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Review Design and Material Selection of Fuel Cladding Materials for Possible Further Enhancement

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**Contents**

Executive Summary…………………………………………………………………………….3

Purpose of this Project Description……………..…………………………………………….4

Need for the Project……….………………………………………………………………...…4

Suitability of Supercritical Water Reactor Fuel Cladding…………………………………..5

Design Criteria……..……………………………………………………………………………5

Proposed Fuel Cladding Design

* Swelling………………………………. ………………………………………….….....6
* Mechanical Strength…………………………………………………………….……..6
* Mechanism…………………………………………………………………………......7
* Lifetime of Fuel versus Cladding Material………………………………………...…7
* Corrosion Resistance……………………………………………………………….…8
* Heat Transfer………………………………………………………………………...…8

Regulatory…………………………………………………………………………………….…9

Conclusion…... ……………………………………………………………………………..…..9

Project Schedule……………………………………………………………………………....10

Acronyms……………………………………………………………………………………….11

References………………………………………………………………………………….….12

**EXECUTIVE SUMMARY**

In the 21st century the demand of electric power is still in the uprising, especially in developing countries such as China and India. To satisfy these power needs, countries have looked towards the Generation IV (Gen IV) nuclear reactors but require further design and investigation before decisions can be made. The benefits of the Gen IV nuclear reactor design are they are more efficient at utilizing the energy from the nuclear fuel pellets and also produce less nuclear waste than older models. Among all the Gen IV nuclear reactor designs, the Supercritical Water Cooled Reactor (SCWR) is shown to be the most promising due to its system simplicity and high efficiency compared to other Gen IV reactors. However due to the extreme heat and pressures that the SCWRs produce and operate under, older generation components are not compatible. In this project students will design and investigate the requirements of nuclear fuel cladding that will suitable for the SCWR design.

**PURPOSE OF THIS PROJECT DESCRIPTON**

The demand for an efficient, cleaner and more environmentally friendly power has been growing continuously over the last century. As a response to this, countries have been spending money on the research and development of nuclear reactors with a hope of developing a nuclear power plant that has a higher thermal efficiency and lesser impact on the environment. To improve the efficiency of power generation, Generation IV reactor concepts utilize higher core temperatures. Canada’s contribution to the Generation IV International Forum (GIF) for next generation reactors is to develop the Supercritical Water reactor (SCWR) concept. Several designs have been developed, all of which feature high temperature and pressure in the fuel channels. These conditions then act on the fuel cladding.

For Generation III reactors, the performance requirements of the cladding are well established. However, the suitability of these requirements for materials at the higher temperature and pressure conditions expected in an SCWR needs to be assessed. An investigation of alternate materials, such as SiC, Inconel, and 304 stainless steel, should be performed to determine their suitability as cladding materials in an SCWR.

In this thesis project, performance requirements for cladding in an SCWR will be developed, and the properties and characteristics of a candidate for cladding materials will be identified. The materials will be evaluated against performance factors to identify strengths and weakness of the materials and a preferred material will be recommended.

**NEED FOR THE PROJECT**

Supercritical Water Reactors function with high temperatures, neutron flux and pressure in the fuel channels, this contributes to high thermal efficiency and decrease in harmful effects to the environment when compared to older models. The fuel cladding needs the ability to withstand high temperature and pressure as well as be corrosion resistant and avoid stress cracking. It also needs to be resilient to irradiation induced creeping and swelling from fuel pellet expansion. The SCWR has many features that show the direction of the new generation of reactors and also why there needs to be more research into the fuel cladding. Also, why the newer generation models will be producing less waste, it is not negligible and will still need to be dealt with like any other similarly classed radioactive waste.

This proposed project will investigate the designs of nuclear fuel cladding in a SCWR.  The objective is to have a cladding material which can function in the Gen IV reactors and can be resistant to all the forces it may experience.

**SUITABILITY OF SUPERCRITICAL WATER REACTOR FUEL CLADDING**

Generation IV supercritical water reactors operate at high temperature, high neutron flux and high pressure when compared to other reactors used in Canada. To improve the efficiency of power generation, Generation IV reactor concepts utilize the higher core temperatures. SCWR is proven to be effective by the high thermal efficiency of +40% while light water reactors (LWR) only run at 33%. The SCWR design was enhanced from the existing LWR technology. Supercritical water is 90% more effective at energy transfer than light water at room temperature. The fuel cladding material must provide proper functions for SCWR that operates above the critical point of water. The critical point of water is at 374°C with a pressure of 22.1 MPa. The operating pressure of SCWR is 25 MPa and the outlet temperature of the coolant is 550 - 625°C depending on the design chosen by the respective country that is developing it. The primary choice of fuel for SCWR is an oxide fuel while a metallic fuel has been considered as the secondary choice for the fast-neutron-spectrum SCWRs.

**DESIGN CRITERIA**

A cladding is needed to ensure the fuel does not escape into the coolant causing damage. If fuel is escapes into the coolant, there will be less fuel available to generate the high temperatures and there may be risk of radionuclide release. The main fundamental requirements are to achieve functionality and safety in the SCWR. Cladding performance metrics must be clearly established before an SCWR reactor can be designed. Cladding must perform as well as the currently licensed zirconium-based cladding materials. Performance requirements will be established with regard to thermal expansion, conductivity, neutron mechanism, corrosion rates, strength/structural integrity (normal and off-normal conditions), fuel pin lifetime, fuel burn-up, radiation and creep resistance, chemical compatibility with nuclear fuel options and long-term dry storage requirements. These requirements will justify the investment that will be required by CNSC to license and adopt a fuel cladding system for SCWR.

* ***Strength/ Structural integrity of cladding material***

When designing fuel cladding, it is important to look at the environment it will be operating in and the resulting stresses that it may experience.  This includes longitudinal stresses and hoop stresses.  These stresses are a result of the swelling which is the physical expansion of the fuel pellets as they heat up.  In addition, stress is introduced from the outside environment; the supercritical water that the cladding needs to operate in produces immense pressures and temperatures, these factors can compromise the cladding and cause a failure.

The material selected needs to not fail on the microscopic or macroscopic level.  The need to analyze the produced pressures inside the cladding during 100%FP and find a material which can resist this pressure given the safety factor will need to be determined.  This will be done with the program EngineeringToolBox which takes as inputs: the inside pressure, outside pressure, inside radius, outside radius and radius to a point to solve for the stresses in a thick-walled cylinder.  
 A material will be considered structurally sound if the max stress it experiences axially, longitudinally and at a point, is all less than the stress required for the material to fail.  Considerations need to be taken on how Young’s Modulus changes from irradiation, temperature and pressure.

* ***Neutronics of Cladding***

The possible material that should be used for cladding in a SCWR must have a low neutron cross section (have high neutron transparency). A material with high neutron capture cross-section collects more neutrons and causes lower fission rates. A low neutron capture cross- section allows fewer interactions to occur and allows for higher energy neutrons and more efficient energy transfer to the moderator. Having higher energy neutrons encourages higher fission rates and allows heat to be generated at higher temperatures that is similar to the SCWR environment.

Creep strength is an important aspect that the appropriate material must also possess. Materials for fuel cladding must have high creep strength to decrease the occurrence of stress corrosion cracking. Stress corrosion cracking is a frequent issue in SCWRs so to ensure this problem does not occur; the chosen material must have high creep strength at high temperature. To achieve the high creep strength, the metal used as cladding could have a uniform arrangement of oxide particles which help as a buffer in absorbing the neutrons.

The material chosen for the cladding must have low neutron activation. The lower a material’s neutron activation value, the lower the risk of erosion or meltdown. This is especially important in the high irradiating environments in an SCWR.

In a SCWR, if the cladding material is not able to withstand the high temperatures and pressure than the lifetime of the fuel will not last as long or will not be able to operate at optimal power. The wrong cladding material could cause fewer fission reactions to occur and not allow the SCWR to run at the high temperatures or pressure that makes the SCWR so desirable.

***Corrosion resistance of fuel cladding in SCWR Environment***

Designing a high radiation resistant material that can also withhold the lattice integrity is vital to this project. This design will need to take into account the concepts of grain size and texture, special grain boundaries and radiation-defect sinks.

Chemical corrosion may also exist through the interactions of the cladding with the moderator and with the fuel itself. Having goals to determine the proper materials that is inert and will not form depositions that could obstruct flow are important. It is our objective to find a material that is inert to these chemicals and metals to ensure no depositions are formed that could obstruct flow. The fast flowing environments also create a source for erosion corrosion which is impossible to prevent completely, monitoring will be required to determine the exact effects of this erosion.

The easiest method to obtain the losses caused from corrosion inside the wall would be to measure the amount of material in the IX column filters and measure how much material that originated from the cladding is now in these columns. Corrosion losses from the interactions on the outside of the cladding would be measurable by periodically measuring the cladding diameter and comparing it to the original to obtain the change in diameter. A erosion simulation and calculation will be required.

***Heat transfer through the fuel sheath***

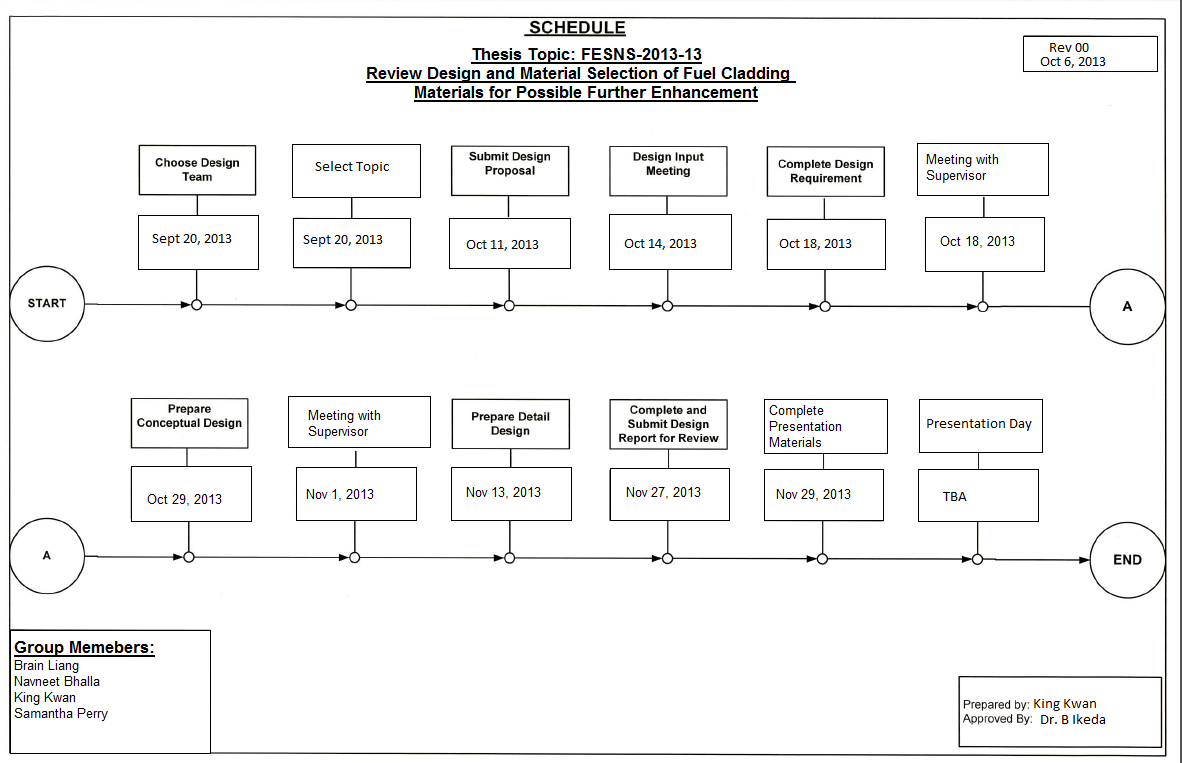
Fuel cladding material must provide the needed thermal conductivity to maintain thermal efficiency of the SCWR within the range of 45 – 50 %. In nuclear fuels, this relationship is more complex because conductivity also becomes a function of irradiation as a result of change in the chemical and physical composition. The major factors are temperature, porosity, oxygen to metal atom ratio, PuO2 content, pellet cracking, and burn up. The second largest resistance to heat conduction is in the fuel rod due to the gap. Therefore, fuel centerline temperature profiles will be calculated based on a no-gap condition and with a gap with widths of 20 μm and 36 μm. The calculation will also be performed to determine the temperature of the fuel in the radial and axial directions. The sheath temperature is high at SCWR conditions; therefore, it is necessary to take into account the radiative heat transfer.

**REGULATORY**

Safety requirements are always a key component in the nuclear industry and within Canada prescribed nuclear equipment are require to be certified. For this design project students will also examine the regulations from Nuclear Safety and Control Act (NSCA), radiation protection regulations and license to construct under Class I nuclear facility, to ensure all safety measurements are encountered.

**CONCLUSION**

As mentioned, the Supercritical Water-cooled Reactors design is of the most promising design of the Generation IV reactors because of its simplicity and high efficiency values. The SCWR design has the ability to operate at high temperature and high pressure while producing less nuclear waste. The proposed material used for fuel cladding must be able to ensure high creep strength, low neutron capture cross section and low activation. This document has proposed further research into the appropriate material for fuel cladding in the SCWR. The research will be shown in a report and formal presentation both given in early December.

**PROJECT SCHEDULE**

**ACRONYMS**

CNSC – Canadian Nuclear Safety Commission

FP- Full Power

Gen IV – Generation IV

GIF – Generation IV International Forum

LWR – Light Water Reactor

NSCA – Nuclear Safety and Control Act

SCWR – Supercritical Water-cooled Reactor

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