Supercritical Water-Cooled Reactor (SCWR) Development through GIF Collaboration

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Abstract. The Generation IV International Forum (GIF) was established to conduct collaborative research and development (R&D) that will lead to the development of fourth generation advanced nuclear energy systems. Six concepts were selected for further development through GIF collaboration, among which the Supercritical Water-Cooled Reactor (SCWR) is the only GIF concept that uses water as coolant and is, therefore, a natural evolution of current advanced water-cooled reactor technologies. The SCWR operates above the thermodynamic critical point (374°C, 22.1 MPa). The main advantage of the SCWR is improved economics because of the higher thermal efficiency and the potential for plant simplification. Two design options are considered for the SCWR: a) pressure vessel and b) pressure tube designs. The R&D needs for assessing the technical feasibility (e.g., thermal-hydraulics, materials, water chemistry, etc.) are common to both designs, and provide valuable collaboration opportunities for countries and organizations pursuing either option. Major features of the SCWR, various conceptual designs under consideration by the GIF SCWR members, and GIF collaboration target and R&D plan are presented in this paper.

1. INTRODUCTION

According to the latest update of the International Atomic Energy Agency's annual projection of the global nuclear electricity generation capacity [1], both the low and high projections for 2030 are estimated 8% higher than last year's projections. The expectation for nuclear power has been rising due to concerns about energy supply security and global climate change. The demand for nuclear energy is estimated to further increase and diversify even after 2030.

To meet the challenges to nuclear energy in future societies, the Generation IV International Forum (GIF) was established ten years ago to conduct collaborative research and development (R&D) that will lead to the development of fourth generation, or Generation IV, nuclear energy systems. Six concepts were selected in 2002 for further development through the GIF collaboration: 1) Very-High-Temperature Reactor (VHTR), 2) Sodium-cooled Fast Reactor (SFR), 3) Supercritical Water-cooled Reactor (SCWR), 4) Gas-cooled Fast Reactor (GFR), 5) Lead-cooled Fast Reactor (LFR), and 6) Molten Salt Reactor (MSR).

The international collaboration to develop the SCWR started in 2002, when the first Information Exchange Meeting was held among several countries that had been interested in the concept and that had already started undertaking some R&D work. The provisional GIF SCWR System Steering Committee (SSC) was established in 2003 and started discussions to develop a System Research Plan (SRP) that identifies key R&D areas, projects and timelines for the multilateral development of the SCWR. In 2005, five countries signed the GIF Framework Agreement – a treaty level document that provided the mechansim by which countries could undertake research to support the development of the six GIF concepts. Following the Framework Agreement, the System Arrangement for the international R&D of the SCWR was signed in 2007, which gave a framework for collaboration among GIF members and allowed for the formalization of the SSC. The GIF SCWR SSC members are currently Canada, Euratom, and Japan with the Republic of Korea and France participating as observers. The objective of this paper is to present major features of the SCWR and its conceptual designs under consideration by the GIF SCWR members as well as GIF collaboration target and R&D plan.

2. TECHNICAL FEATURES AND POTENTIAL ADVANTAGES OF SCWR

The SCWR is the only GIF concept that uses water as coolant and is, therefore, a natural evolution of current advanced water-cooled reactor technologies. It is designed using the successfully deployed pressure-vessel or pressure-tube reactor technologies. The primary system of the SCWR is shown in Figure 1.

Operating pressure and temperature ranges of SCWR, PWR and BWR cores are compared in Figure 2. In PWR and BWR cores, reactor coolant temperature remain subcooled or saturated due to the limitation caused by abrupt degradation in heat transfer at fuel rod surfaces covered by steam. The SCWR core is operated above the critical pressure of water (22.1MPa), where reactor coolant experiences no phase change and the coolant temperature can exceed the pseudo-critical temperature, which corresponds to the boiling temperature at subcritical pressure.

The potential technical advantages of the SCWR over current water-cooled reactors are derived from the above-mentioned features as follows:

- High thermal efficiency

High temperature and high pressure of turbine inlet steam lead to high thermal efficiency. Inlet pressures of current light water reactors (LWRs) and pressurized heavy water reactors (PHWRs) are usually at around 7MPa and their temperatures are at or near the saturation temperature. Turbine inlet steam pressure and temperature of SCWR are much higher. The thermal efficiency of SCWRs is expected to be 1.2 to 1.4 times higher than that of current water cooled reactors.

- Simplification of plant system and low capacity components

Without phase change in the core, the SCWR plant system can be simplified by eliminating recirculation system and steam-water separation system in BWR, or steam generators and a pressurizer in PWR. The reactor coolant flow rate of SCWR is much smaller than that of BWR and PWR because the enthalpy rise in the core is much larger, which results in low capacity components of the primary system.

Furthermore, the SCWR incorporates advances from supercritical fossil power plant technologies that have been operating successfully for more than 40 years. The main fossil power plant technology that will be used in the SCWR is supercritical turbines that can be incorporated in a direct thermodynamic cycle to increase thermal efficiency. The R&D task for developing the balance of power (BOP) of the SCWR would be very limited or almost none. In addition, using a direct cycle at supercritical conditions simplifies the plant system and eliminates certain components, which results in significant reduction in capital cost.

These technical advantages would lead to considerable reduction of the capital cost. The construction cost of SCWR plants has been targetted at $900/kW in the GIF Roadmap [2].

The combination of advanced water-cooled reactor technology and advanced supercritical fossil technology is expected to result in a reactor concept that can be used to generate base-load electricity very economically and efficiently. This feature also makes the SCWR a very attractive concept for utilities, especially those that have experience with both water-cooled reactors and supercritical fossil plants.

The GIF has set goals for Generation IV nuclear energy systems, which are economics, safety, sustainability, and proliferation resistance and physical protection (PRPP) [2]. While the SCWR is highly rated in economics, it can also have significant improvements in the other GIF metrics. In the safety area, the starting point is to use safety features that are employed in current GenIII and GenIII+ technologies with the objective of providing further enhancements, wherever possible. In the sustainability area, the increase in thermal efficiency attributed to the high outlet temperature provides initial improvement in resource utilization. In addition, the SCWR can also be designed as a fast reactor option in the pressure vessel (due to the significant decrease in the density of water above the pseudo-critical temperature) or the option of using thorium in the pressure-tube version. Both design options provide opportunities to introduce advanced fuel cycles that aim at improving the sustainability and proliferation resistance metrics. In the area of physical protection, enhancements will be incorporated in the early design stages by incorporating lessons learnt from operating water-cooled reactors.

3. CONCEPTS OF SCWR UNDER CONSIDERATION

Current SCWR R&D efforts clearly demonstrate the flexibility of this concept and the options that are available to design a practical and viable system. For example, the SCWR can be designed with a thermal, fast, or a mixed neutron spectrum due to the significant change in water density as the temperature changes across the pseudo-critical point. In addition, the SCWR can be designed using the pressure-vessel or pressure-tube reactor technologies. These options have resulted in a number of conceptual designs. The current SCWR conceptual designs under consideration by the GIF SCWR members are as follows:

In Japan, the University of Tokyo has been developing thermal and fast spectrum concepts. These are pressure-vessel design concepts known as the Super LWR (thermal version), and the Super Fast Reactor (fast version) [3-5]. The Super LWR has a reactor internals similar to that of PWR. The clustered control rods are vertically inserted into and withdrawn from the core by the control rod drives (CRDs) mounted on the upper head. The coolant provided through the inlet nozzles mostly flows upwards into the upper dome, and then downwards into the water rods of all fuel assemblies (FAs) and into the active channels of the peripheral FAs as schematically shown in Figure3. The Super Fast Reactor core has a very high power density of around 300MW/m^3. Negative void reactivity is achieved by adopting solid moderator in the blanket assemblies. The overview of Super Fast Reactor is shown in Figure 4. Another thermal spectrum concept is under development through collaboration among academic, research, and private organizations in Japan [5, 6]. The CRDs are mounted on the vessel bottom, and the fuel assemblies and cruciform control rods similar to those of BWR are adopted. The core outlet coolant temperature is targetted at 560°C, which will enable elimination of moisture separators or moisture separator heaters and utilization of a combined high and intermediate-tubine, resulting in a more simplified and compact plant.

The High Performance Light Water Reactor (HPLWR) is under development in Europe [7]. It is a pressure vessel type reactor similar to a PWR with control rods supplied from the top, but with a higher system pressure of 25 MPa. Figure 5 illustrates the latest design concept. The core includes additional moderator water in water rods inside assemblies and in gaps between assembly boxes to provide a thermal neutron spectrum. Different from current LWR design, the coolant is heated up in three steps from 280°C at reactor inlet to 500°C at core outlet. Mixing chambers above and underneath the core, which are foreseen between each heat up step, eliminate hot streaks and keep the peak cladding temperature below 630°C. The target thermal core power is 2300 MW, which results in a net electric power of 1000 MW. More details are reported in [8]. The containment and safety system design, shown in Figure 6, is based on latest BWR concepts with a pressure suppression pool and core flooding pools, including active and passive residual heat removal systems.

Canada is persuing the development of a pressure tube version of the SCWR, which is the natural evolution of Canada's CANDU® technology. A fundamental approach in developing the CANDU-SCWR is to utilize proven advances in supercritical fossil turbine technology to specify reactor outlet temperature and pressure. This approach led to the selection of 25 MPa and 625°C as reference core outlet parameters [9]. The proposed CANDU-SCWR reactor adopts the advanced thorium fuel cycle as reference. It maintains the CANDU feature of separating coolant and moderator. The low-pressure and slightly subcooled heavy-water moderator fascilitates the introduction of a flashing-driven passive loop cooling system to enhance further the reactor safety characteristics. The increase in coolant temperature poses challenges to pressure-tube material. An advanced fuel channel design, shown in Figure 7, is being introduced to reduce the pressure-tube temperature and yet withstand the supercritical coolant pressure. In addition, this design would allow the moderator to continue acting as a backup heat sink (as in the current CANDU fleet). The thermal efficiency of the CANDU-SCWR reactor can further be enhanced through the adoption of the reheat-cycle option (the technology has also been proven in fossil plants) [10]. Furthermore, implementing the reheat cycles allows the possibility of combined power and heat applications in the plant. Figure 8 shows the overview of CANDU-SCWR. The development of the CANDU-SCWR is currently under development through collaborations between Atomic Energy of Canada Limited (AECL), federal laboratories, Natural Sciences and Engineering Research Council (NSERC), and universities.

SCWR-SM is a pressure vessel design under development in the Republic of Korea that utilizes a solid ZrH_2 moderator. A conceptual design of a 1400 MWe reactor core has shown reasonable results although a further refinement is definitely needed [11-15]. The idea of a solid moderator has been introduced since it was believed to simplify the coolant passage in a reactor upper dome. The shape of the solid moderator is basically a cross type and another improved version is being studied. As shown in Figure 9, the fuel assembly has a 21x21 fuel rods array with a pitch of 1.15 cm, and the fuel assembly pitch is 25.15 cm, including a 1 cm gap between the fuel assemblies. The fuel assembly is composed of 300 fuel rods, 25 cruciform-type solid moderator pins, and 16 single solid moderator pins. The conceptual SCWR core contains 193 fuel assemblies with a typical four-batch fuel-loading pattern. The design limit for the maximum linear heat generation rate is assumed to be 390 W/cm, which is the same as that of a light water reactor, while the average linear heat generation rate of the conceptual SCWR core is 144.2 W/cm. The power peaking factor limit associated with the maximum linear heat generation rate is determined to be 2.7. A conceptual design study for a 1700 MWe core has been started recently with a sensitivity study [15]. Figure 10 shows a concept of 1700 MWe core design.

In addition to the concepts developed by the GIF SCWR members, a mixed core design (SCWR-M) is being developed at Shanghai Jiao Tong University in China [16]. It is a pressure vessel concept, and the core is devided into thermal-spectrum and fast-spectrum zones. The coolant entering the pressure vessel flows downwards through the thermal zone at first and then flows upwards through the fast zone.

The parameter ranges of the above design concepts are summarized in Table 1.

4. GIF COLLABORATION TARGET AND R&D PLAN

The above design concepts have very similar challenges in combining existing advanced water-cooled reactor technologies with supercritical fossil technologies. This provides opportunities for collaboration in common R&D areas that are needed for any of the SCWR conceptual designs. For example, challenges in the selection of materials for the core components and the specification of suitable water chemistry require significant R&D that is common to all designs. In addition, R&D will be needed in other areas such as thermal-hydraulics and safety to extend the range of existing data to supercritical conditions. New or upgraded facilities that operate at supercritical conditions will be needed to perform in-core and out-core tests to produce data and information needed for design and licensing.

The SCWR SSC has been established to promote the collaborations in common R&D areas and has set an aggressive target to enable a small size prototype reactor to be in operation after 2020. This target requires that essential R&D be completed by around 2020, and recognizes that some confirmatory work would be completed during the construction phase of the prototype.

The critical-path R&D projects required to establish the viability of the baseline SCWR that will meet future capital and market cost targets are identified as follows:

- System integration and assessment—Definition of a reference design(s) that meets the Generation IV requirements of sustainability, improved economics, safe and reliable performance, and demonstrable proliferation resistance. This work will involve identification of an achievable outlet temperature based on materials and fuel performance, and linkages to proven steam cycles in supercritical fossil plants. An important collaborative component of this project is to design and construct an in-reactor fuel test loop to qualify the reference fuel design.

- Thermal-hydraulics and safety— Significant gaps exist in the heat transfer and critical flow database for the SCWR. Data at prototypical SCWR conditions are needed. The design-basis accidents for an SCWR will have some similarities with conventional water cooled reactors, but the different thermal-hydraulic behavior and large changes in properties around the critical point compared to water at lower temperatures and pressures will have to be better understood and described more fully.

- Materials and chemistry—Selection of key materials for use both in-core and out-core, for both the pressure-vessel and pressure-tube designs. A reference chemistry level will also be sought, based in large part on materials compatibility and the radiolysis behavior, which needs to be more fully described.

- Other R&D projects, which will improve SCWR performance, but are not on the critical path to the development of the baseline SCWR concept, include:

- Hydrogen production—The hydrogen production techniques that can, technically and cost-effectively, be coupled to an SCWR need to be defined and validated.

- Fuel and Fuel Cycles—The reference fuel cycle remains an enriched uranium-oxide fuel. Alternate fuel cycles that improve the sustainability metrics, and/or match the indigenous resources of a given country/utility need to be investigated.

- Fast SCWR—Development of a fast-spectrum, MOX-fuelled SCWR core will require design of lattice configurations with negative void reactivity feedback, design of safety systems capable of handling much higher core power densities than for the thermal system, and development of materials resistant to radiation doses up to 100–200 dpa.

5. CONCLUSIONS

The SCWR is a water-cooled reactor that operates above the thermodynamic critical point of water. Several design options using pressure-vessel and pressure-tube reactor technologies are currently under consideration with the aim of providing a spectrum of possibilities for next generation water-cooled reactor technology. These design options are being used to define common high-priority R&D areas and projects in GIF, which gives the framework for R&D collaborations.

The SRP for the SCWR has been developed by the GIF SCWR SSC that outlines the R&D areas and requirements for the SCWR development. The target of GIF collaboration has set to complete essential R&D by around 2020 to provide sufficient information to enable the design, licensing, and construction of a prototype reactor in 2020s.

The first Project Arrangement of the international R&D of the SCWR is going to be signed soon, followed by the second one in near future. Collaborative R&D work for the SCWR development through GIF is about to start. It is expected that this collaboration will lead to commercialization of the SCWR to meet future needs for nuclear energy and to show a successful case based on the GIF development model.

ACKNOWLEDGEMENTS

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Table 1. SCWR Conceptual Design Parameter Ranges under Consideration

Parameter	Reference Value(s) [unit]
Pressure Boundary	Pressure Vessel (PV) or Pressure Tube (PT)
Neutron Spectrum	Thermal, Fast, or Mixed
Burnup (Thermal / Fast)	Up to 60/120 [GWd/tHM]
Fuel	UO_2, MOX, or thorium
Fuel Cycle	Once Through or Closed
Moderator	Light Water or ZrH_2 (PV) or Heavy Water (PT)
Coolant	Light Water
Electric Power	Up to 1700 [MWe]
Operating Pressure	25.0 [MPa]
Core Outlet Temperature	Up to 625 [°C]
Thermal Efficiency	Up to 50 [%]

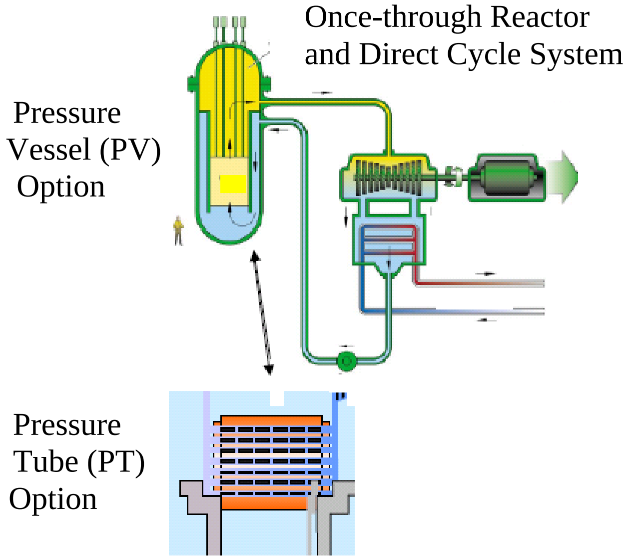

Fig. 1. Primary System of the SCWR

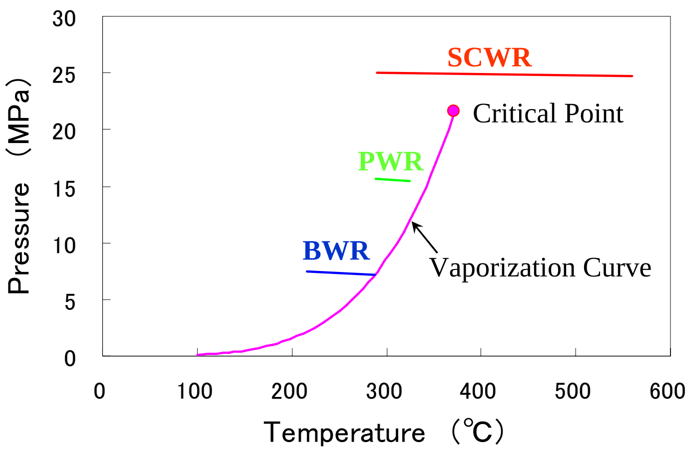

Fig. 2. Operating Pressure and Temperature Ranges of SCWR, PWR and BWR

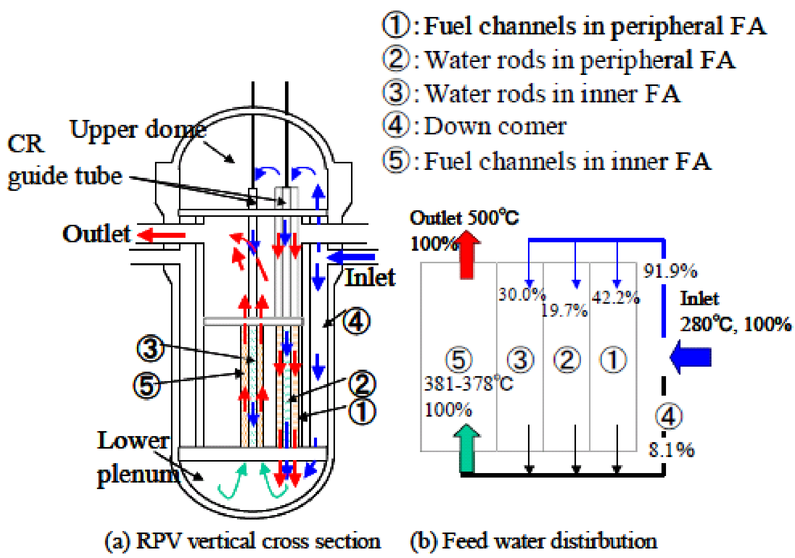

Fig. 3. Coolant Flow Scheme of Super LWR

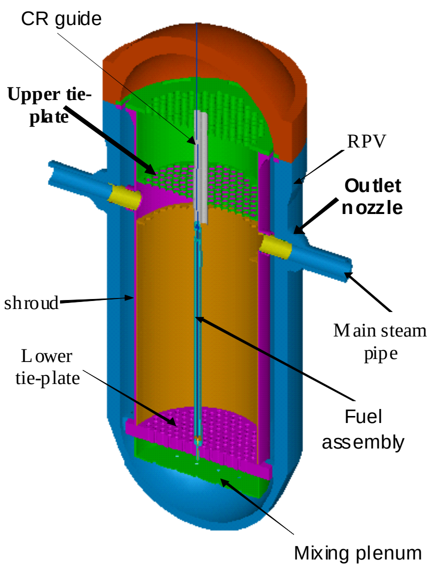

Fig. 4. Overview of Super Fast Reactor

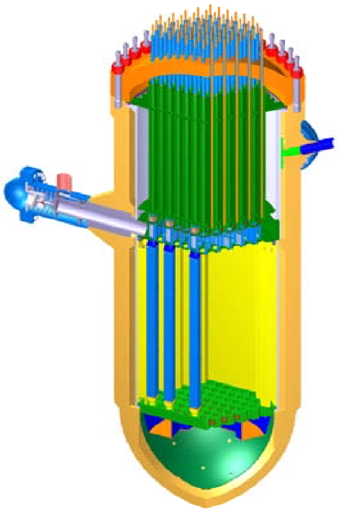

Fig. 5. Reactor pressure vessel design of the High Performance Light Water Reactor (HPLWR)

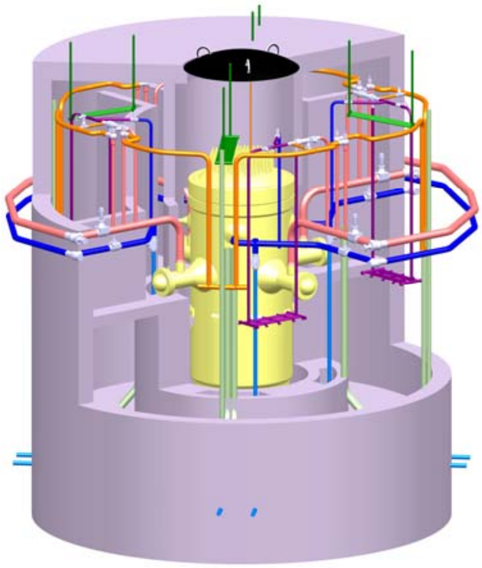

Fig. 6. Containment and safety system design of the HPLWR

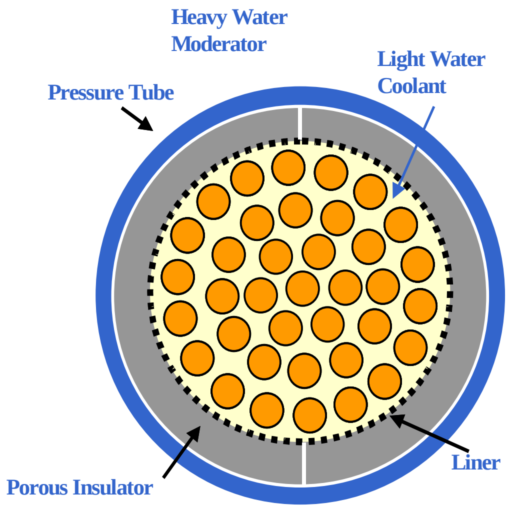

Fig. 7. CANDU-SCWR Advanced Fuel Channel Design

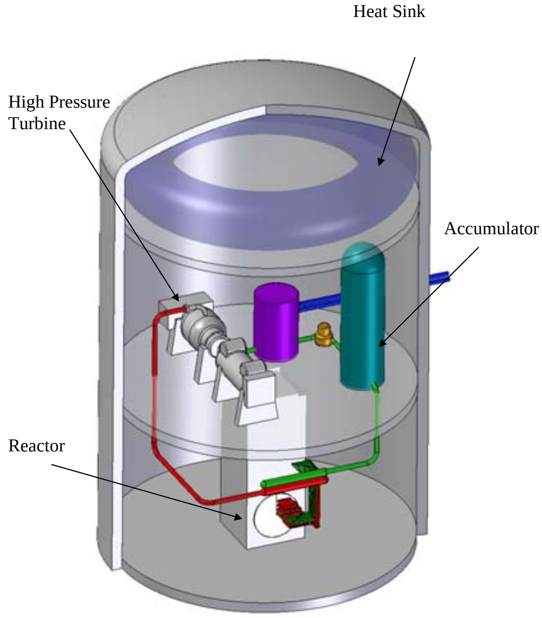

Fig. 8. Overview of CANDU-SCWR

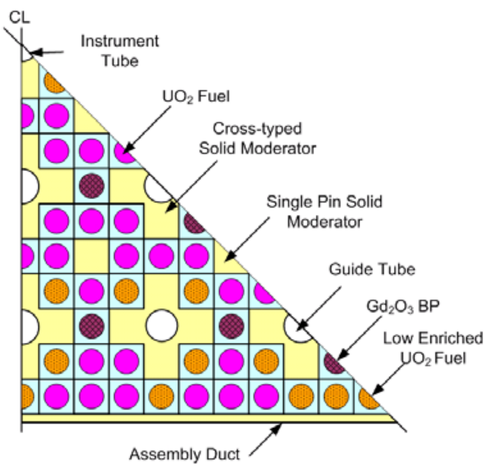

Fig. 9. Fuel Assembly Design of 1400 MWe Core of SCWR-SM

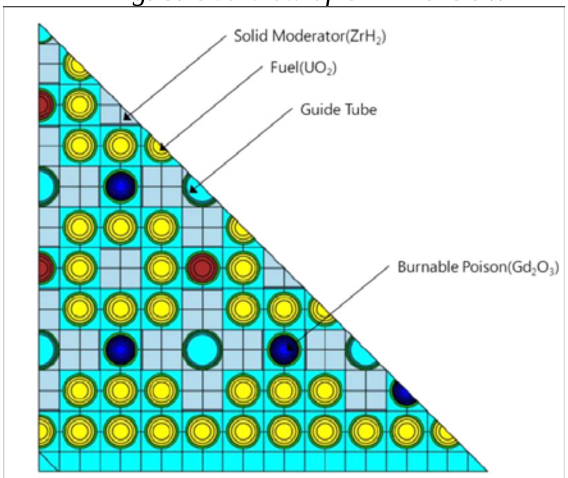

Fig. 10. Fuel assembly design of 1700 MWe core of SCWR-SM