COLLABORATIVE APPROACH IN DEVELOPING A SMALL SUPERCRITICAL WATER-COOLED REACTOR

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ABSTRACT – A joint Research and Development (R&D) project between University of Saskatchewan and Atomic Energy of Canada (AECL) is being established to develop a concept of the small Canadian supercritical water-cooled reactor (SCWR) for power generation and process heat in remote areas. This project will be led by professors at the university and supported by technology experts from AECL. It integrates student training with a significant contribution to the reactor concept development. Students from various disciplines will combine results from physics, fuel, thermalhydraulic, control, material, and chemistry analyses to develop the core and fuel channel configurations and fuel design. This project would enhance the R&D expertise and capability of University of Saskatchewan and facilitate training of highly qualified persons (HQPs) for nuclear and non-nuclear industries at Saskatchewan and in Canada.

1. Introduction

Atomic Energy of Canada Limited (AECL) is leading the R&D for the Canadian Super-Critical Water-cooled Reactor (SCWR) concept, which has evolved from the well-established pressure-tube type CANDU®[1] reactor [1]. The Canadian SCWR is designed to produce electrical energy as the main product, plus process heat, hydrogen, industrial isotopes, and drinking water (through the desalination process) as supplementary products, all within a more compact reactor building. Another potential application of the available co-generated process heat is the extraction and refining of oil sands, which is presently achieved using co-generation with natural gas turbines and process heat. The extraction and upgrading process requires: thermal power to lower the viscosity and extract the oil; electric power for separation and refining equipment; and hydrogen gas for upgrading the oil product prior to transport.

Some of the advanced features of the proposed Canadian SCWR are as follows:

- (Improved) Passive Safety - Passive decay heat removal based on natural circulation and radiation cooling is used to mitigate accident scenarios. The design goal for ensuring “no-core-melt” is likely achievable by using passive decay heat removal, thus assuring that fuel melting does not occur, even if all emergency injection systems fail, and containment integrity is not challenged;

- (Sustainable and Proliferation Resistant) Thorium Fuel Cycle – The Canadian SCWR could have the capability to operate, in addition to the uranium-based fuel cycle, with thorium-uranium-233 and thorium-plutonium fuel cycles (burning up excess plutonium) and significantly reducing spent fuel amounts and heat loads in a proliferation resistant fuel cycle;

[1] CANDU – Canada Deuterium Uranium (a registered trademark of AECL).

- (Improved) Economics – At SCW operating conditions, thermodynamic cycle efficiency increases significantly. Up to 50% increase in cycle efficiency (i.e., from about 33% to 50%) as compared to current nuclear power plants is possible, resulting in reduced generating cost.

These advanced features facilitate the Canadian SCWR to potentially meet all technology goals defined by the Generation IV International Forum (GIF).

The reference Canadian SCWR concept would generate about 1200 MW electricity. It is cooled with light water and moderated with heavy water. The advantage of the Canadian SCWR is its modular configuration, which allows adjusting the power output to meet the needs. In addition to the 1200-MW concept, a 300-MW concept has been proposed for power generation and process heat in remote areas [2]. Other than the number of fuel channels, the two concepts have a lot of similarities. Despite of the similarities, additional research work is required to support the development of the small SCWR concept.

A joint project is being established between University of Saskatchewan and AECL to develop the advanced technologies associated with the Canadian SCWR concept. These technologies are ideal for expanding the knowledge-base of professors and training the undergraduate and graduate students in a wide variety of subject areas. This paper describes the arrangement, components, and training aspect of the joint project in developing the small Canadian SCWR concept between University of Saskatchewan and AECL.

2. Small Canadian SCWR Concept

The small Canadian SCWR concept is a scaled down version of the Canadian SCWR concept being developed at AECL. It consists of 120 fuel channels that is capable to generate 300 MW(e) (the amount of power generation can be adjusted with the number of fuel channels to meet the local requirement). The reactor is operated at supercritical conditions (pressure of 25 MPa and fluid temperature of 625 ºC) at the turbine inlet with high cycle efficiencies (up to ~50%). The supercritical turbine technology and associated components used in the balance of plant (BOP) are similar to those in existing supercritical fossil-fired plants. Therefore, minimal R&D are required with the BOP side of the nuclear plant.

The small Canadian SCWR core consists of pressure-tube type fuel channels inside a low pressure calandria vessel that contains sub-cooled heavy-water moderator surrounding the fuel channels. Each fuel channel is a sub-module itself, consisting of a pressure tube and a ceramic insulator enclosed inside a stainless steel sleeve. The moderator is in direct contact with the pressure tubes, providing cooling under normal operation and postulated accident scenarios. This design feature enables the use of a flash-driven passive moderator cooling – an inherent safety feature of the proposed design. A major safety goal is to achieve a passive "no core melt" configuration for the channels and fuel, so the features and systems directly reflect this desired attribute. The use of modular channels, a low pressure moderator, completely passive decay heat removal, "walk-away" safety case, plus high plant thermal and conversion efficiency represent a unique combination of features not found in any alternate candidates and proposals of the small modular reactor (SMR) concept.

2.1 Thermodynamic Cycle

The thermodynamic cycle of the small Canadian SCWR closely matches the current advanced turbine configuration of a SCW fossil power plan, where the high-pressure SCW coolant is directly fed into steam turbines. The direct-steam cycle facilitates using existing high-pressure turbines (HPTs) operating at a pressure of 25 MPa and temperature of 625 °C, corresponding to a thermal efficiency of 48% (which represents an improvement of 40% in efficiency (at about 35%) over current LWR designs). The sizes of the high-pressure and intermediate-pressure turbines are relatively small compared to the low-pressure turbine, thus providing an opportunity to simplify the layout, with all high-pressure sections placed inside the reactor building, also improving safety. The low pressure turbine can then be located outside the main containment or reactor building. A schematic diagram of the direct steam cycle is shown in Figure 1 [3], where a moisture separator reheater (MSR) is installed to reduce the steam moisture inside the low pressure turbines.

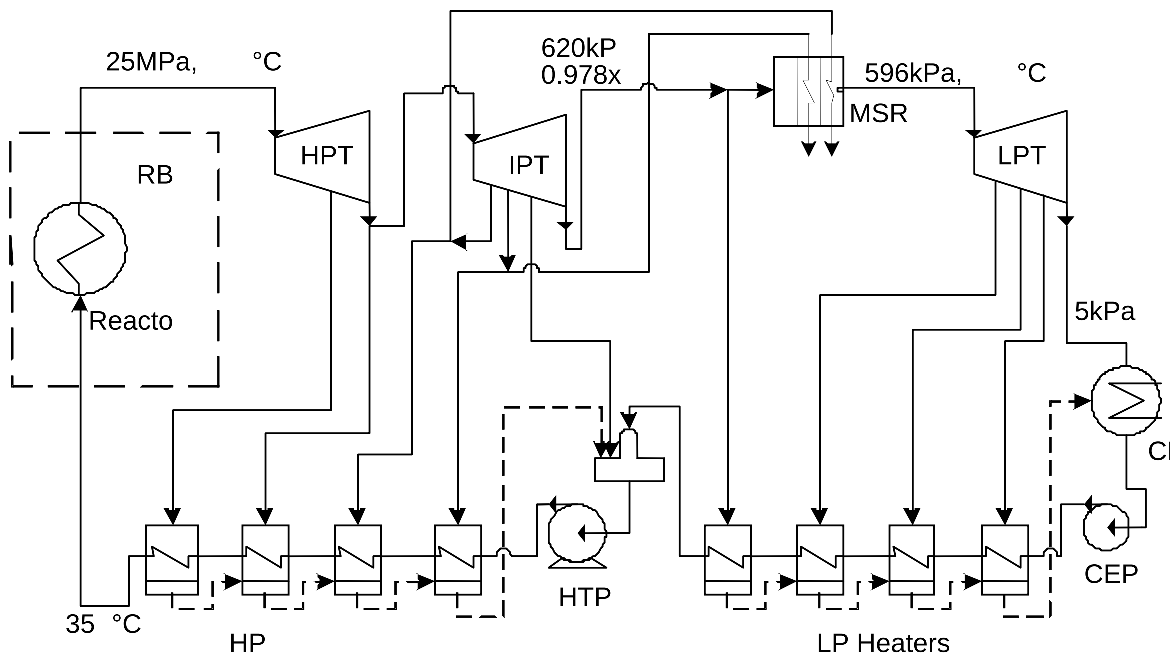

Figure 1 Schematic of Direct Steam Cycle with Moisture Separator Reheater in SCWR Plant.

2.2 Reactor Core Design

The proposed small Canadian SCWR concept consists of a pressurized inlet plenum attached to a traditional channel-type core. It differs from traditional pressure-tube heavy-water reactor designs in three major features: (1) uses an inlet plenum instead of inlet feeders, (2) adopts a vertically oriented reactor core, and (3) refuels off-line. Figure 2 illustrates the core configuration of the small Canadian SCWR.

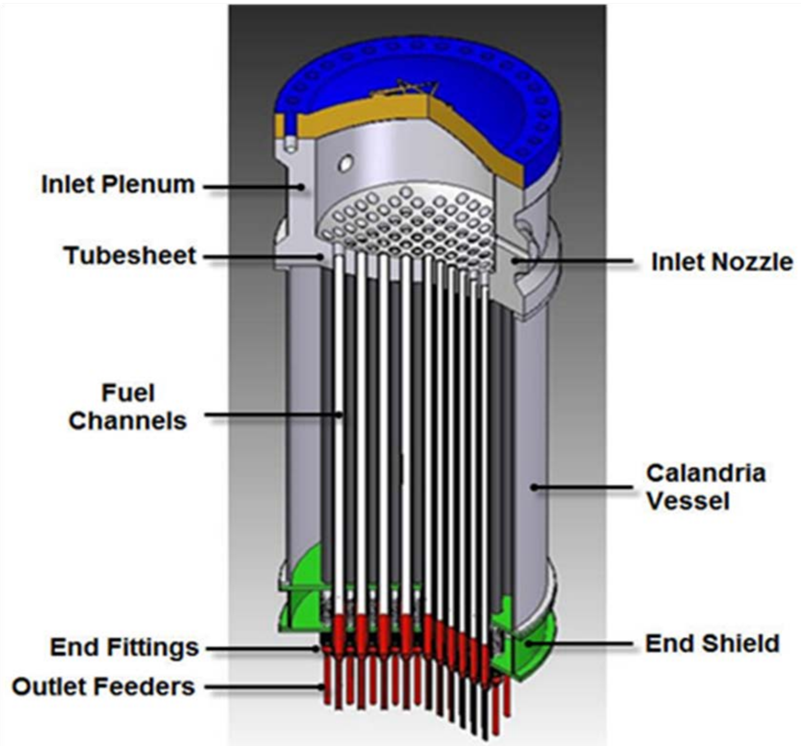

Figure 2 Schematic Diagram of the Preliminary small 300 MW(e) Canadian SCWR.

The water enters the inlet plenum through inlet nozzles (inlet pipes are not shown). It flows into the fuel channels that are connected to the tubesheet at the bottom of the inlet plenum. The water conditions at the inlet of the fuel channel are designed at the supercritical pressure of 25 MPa and the subcritical temperature of 350 ºC. As the water is forced vertically through the fuel channel, it is gradually heated up with the energy generated by the fuel. The supercritical water exiting from the fuel channels is collected in the outlet header at an average 625 ºC temperature chosen specifically to match existing and expected supercritical water turbines in thermal power plants. The reactor core inter-channel spacing (or lattice pitch) is selected to be 250 mm based on the optimisation of fuel to moderator ratio to achieve a negative void coefficient, negative power coefficient and a high fuel burnup target.

2.3 Fuel Channel

The fuel channel consists of a pressure tube and a ceramic insulator. A stainless steel clad is introduced to house the insulator avoiding loose pieces being transported to the turbine high-pressure. The fuel assembly is inserted inside the fuel channel. Despite of the high coolant temperature, the insulator maintains the pressure tube close to the moderator temperature. Figure 3 illustrates the cross-sectional view of the fuel channel configuration. In the event of a loss-of-coolant accident without emergency core cooling, heat can be removed from the fuel via passive heat rejection through the insulator into the moderator. This would maintain the fuel cladding temperature below its melting point.

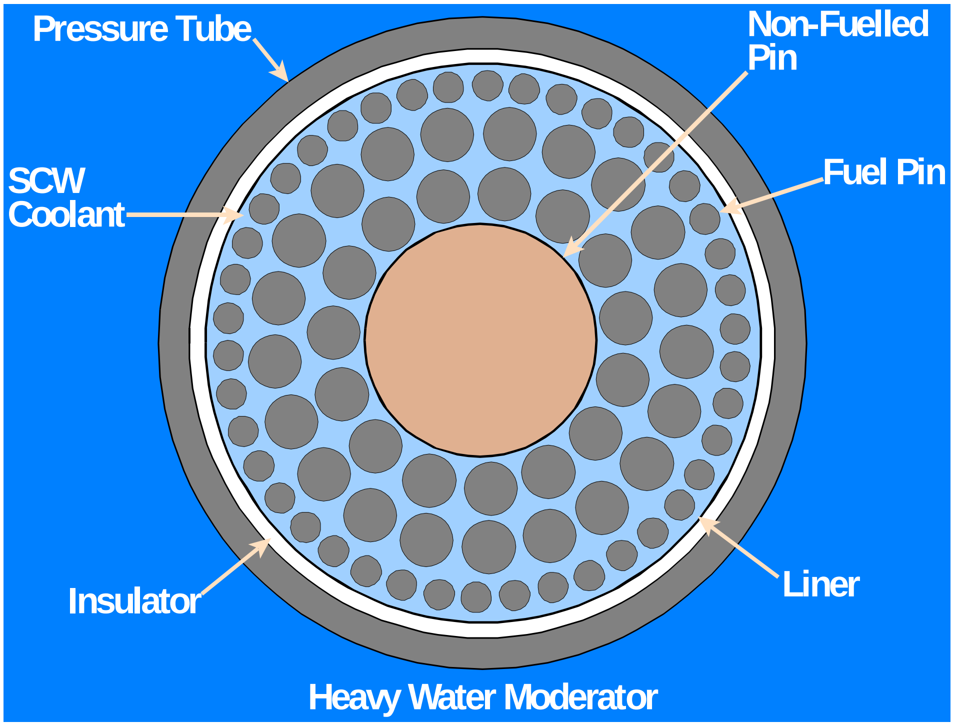

Figure 3 Schematic Diagram of the Fuel Channel for the Small Canadian SCWR.

2.4 Fuel Design

By using heavy-water moderation in a pressure-tube design provides a great flexibility in the selection of nuclear fuel. Either enriched Uranium or Thorium can be used as fuel. Recent studies of thorium-based fuel cycles in contemporary CANDU reactors demonstrate the possibility for substantial reductions in natural uranium (NU) requirements of the fuel cycle via the recycle of U-233 bred from thorium [4]. Thorium itself does not contain a fissile isotope. Neutrons must be provided by adding a fissile material, either within or outside of the thorium-based fuel. This fissile isotope is typically enriched uranium, U-233 (which is bred from an earlier thorium cycle) or reactor-grade plutonium (extracted from spent fuel).

The fuel assembly consists of three concentric rings of fuel pins and a large non-fuelled centre pin. While the optimization of the number of pins in each ring and the pin diameters is on-going, the tentative fuel assembly includes 15 pin in the inner ring, 21 pins in the intermediate ring, and 42 pins in the outer ring. The non-fuelled centre pin is mainly introduced to reduce coolant void reactivity. Several fuel cladding options (including austenitic stainless steel, ferritic / martensitic steel, and oxide dispersion strengthened steel) are being considered.

2.5 Calandria Vessel Design

The calandria vessel holds the moderator that surrounds the fuel channels. Its design pressure is set by safety considerations to completely retain and mitigate the consequences of any postulated instantaneous channel failure or rupture. An end shield with spherical steel balls is installed as the neutron reflector at the bottom of the reactor. The moderator operates slightly sub-cooled and is an effective heat sink during off-normal operation and potential accident conditions. A passive moderator cooling system is installed to remove decay heat from the fuel in a large-break loss-of-coolant event (see Figure 4). It could reject decay heat from the fuel (through the fuel channel) to the ultimate heat sink continuously avoiding challenges to fuel and clad integrities (hence no fuel melting).

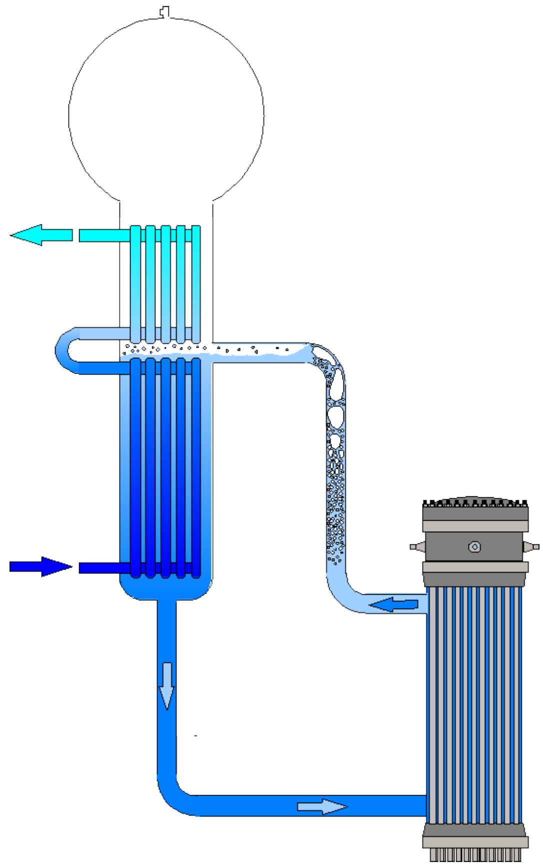

Figure 4 Schematic Diagram of the Passive Moderator Cooling System.

3. Collaboration in Developing the Small Canadian SCWR Concept

The small Canadian SCWR concept is an extension of the reference concept with primarily a reduction in the number of fuel channels matching the designed power output. This change has led to a reduction in core size and would require revisions of various core-component designs. The change in core size would affect the neutronic characteristics (e.g., larger effect of leakage for the small than large core size). A neutronic design specifically for the small Canadian SCWR must be performed. Furthermore, many components in the reference concept (and hence the small concept) can still be optimized and sensitivity assessments are required to increase confident of the current design and support future design changes.

Collaboration is being established between University of Saskatchewan and AECL to develop the small Canadian SCWR concept. AECL is the developer of the small Canadian SCWR concept and is responsible for establishing the detailed design of reactor components. University of Saskatchewan will focus on providing design and research supports and training of highly qualified persons. Researchers from the university will work together with AECL technology experts to supervise undergraduate students, graduate students, and post-doctoral fellows on various tasks of the project.

A multi-phase collaborative project between University of Saskatchewan and AECL has been planned to support the development of the small Canadian SCWR concept. The first phase focuses on the initiation of fuel-cladding-material development within two years. It consists on several analytical tasks related to reactor physics, materials and thermalhydraulics disciplines. The second phase focuses on the overall design to be completed within five years. It covers a large number of design, experimental, and analytical tasks that require knowledge in mechanical design, reactor physics, materials, chemistry, thermalhydraulics, and electronic.

Students participating in the project will work together to complete a task, integrating knowledge and skills from complementary areas of nuclear research. Graduate students will be jointly supervised directly by university supervisors and AECL technology experts. They will in turn supervise undergraduate students to work on relevant projects to their research. This innovative project provides the students with the following learning opportunities:

- The small Canadian SCWR presents aspects that are challenging to model, such as the density and temperature profiles of the supercritical water coolant.

- The use of plutonium-thorium based fuel and an advanced high-efficiency fuel channel design introduces students to advanced fuel and fuel channel designs. Other options using low-enriched uranium fuel or a mix of low-enriched uranium and thorium fuel will also be explored.

- Shared features with contemporary reactor technologies, e.g., the pressure tube and heavy water moderator combination common to pressurized heavy water reactors and the large coolant density and temperature gradients found in boiling water reactors will reinforce students' understanding of these technologies.

- Cooperation between students to achieve project goals will reinforce group work and serve as a team building exercise. Students will work in groups and will be in a position to assist each other based on similar / overlapping activities. They will be required to collaborate at various stages of the project and will have to combine their results in order to successfully complete the multi-discipline project.

3.1 Description of the First Phase of the Collaborative Project

The first phase of the collaborative project facilitates the introduction of the project to the university (i.e., project set-up phase). It is a two-year project focusing on a specific scope allowing the project infrastructure and interaction with AECL to be established at the university. This small project will train one graduate student in the Master Program and six fourth-year undergraduate students.

The objective of the first phase of the collaborative project is to examine the impact of nickel content on material corrosion behaviours. Many austenitic steels with good high temperature creep strength and corrosion resistance, such as Alloy 800H, contain high concentrations of nickel. In addition, nickel-based alloys have higher creep strength and corrosion resistance under proposed SCWR conditions than the austenitic stainless steels. However, available data show that neutron irradiation significantly reduces their tensile ductility and leads to void swelling. Nickel has a higher cross-section for thermal neutron capture than iron and chromium, reducing neutron economy and forming Helium, which can lead to embrittlement.

A proper evaluation of the material corrosion behaviours requires the operating conditions (mainly pressure and temperature), which are obtained from thermalhydraulics calculations. With the change in local power and flow conditions, the temperature of fuel cladding varies around and along the fuel pin. While a complex modelling of flow and enthalpy distributions in the fuel assembly is possible using a subchannel code, a simplified one-dimensional model of the fuel assembly is proposed to establish the axial cross-sectional-average cladding-temperature distribution.

The large density variation along the fuel assembly in the fuel channel of a small Canadian SCWR affects considerably the neutronic characteristic and hence the power and cladding-temperature distributions. A neutronic calculation is therefore required to establish the power distribution accurately in support of the thermalhydraulics calculation. AECL will provide the executable WIMS-AECL code to students for performing the neutronic analyses. As indicated previously, the nickel content in the cladding material will also have an impact on neutronic characteristics of the reactor core. Therefore, an iterative approach must be applied in the project to understand the overall impact of nickel content on material corrosion behaviours. Figure 5 illustrates the inter-relationship between disciplines required to complete the project.

The final output from the project, a report comparing evaluating the effects of nickel content in the fuel cladding material based on physics/neutronics, thermalhydraulics and materials performance-based metrics, will be a significant contribution to the development of the small Canadian SCWR, and to SCWR technology in general.

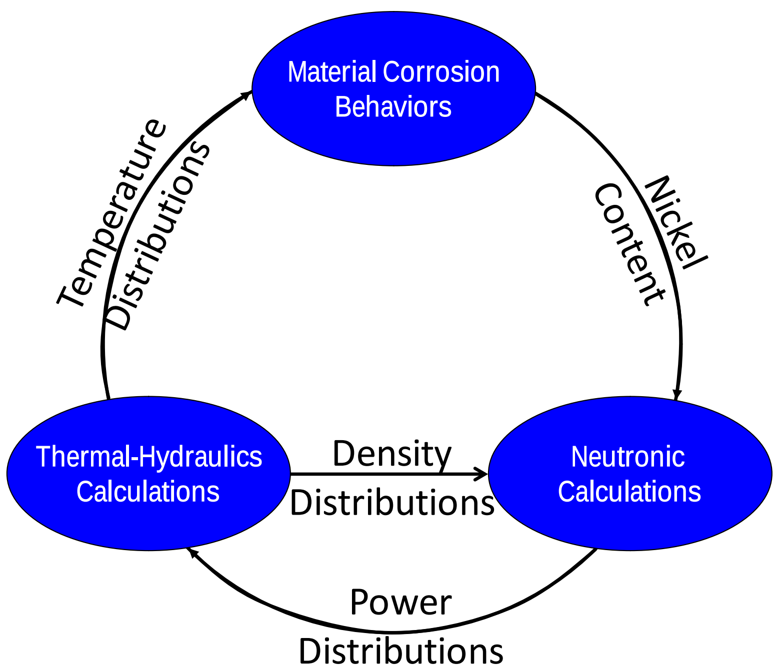

Figure 5 Inter-Relationship between Disciplines in Establishing the Impact of Nickel Content on Material Corrosion Behaviours.

3.2 Description of the Second Phase of the Collaborative Project

The second phase of the collaborative project will cover all aspects of the small Canadian SCWR concept development within five years. It consists primarily of analytical studies supporting the in-core and out-of-core component designs, neutronic design, fuel design, and safety-system design.

Experimental studies will also be needed to enhance the confidence of the design calculations and the understanding of phenomena. Graduate students enrolled in the Master or Ph.D. Program will carry out most of the design calculations and will be supervised jointly by university researchers and AECL technology experts. These graduate students will in turn supervise undergraduate students working on subtasks relevant to their research.

3.2.1 Component Conceptual Design

The core of the small Canadian SCWR concept is smaller than that of the reference design. Its structure, therefore, must be designed although the experience gained from the reference core design is applicable and could expedite the process. Several key items of consideration are the inlet plenum, the calandria vessel, inlet and outlet pipings, the moderator cooling system, containment, and the header configuration.

3.2.2 Neutronic Conceptual Design

The core-size reduction will affect the neutronic characteristics of the small Canadian SCWR concept. A full neutronic conceptual design is required to establish the fuel composition, burnups, and power distributions. As indicated previously, a mix of thorium and plutonium is adopted as the reference fuel composition. Two sensitivity studies are proposed to examine two other options: slightly enriched uranium fuel and a mix of slightly enriched uranium and thorium fuel.

3.2.3 Fuel Conceptual Design

The fuel assembly and fuel-element designs for the small SCWR concept are the same as those for the reference SCWR concept. Therefore, no additional analysis is anticipated. Nevertheless, selected supporting analyses on cladding material development and fuel optimization are planned to expedite the fuel design process.

3.2.4 Safety-System Conceptual Design

The configuration of the safety-system conceptual design for the small Canadian SCWR concept is similar to that for the reference concept. Additional sizing calculations are needed to fit the system into the containment.

3.3 Infrastructure Enhancement

Experimental studies will be required to support design calculations and expedite material developments. Several experimental facilities are available at University of Saskatchewan but are designed for subcritical pressures. A feasibility study will be performed to enhance these facilities for experiments at supercritical pressures. Furthermore, additional facilities may be needed to be constructed for new experiments.

4. Conclusions

- A collaborative project is being established between University of Saskatchewan and AECL to develop the small Canadian SCWR concept for power generation and process heat in remote areas. It integrates innovative development and student training in multi-disciplinary technology.

- The project is separated into two phases focusing on the material-corrosion behaviours and overall conceptual design. Each phase requires active participations of university researchers and AECL technology experts, who will supervise directly graduate students participating in the project, who will in turn supervise undergraduate students.

- This project would enhance the R&D expertise and capability of the university and facilitate training of highly qualified persons (HQPs) for nuclear and non-nuclear industries at Saskatchewan and in Canada.

5. References

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