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SuperSafe Reactor© (SSR): A SUPERCRITICAL WATER-COOLED SMALL REACTOR

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ABSTRACT – A new small modular reactor (SMR) is presented for a 300 MW(e) nuclear generating station, which is referred to as the SuperSafe Reactor© (SSR). The SSR is a smaller version of the Canadian supercritical water-cooled reactor (SCWR), which is designed to operate at supercritical conditions (pressure of 25 MPa and fluid temperatures of up to 625ºC) at the turbine inlet with a high cycle efficiency of greater than 45%.

The supercritical turbine technology and associated components used in the balance of plant are similar to and derived from existing supercritical fossil-fired plants. To avoid a large pressure vessel subject to supercritical water pressures and for enhanced safety, the reactor core consists of multiple fuel channels, which are submerged in a subcooled heavy-water moderator pool inside a low-pressure calandria vessel. Each fuel channel consists of a pressure tube, a ceramic insulator and a fuel bundle assembly. Energy from nuclear fission at normal operating conditions is used to heat the light water coolant to the supercritical state so that very high thermal efficiencies can be achieved. To provide inherent safety, the moderator provides additional cooling to fuel channels under postulated accident scenarios. This design feature also enables the use of a natural circulation flashing-flow driven passive moderator cooling. Another inherent safety feature of the proposed design and a major safety goal is to achieve a passive "no core melt" configuration for the channels and fuel.

1. Introduction

The supercritical water cooled reactor (SCWR) is one of six candidate designs selected by the Generation-IV International Forum (GIF) to examine new design concepts. Employing the existing supercritical water technology used in coal plants for the balance-of-power systems, the SCWR design effort focuses mainly on the core configuration to generate supercritical steam, closely matching the conditions found in existing and planned high-pressure turbine designs (thereby markedly increasing the thermal efficiency compared to the conventional nuclear power plants and coming close to 50%). AECL Chalk River Laboratories is developing a 1200 MWe SCWR, which has evolved from the well-established pressurized-channel type CANDU® reactor. The general concept was described in [1] and a smaller version of this reactor design, named SuperSafe Reactor© (SSR), was proposed in [2]. The present paper describes the latest core design and features of the SSR.

2. Reactor core

The proposed reactor core design, shown in the Figure 1 schematic, uses a pressurized inlet plenum (at the top) attached to a low-pressure calandria vessel (at the bottom) that contains heavy water moderator surrounding some 108 pressure tubes, this number being flexibly chosen to match the desired power output. Each tube contains full length fuel assemblies, with the reactor using batch refueling and oriented vertically for the ease of refueling. A simplified schematic is given in Figure 1. The light water coolant enters the inlet plenum through inlet nozzles and then enters the fuel channels that are connected to the tubesheet at the bottom of the inlet plenum in a leak-tight manner. Inlet conditions are subcritical at a pressure of about 26 MPa and a temperature of 350ºC [1]. The fuel assembly is a re-entrant or double flow pass configuration, with a central flow channel, in which the coolant is forced vertically downwards. At the bottom of the fuel channel, the subcritical flow exits the flow tube, changes flow direction and flows up through the fuel elements. While flowing up, the coolant gradually becomes supercritical with the heat generated by the fuel. The supercritical water exiting the fuel channels mixes in the outlet plenum, which is located inside the inlet plenum, at an average temperature of up to 625ºC (depending on material capabilities) and at a pressure of 25 MPa. The outlet temperature is chosen specifically to match the thermodynamic and flow conditions used for existing SCW turbine designs in thermal power plants.

The preferred inlet plenum material is forged SA508, a quenched and tempered vacuum-treated steel, with the bottom of the inlet plenum, called the tubesheet, machined to form a square array of holes about the same size as pressure tubes. The outlet plenum, located within the inlet plenum, sees approximately a 0.5 MPa pressure differential, which is equivalent to the pressure loss of the coolant in the fuel assembly. It is likely to be made from a creep resistant Ni-based superalloy used in existing SCW boilers.

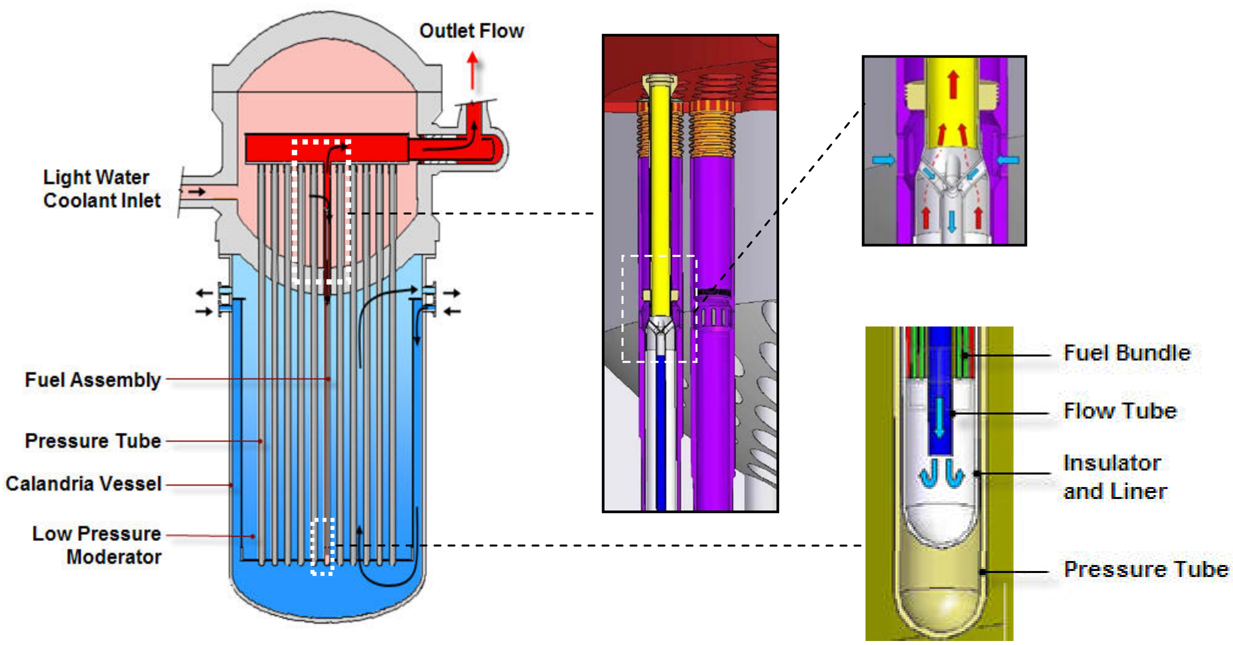
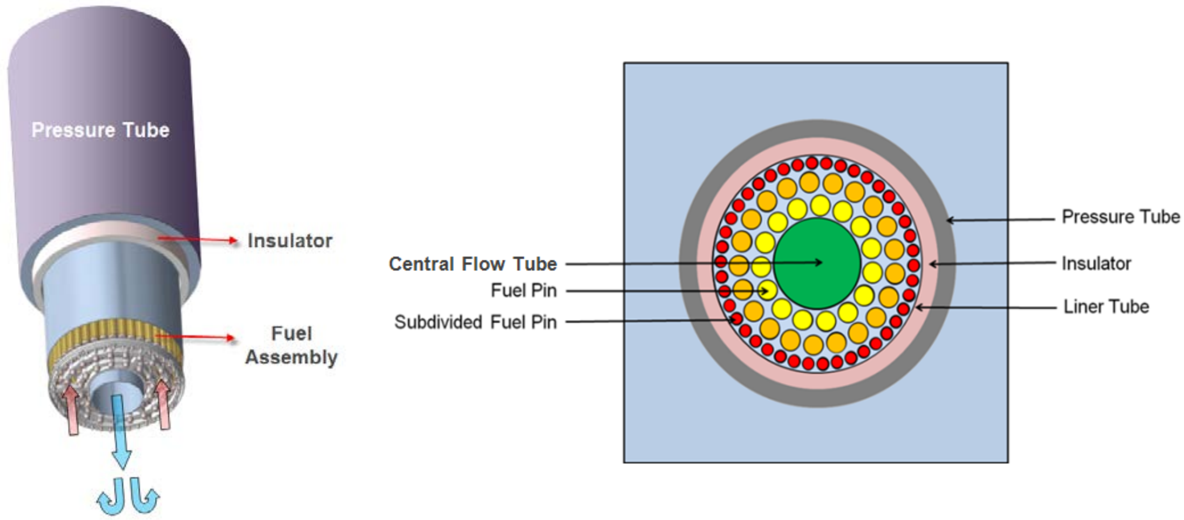


Figure 1 SSR Reactor Core and Flow Streams

The fuel channels are small diameter (181.4 mm OD) pressure tubes that are in direct contact with the moderator, and for optimal physics purposes are made from a zirconium alloy with low neutron cross-section. A ceramic insulator, yttrium-stabilized zirconia (YSZ) with excellent thermal resistance, is placed between the fuel bundles and the pressure tube to maintain the pressure tube temperature close to the cold moderator temperature. Since the physics, thermal hydraulics and mechanical aspects are coupled, fuel bundle optimization studies (which are ongoing) must ensure that burn-up, enrichment, reactivity coefficients, axial and radial power profiles, fuel and cladding temperatures, linear power rating, reactivity, and stability are well behaved during the fuel cycle [1], [3]. The current fuel bundle and nominal fuel channel dimensions are shown in Figure 2.



(a) Fuel Channel (b) Fuel Bundle

Figure 2 SSR (a) Fuel Channel and (b) Fuel Bundle Cross Section

3. Advance safety concepts

Two major principles are being followed: ensure passive natural circulation and radiative cooling for the reactor core for indefinite time intervals in any postulated accident; and provide assured ultimate heat sinks (UHS) which avoid fuel melting and minimize any consequent activity release.

3.1 Negative reactivity coefficients

The SSR fuel is specifically designed by choice of enrichment, burnable poison and fuel-to-moderator ratio to exhibit a negative coolant void reactivity coefficient and negative overall power coefficient throughout the residence time in the core [1]. Therefore, a large power pulse will automatically reduce the reactivity and limit the peak power below an acceptable level.

3.2 Passive safety

As in most other pressure-tube type nuclear reactors, the SSR has a low-pressure moderator that surrounds the high-pressure fuel channels. This configuration provides a unique safety enhancement in that unwanted excess heat (i.e. decay heat at accident conditions) can be independently removed by the surrounding moderator as well as by the circulation of the primary fluid. Hence, the SSR is equipped with two independent cooling systems. The first safety system is the primary-coolant safety system (PCSS) which is similar to the safety systems proposed for advanced boiling water reactors. The PCSS is intended to have the capability to remove decay heat through natural circulation and floods the reactor core with emergency coolant in case of any LOCA. The second (diverse and independent) cooling system is the moderator safety system (MSS) that provides a new passive layer of safety for the defense-in-depth approach. In all accident scenarios, the PCSS activates first and prevents the fuel from overheating. For the extremely unlikely scenario of the total loss of coolant combined with the loss of PCSS function, the moderator-based MSS is activated. Both the coolant-based and moderator-based cooling systems are designed to remove 100% decay heat independently and passively.

3.3 No-Core melt concept

One key safety goal is to avoid core (i.e. fuel and fuel cladding) melting using moderator passive heat removal, even assuming complete loss of all primary coolant flow, emergency cooling systems, and station power supplies. This is possible in the SSR because the unique feature of the distributed channel core is that the decay heat can be removed by passive radiative cooling from the fuel bundle to the insulator, and then thermally conducted out to the pressure tube and moderator which are still at low temperature. Analyses show that close to 2% of decay heat power can be removed without exceeding clad and fuel melting temperatures in the hottest (inner ring) of fuel pins [4]. The safety limit is then placed on both channel power and peak pin rating to attain this goal. Hence, as long as pressure tubes and moderator are intact, fuel element temperatures will not reach melting temperature. In the SSR this is called the "no-core melt concept."

3.4 Passive and very long-term heat removal

The goal is to provide passive UHS for an indefinite time. The long-term heat removal strategy of SSR is to use the combination of a large water reservoir and air coolers as heat sinks in the event of a complete station blackout and loss of all emergency power supplies. This is achieved by maintaining sufficient water in the containment as a heat sink until the decay power is reduced to 0.5% of full power (24 hours after blackout) at which point air cooling itself becomes sufficient to remove decay heat indefinitely.

3.5 Leak-before-break and severe accident management

It is best to prevent accidents. To prevent the worst-case scenario of a complete pressure-tube rupture, two independent and diverse leak/crack detection systems are engaged to ensure pressure tube leaks will be detected before a large break. Upon detecting the leak, reactor will be shutdown and depressurized to prevent pressure tube rupture. If a pressure tube ruptures, its effects will be mitigated by the calandria vessel design, such that the calandria vessel will remain intact even when multiple pressure tubes are ruptured.

4. Summary and conclusions

A conceptual small supercritical water cooled pressure-tube reactor design is presented. When compared to other pressure-tube reactors, this concept offers simpler mechanical design, enhanced safety and reduced operating and capital cost. Refinement of this conceptual design via optimization of the fuel, safety and layout is proceeding.

5. References

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