allow for the addition of water to maintain water in the pool indefinitely. This strategy is much like that of the AP1000 plant in that water condenses on the inside of containment as a result of the wall being cooled by external water.
VI. ACCIDENT SCENARIOS

The passive safety system functions described above work together during various initiating faults to safely shutdown the plant. The plant responses to an extended station blackout and a LOCA event have been evaluated; the sequence of events for each is discussed below. In both scenarios the fault occurs during normal full power operation (See Figure 2).

VI.A. Extended Station Blackout

In the unlikely event of an extended station blackout where both on-site and off-site power is lost, the control rods drop, as a result of the loss of power, shutting down bulk power production. The reactor coolant pumps, the main feedwater pumps and recirculation pumps also lose power as well and coast down. Natural circulation is established in the RCS and secondary side of the steam generator with the loss of forced flow. Since no additional inventory is being added to the steam drum, the drum level begins to drop (see Figure 3).

Eventually, the inventory in the secondary side of the steam generator boils off completely. Prior to this occurring, a protection system signal will actuate the valves below the CMTs. Cold CMT water is then free to flow into the RCS. Hot RCS water would enter the CMTs and be cooled as a result of heat transfer to the secondary side. The CMT heat exchangers receive cooling water via natural circulation from the above ground UHS tanks. As heat is added to the UHS tanks, temperature begins to rise to the boiling point. Each UHS tank is sized to accommodate decay heat removal from the core and spent fuel pool for at least 72 hours. Connections to each UHS tank allow for the heat removal to continue indefinitely (See Figure 4).
VI.B. Loss of Coolant Accident

In the unlikely event of a loss of coolant accident (e.g., DVI line break), the RCS inventory decreases and as a result the RCS pressure and pressurizer water level decrease. As pressure drops, the pressurizer heaters will actuate in an attempt to maintain pressure. Water level and pressure continue to drop until a protection system setpoint is reached. Upon expiration of applicable delays, the rods enter the core significantly reducing the heat generated. Shortly after reactor trip, redundant isolation valves between the steam generator tubes and the steam drum are closed and a protection system signal would be generated to open the valve below the four CMTs.

With the CMT valves open, the relatively cold, highly borated CMT water would flow into the RCS. Hot RCS water would enter the CMT and be cooled as a result of heat transfer to the secondary side. The CMT heat exchanger receives cooling water via natural circulation from the above ground UHS tank.

Some of the RCS inventory provided by the break to containment will condense; the condensate will collect at the bottom of containment. As the pressure in containment increases, a disk in the ICP tank will rupture to equalize the ICP and containment pressures (See Figure 5).

As additional inventory is released to containment and CMT heat transfer occurs, the water in the UHS tanks and the OCP begins to boil. As RCS water level reaches the elevation of the CMT balance lines, steam enters the lines and breaks the natural circulation of liquid water. The CMT then drains cooling water to the reactor vessel (See Figure 6).
With the ICP tanks and CMTs drained, the water level in the containment sump will be high enough to overcome the pressure differential into the reactor vessel and flow will be established. The water heated to steam by the core will exit the reactor vessel through the vent path established through the ADS valves. Some steam will also condense in the CMT heat exchanger tubes and return to the reactor vessel. Outside of the reactor vessel, the steam will continue to condense on the containment wall with the condensate returning to the sump. This process will continue indefinitely as long as there is water in the OCP.

The OCP will continue to boil, as it does, the water level will drop until the float valves in the lines connecting the OCP to the UHS tanks automatically open. Once opened, water from the UHS will refill the OCP. Each UHS tank is sized to accommodate decay heat removal from the core and spent fuel pool for at least 72 hours. Connections to each UHS tank allow for the addition of water to maintain water in the pool indefinitely (See Figure 8).

Preliminary analysis results of a LOCA event for the Westinghouse SMR are described in detail in Ref. 2.

VII. CONCLUSIONS

The Westinghouse SMR is taking the passive safety principles of the AP1000 plant to the next level of safety (See Table I). As described, the systems safely shut down the nuclear reaction, remove decay heat following shutdown, assure that the reactor core remains covered with water to maintain effective cooling and provide long-term cooling and shutdown during LOCA and Station Blackout events.

<table>
<thead>
<tr>
<th>Function</th>
<th>AP1000</th>
<th>Westinghouse SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Term Reactivity Controls</td>
<td>Control Rods</td>
<td>Control Rods</td>
</tr>
<tr>
<td>Long-Term Reactivity Controls</td>
<td>2 CMTs</td>
<td>4 CMTs</td>
</tr>
<tr>
<td>Decay Heat Removal</td>
<td>1 PRHR / PCS</td>
<td>4 CMTs w/ integral heat exchangers</td>
</tr>
<tr>
<td>Long-Term Makeup Water Supply</td>
<td>1 iRWST / Sump</td>
<td>2 ICP Tanks / Sump</td>
</tr>
<tr>
<td>Ultimate Heat Sink</td>
<td>PCS (72 hours)</td>
<td>2 UHS Tanks (72 hours each)</td>
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</table>

ACKNOWLEDGMENTS

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ACRONYMS

- ADS        Automatic Depressurization System
- CMT        Core Makeup Tank
- CRDM       Control Rod Drive Mechanism
- DVI        Direct Vessel Injection
- ICP        In-Containment Pool
- iRWST      In-Containment Refueling Water Storage Tank
- LOCA       Loss of Coolant Accident
- OCP        Outside Containment Pool
- PCS        Passive Containment Cooling System
- PWR        Pressurized Water Reactor
- RCS        Reactor Coolant System
- SMR        Small Modular Reactor
- UHS        Ultimate Heat Sink

REFERENCES
