CHAPTER 1 INTRODUCTION

1.1. Background

Generation IV reactor, or better known as Gen-IV reactor, is a proposed nuclear power plant aimed at being safer, more efficient, and cleaner (İlhami and MacEachern, 2018). Gen IV reactors are proposed by the Generation IV International Forum (GIF), some examples including Very-high Temperature Reactor (VHTR), Sodium-cooled Fast Reactor (SFR), Gas-cooled Fast Reactor (GFR), Lead-Cooled Fast Reactor (LFR), Super Critical Water Reactor (SCWR), and Molten Salt Reactor (MSR).

GFR is one of the proposed Generation IV reactors that utilize gas as a coolant to transfer heat efficiently. Ndayiragije et al. (2024) state that GFR employs gas, predominantly inert gas, to maintain optimal cooling performance while relying on fast neutrons to sustain the fission process. This advanced reactor design enables the utilization of natural uranium as fuel, providing a more sustainable approach to nuclear energy production. The ability to operate with natural uranium reduces dependence on extensive fuel enrichment and minimizes the need for complex reprocessing techniques, contributing to enhanced fuel cycle efficiency and resource sustainability.

Cladding is a component of GFR that function as protection for nuclear fuel so that it will not get contact with coolant or even worse melting the core. To ensure this will not happen, cladding must withstand extreme condition, including radiation damage and high temperature. Moreover, it is also has low absorption cross section in order to reduce neutron absorption and maintain nuclear chain reaction. One of the most common material to use in GFR is silicone carbide or SiC because this material has melting point of 2700 K (2426,85 ˚C) and low absorption cross section (Daoud et al., 2022). Another material that commonly use as cladding is zirconium carbide (ZrC) due to excellent thermal stability and corrosion resistance (Pylypenko and Yefimov, 2024; Shu et al., 2021). However, these materials have their disadvantage, such as SiC which exhibit a weak characteristic and brittle failure (Yin, 2020). Furthermore, ZrC also has some downsides, including the Debye temperature, a material specific value that serves as a temperature scale for atomic vibration in a solid, is generally lower than SiC, which is detrimental for high-temperature nuclear application (Jiang et al., 2017). After neutron pass cladding, it will collide with another neutron creating nuclear chain reaction. To preserve number of neutron inside the core, reflector surround the core of GFR so that neutron will always be inside of the core.

Reflector is a component that reflect or bounce neutron back inside the core. This component reflects neutron is to make sure reactor has steady nuclear chain reaction (Frybort et al., 2020). This component should use material with high scattering cross section and low absorption cross section, one of them is beryllium oxide (BeO). BeO is mostly chosen due to high thermal conductivity and radiation resistance that make it suiTable for reflector (Li et al., 2021). Furthermore, BeO is also efficient neutron reflector choice to improve initial k_{eff} and flattening radial power distribution (Zhong et al., 2022). Despite of these facts, BeO has several issues, such as the moderating effect creating disruption in power distributions with peaks at the core boundary (Merk et al., 2021).

Shield works as additional protection of neutron leakage by absorbing neutron that pass reflector. Shield should have high absorption cross section material such as Gadolinium-doped nickel. Gadolinium-doped nickel alloys function as shielding by minimizing neutron tunneling effects, with effective shielding achieved when the particle size of Gd-rich phases remains below 20 μm (Li et al., 2024) but now boron carbide (B_4C) is the most popular material for shielding due to the significant reduce of neutron transmission (Saenpoowa et al., 2023). However, B_4C has a disadvantage, including less effective in fast spectra .

Ti-based alloys have garnered increasing interest in recent years due to their outstanding mechanical strength, corrosion resistance, and versatility in both nuclear and biomedical applications. Hiremath et al. (2024) reported that Ti-Nb-Fe-Cr alloys are utilized in fields such as nuclear reactor shielding, fuel cladding, and medical implants; however, their effectiveness is limited to an energy range of 1 keV to 15 MeV, which may restrict their utility in broader nuclear environments. Almisned et al. (2024) studied Grade 26 titanium alloy and found it to exhibit excellent mechanical strength and low contamination potential in coolant materials, making it a promising candidate for reactor components, although the study did not address mechanical factors such as irradiation or corrosion over time. TiCrNiAlSi/ZrC has also been investigated as a potential structural material, with Jiaoxi et al. (2016) demonstrating its enhanced oxidation resistance, a crucial feature for materials exposed to high temperatures and reactive environments in nuclear reactors. A recent development by Liu et al. (2023) focused on the microstructure of Ti-V-Cr-Nb-Ta, showing that homogenization heat treatment can significantly increase hardness, highlighting the role of thermal processing in improving the mechanical performance of high-entropy Ti-based alloys. These studies collectively emphasize the growing potential of titanium-based alloys in advanced nuclear systems, while also pointing to the needed for further research into their neutronic characteristic under reactor operating conditions.

Ti-V-Cr-Nb-Ta generally adopts a body-centered cubic (BCC) structure, frequently containing Laves phase precipitates (Gao et al., 2023). Gao suggest that adding Cr to TiVNb enhances BCC phase stability and improves corrosion resistance, particularly in high-temperature environments. Ti-V-Cr-Nb-Ta exhibits great resistance to high-temperature corrosion (Strozi et al., 2021) making the material sustainable for a long term. Common applications of Ti-V-Cr-Nb-Ta include biomedical fields, such as osseous implants and surface treatments, where its excellent elastic properties are advantageous (Beilner et al., 2021). With these advantages, Ti-V-Cr-Nb-Ta could be a potential the structural material for GFR, particularly cladding, reflector, and shielding.

Neutronic analysis can be defined as analysis of how neutron behave within a system (Zohuri, 2019). Calculation and simulation of neutronic analysis in nuclear reactor could be done in two ways, which are deterministic and stochastic. Deterministic calculation is a computational tool that solves the neutron transport equation to determine the reactor's behavior (Gordon et al., 2024), such as diffusion equation, Boltzman transport equation, S_N method, and P_N method. One of the researches done in deterministic calculation was conducted by Zhou et al. (2022) where they employs a deterministic method to model self-powered neutron detectors in pressurized water reactor (PWR) and Syarifah et al. (2022) which use SRAC-COREBN specifically for PWR with mixture of uranium and plutonium nitride (UN-PuN) as fuel. Eventhough a lot of researches use deterministic method, it has some disadvantages, such as geometry limitation for complex geometry, difficulty in capturing statistical uncertainty, and treatment of boundary conditions and scattering are challenging. Another method is called stochastic that uses randomness in neutron kinetics, particularly low neutron source. This method has some advantages including high accuracy, geometry flexibility, and typically lower memory that deterministic methods. Stochastic method also has disadvantages such as demand for high CPU/GPU and requirement of many samples for low variance results (Cox et al., 2022; Zheng et al., 2019). Some researchers, such as Huang et al. (2022) use stochastic to analyze uncertainty in system performance. Stein & Dubi (2020) also used this method to modelling power fluctuations over time. One of the most popular software to use stochastic method in reactor is OpenMC

OpenMC is an open-source Monte Carlo neutral particle transport application originally developed for neutron and photon transport simulations (Tramm et al., 2024). According to Mahfudin & Setiadipura (2020), OpenMC is the most popular software for Monte Carlo method because of its capabilities extend beyond traditional neutron transport to include criticality analysis of advance reactor designs. OpenMC also shows an excellent reliability and accuracy which is proven by Lababsa et al. (2024) where they proved the experimental data and established codes like MCNP5, achieving discrepancies below 5% with experimental measurement and relative differences below 1% in code-to-code comparisons. OpenMC also has several features, including calculating multiplication factor, visualization of neutron flux distributions, calculating inreaction rates (scattering, absorption, fission, etc.), and proving the neutron energy spectrum. With these reasons, this research will be focus on the neutron characteristic of GFR with Ti-V-Cr-Nb-Ta as targeted component using OpenMC code

1.2. Purpose of the Research

The purpose of this research is to investigate the GFR’s neutronic characteristic when Ti-V-Cr-Nb-Ta, specifically Ti_{20}-V_{20}-Cr_{20}-Nb_{20}-Ta_{20} and Ti_{25}-V_{25}-Cr_{5}-Nb_{20}-Ta_{25} is applied as cladding, reflector, and shielding.

1.3. Benefits of the Research

The results of this research are expected to serve as a reference in GFR design studies related to structural materials. The insights gained from this study could support the development of advanced materials for safer and more efficient reactor operation.

1.4. Scope of the Research

The reactor model utilized in this study is a GFR simulated using OpenMC. The reactor core is filled with helium gas, serving as the primary coolant. The chosen fuel for this reactor consists of UN and PuN because UN-PuN has higher atom density, high thermal conductivity, and high melting point. Furthermore, the Ti_{20}-V_{20}-Cr_{20}-Nb_{20}-Ta_{20} and Ti_{25}-V_{25}-Cr_{5}-Nb_{20}-Ta_{25} will be apply in cladding, reflector, and shielding. The parameter that would be considered include multiplication factor, neutron flux distribution, absorption and scattering rate of Ti-V-Cr-Nb-Ta in each components, fission rate, and neutron energy spectrum.

1.5. Hypothesis

The hypothesis of this research is that GFR could perform better if Ti-V-Cr-Nb-Ta as shielding and reflector due to the cross-section properties, specifically absorption and scattering cross-section.