Chapter 1

Introduction

1.1 Motivation

The impact of climate change on natural and human systems brought about by elevated Greenhouse Gas (GHG) concentrations is increasingly apparent such as increases in global average surface temperatures, sea levels, and larger climate extremes [1]. Energy use and production contribute to two-thirds of the total GHG emissions [1]. Furthermore, as the human population increases and previously under-developed nations rapidly urbanize, global energy demand is forecasted to increase. Energy generation technology selection profoundly impacts climate change via growing energy demand. Large scale deployment of emissions-free nuclear power plants could significantly reduce GHG production [1]. However, large scale nuclear power deployment faces challenges of cost and safety [2]. The nuclear power industry must overcome these challenges to ensure continued global use and expansion of nuclear energy technology to provide low-carbon electricity worldwide to battle climate change. To enhance the role of nuclear energy in our global energy eco-system, the Generation IV International Forum was created to lead and plan the research and development roadmap to support a new generation IV of innovative nuclear energy systems [3]. Generation IV nuclear systems' goals are defined in four areas: sustainability, economics, safety and reliability, proliferation resistance and physical protection [3]. Table 1.1 summarizes the goals in each area.

An evaluation and selection methodology was developed based on the goals, culminating in selecting six Generation IV systems: Gas-Cooled Fast Reactor System (GFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-Cooled Fast Reactor (SFR), Supercritical-Water-Cooled Reactor System (SCWR), and Very-High-Temperature Reactor System (VHTR) [3]. The reactor systems of interest in this proposed work are the MSR and VHTR systems. The

Table 1.1: Goals of Generation IV Nuclear Systems [3, 4]

Area	**Goals**
Sustainability	- Have a positive impact on the environment through the displacement of polluting energy and transportation sources by nuclear electricity generation and nuclear-produced hydrogen - Promote long-term availability of nuclear fuel - Minimize volume, lifetime, and toxicity of nuclear waste
Economics	- Have a life cycle and energy production cost advantage over other energy sources - Reduce economic risk to nuclear projects by developing plants using innovative fabrication and construction techniques
Safety and Reliability	- Increase the use of robust designs, inherent and transparent safety features that can be understood by non-experts - Enhance public confidence in the safety of nuclear energy
Proliferation Resistance and Physical Protection	- Provide continued effective proliferation resistance of nuclear energy systems through improved design features and other measures - Increase the robustness of new facilities

MSR system produces fission power in a circulating molten salt fuel mixture. It has a closed fuel cycle tailored to the efficient utilization of plutonium and minor actinides. Molten fluoride salts have very low vapor pressure, which reduces stress on the system. MSR systems also have inherent system safety due to fail-safe drainage, passive cooling, and a low inventory of volatile fission products in the fuel. The MSR system is top-ranked in sustainability because of its closed fuel cycle and excellent waste burndown performance. It rates good in safety and proliferation resistance and physical protection due to its inherent safety features and rates neutral in economics because of its large number of subsystems [3]. The VHTR system has a once-through uranium cycle and is primarily aimed at high-temperature heat applications, such as hydrogen production. It is a graphite-moderated, helium-cooled reactor that uses Tristructural Isotropic (TRISO) fuel, which does not degrade at high burnup and temperature. The VHTR system is highly ranked in economics, because of its high hydrogen production efficiency, safety and reliability, because of the fuel and reactor's inherent safety features. It is rated good in proliferation resistance and physical protection and neutral in sustainability because of its open fuel cycle [3].

In the proposed work, we will be exploring the Fluoride-Salt-Cooled High-Temperature Reactor (FHR) reactor concept, which is a combination of the best aspects of MSR and VHTR technologies. The FHR uses high-temperature coated-particle fuel (similar to the VHTR) and a low-pressure liquid fluoride-salt coolant (similar to the MSR) [5, 6].

In recent years, additive manufacturing technology has advanced and altered the manufacturing and design of components [7]. The automotive and aircraft industry have successfully fabricated parts, with key additive manufacturing technologies relevant to nuclear reactor core structures [8]. Successful examples of additive manufacturing applied in the aircraft industry are Boeings use of additive manufacturing to reduce weight in the 787 Dreamliner [9] and SES-15 spacecraft [10]. Like the nuclear industry, the aerospace industry is highly regulated; thus, successful additive manufacturing applications in the aerospace industry are promising for the nuclear industry. Using additive manufacturing to fabricate nuclear reactor components will drastically reduce cost, timelines, increase safety, and performance by tailoring local material properties and re-designing geometries for optimal load paths [7].

With further advancement of these additive manufacturing technologies, a reactor core could be 3D printed in the near future. Oak Ridge National Laboratory (ORNL) is leading this initiative through the 2019 Transformational Challenge Reactor (TCR) Demonstration Program. The TCR program will leverage recent scientific achievements in advanced manufacturing, nuclear materials, machine learning, computational modeling and simulation to build a microreactor. The program targets to design, manufacture, and operate a demonstration reactor by 2023 [11]. Applying additive manufacturing to nuclear reactor design will enable complex reactor geometries that are not limited by previous manufacturing constraints, opening the door for a re-examination of nuclear reactor optimization [12]. Optimization efforts towards classically-manufactured nuclear reactors and now 3D printed nuclear reactors have focused on uniform shapes such as radius of the core, height of cylinder, enrichment of fuel, etc [12, 13, 14, 15]. Leveraging additive manufacturing technology enables us to surpass classical manufacturing constraints such as straight fuel channels or homogenous fuel enrichment, and look forward to optimizing for arbitrary geometries and parameters such as non-uniform channel shapes, inhomogeneous fuel enrichment throughout the core, etc.

Multi-objective design problems inevitably require a trade-off between desirable attributes [16, 17]. There are many trade-offs in nuclear reactor design; one example is the trade-off between neutron economy and fuel enrichment. A reactor design must have sufficient neutron economy to ensure criticality but also have a low fuel enrichment to reduce proliferation risk. Conflicting objectives means that there is no one perfect solution but a set of equally optimal solutions [16]. Multi-objective problems are challenging to optimize; therefore, they cannot be handled by classical optimization methods such as gradient methods because only the local optimum will be found [18]. Evolutionary algorithms have proven successful methods to optimize multi-objective problems [19] as they can find a solution near the global optimum [18]. They also take advantage of parallel systems for reduced computational cost. The most popular evolutionary algorithms used to solve multi-objective problems are genetic algorithms [16, 19]. Genetic algorithms imitate natural selection to evolve solutions by (1) maintaining a population of solutions, (2) allowing fitter solutions to reproduce, and (3) letting lesser fit solutions die off, resulting in final solutions that are better than the previous generations [18]. We will pursue the evolutionary algorithm optimization technique in this work.

Therefore, in this work, we propose designing an optimization tool that uses the evolutionary algorithm optimization technique with nuclear transport and thermal-hydraulics software. This tool will be used to explore non-uniform FHR reactor core parameters, now possible with additive manufacturing technology, to optimize reactor systems fully.

1.2 Objectives

The proposed work's main objectives were developed based on leveraging open-source artificial intelligence tools with validated open-source nuclear transport and thermal-hydraulics software to create an open-source tool to generate optimal reactor designs quickly. Accordingly, the objectives are listed below.

Model Fluoride-Salt-Cooled High-Temperature Reactor with established nuclear transport and thermal-hydraulics software. To demonstrate success in modeling the FHR with nuclear transport and thermal-hydraulics software before using the optimization tool, we will participate in the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA)'s FHR benchmark [20].

Develop a tool that applies evolutionary algorithms to nuclear reactor design op-

timization. This tool will not re-invent the wheel; it will utilize a well-documented and validated open-source evolutionary algorithm python package with established nuclear transport and thermal-hydraulics software. This tool will run parallel on high-performance computing (HPC) machines. This tool will be open-source and follow the rules for ensuring reproducibility, effectiveness, and usability [21, 22, 23].

Demonstrate nuclear reactor design optimization with the optimization tool for a neutronics problem. We will demonstrate successful implementation of the optimization tool with the nuclear transport software by optimizing a simple FHR model for a single objective function.

Demonstrate hyperparameter tuning with the optimization tool for neutronics problem. Hyperparameter selection will impact the effectiveness of the algorithm for our problem. Therefore, we must conduct hyperparameter tuning to find hyperparameters that work best for our problem.

Demonstrate nuclear reactor design optimization and hyperparameter search with the optimization tool for a neutronics and thermal-hydraulics problem. We will demonstrate successful implementation of the optimization tool and hyperparameter tuning with the nuclear transport and thermal-hydraulics tools for a FHR model.

1.3 Outline

This document outlines the motivation, preliminary work, and future work proposed towards developing an open-source optimization tool that applies evolutionary algorithms to nuclear transport and thermal-hydraulics software to optimize nuclear reactor design. Chapter 1 describes the motivation and objectives of the proposed work. Chapter 2 will present a literature review that organizes and reports on previous relevant work. Chapter 3 will describe the FHR benchmark specifications and the results obtained thus far. Chapter 4 will detail the computational design of the REALM python package. Chapter 5 will demonstrate nuclear reactor optimization with REALM. Chapter 6 will summarize the remaining future work.

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