Design of a PID Controller for a Molten Salt Microreactor

A Thesis
Presented in Partial Fulfillment of the Requirements for the
Degree of Master of Science
with a
Major in Nuclear Engineering
in the
College of Graduate Studies
University of Idaho
by
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May, 2023

Abstract

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Acknowledgements

This work and my coursework was completed under a Graduate Fellowship funded by Nuclear Regulatory Commission (NRC).

Dedication

To my mother, Tammy, who planted and nurtured my love of science. To my father, Paul, who taught me how to design and build, and showed me that I am an engineer. To my cats, Babe and Bunyan, who stayed up with me all those late nights studying and writing. Thank you for your endless support.

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Acronyms

ANS American Nuclear Society.

INL Idaho National Laboratory.

LWR Light Water Reactor.

MSNB Molten Salt Nuclear Battery.

MSR Molten Salt Reactor.

NRC Nuclear Regulatory Commission.

NREL National Renewable Energy Laboratory.

ORNL Oak Ridge National Laboratory.

PID Proportional-Integral-Derivative.

SMR Small Modular Reactor.

Chapter 1

Introduction

The world is attempting to move away fossil fuel as its main energy source [1]. National Renewable Energy Laboratory (NREL) has partnered with over 700 organizations, including large manufacturing companies, to de-carbonize supply chains [2]. Nuclear power has been well established as an alternative for base-load electrical generation with 93 facilities in the United States 435 globally, most of which generate on the order of 1 GWe rather steadily. There remains a need for smaller reactors to be deployed in more dynamic applications such as small remote grids (e.g. islands, military bases, and off-grid industrial sites), manufacturing, and power-peaking [3]. Dow Chemical is working with X-energy to deploy a Small Modular Reactor (SMR) at a Gulf Coast facility by 2030 [4]. Even smaller energy utilizers could turn to micro-reactors to fill their needs; to make this a reality, robust control systems for microreactors such as the MSNB capable of ramping up and down production to fit demand must be designed.

1.1 Background

The Molten Salt Nuclear Battery (MSNB) is a self contained design for a liquid fueled molten salt microreactor [5, 6]. It is fueled by an inorganic form of uranium, UF_4, dissolved in a coolant salt such as $FLiNaK$ (a eutectic mixture of three alkali fluorides) or $FLiBe$ (a mixture of LiF and BeF_2) [7]. Heat is generated in the core by fission, is transported by the natural circulation of the coolant/fuel salt, and rejected to a secondary working fluid in an integrated heat exchanger. Criticality is manipulated using axial control drums, which may be rotated to aim either a neutron reflecting material or a neutron absorbing material towards the core.

Molten Salt Reactors

Molten salts are highly desirable in high temperature applications due to their excellent thermophysical properties [8]. Salt mixtures have been developed to have very wide liquid temperature ranges (i.e. low melting point and high vaporization point). They also have very high volumetric heat capacities compared to other high temperature coolants (which tend to be gaseous), and are able to operate at or slightly above ambient pressure. These properties combine to make molten salts excellent choices in heat transfer and thermal storage applications. Furthermore, they are extremely strong electrolytes which cn be useful as solvents, catalysts, or reagents in certain chemical reactions including a pyrometallurgical method for reprocessing spent nuclear fuel [9].

Molten Salt Reactors (MSRs) are a family of nuclear reactor in which a fuel salt (containing fissile and/or fertile nuclides) is dissolved in a coolant salt [7]. The concept was proven by the Molten Salt Reactor Experiment at Oak Ridge National Laboratory (ORNL) in the 1960s [10]. It has yet to take off beyond the research reactor sector, but it has re-emerged as a Gen-IV reactor concept, with a team at the Shangai Institute of Applied Physics gaining approval to operate a now fully constructed thorium breeding MSR [11]. Some of the benefits of MSRs over more conventional LWRs include:

- Higher operating temperatures allow for use in applications requiring high-grade process heat, and yield higher thermal efficiency [7];
- Lower pressure operating pressure lends itself to inherant safety, and less expensive (thinner) components [8];
- The ability to burn minor actinides supports the goal of reducing global stockpiles of high-level waste [8];
- Natural circulation of the fuel introduces an additional feedback mechanism that presents the possibility of autonomous load following of certain power demand transients [12];
- There is no concern of core melt-down as the reactor is designed for liquid fuel;
- The liquid state homogenizes nuclides throughout the core, which minimizes burn-up gradient to produce a flatter temperature and power profile within the core [13, 14]. The flowing nature also allows for online reprocessing, removing fission products and poisons during operation;

They also carry some demerits:

- Molten salts are very corrosive [15];
- The chemistry of the coolant (not only the fuel) is constantly changing due to fission, transmutation, and impurities from corrosion;
- Lithium is commonplace, so tritium production is unavoidable. Off-gas systems need to be robust to handle tritium as well as radionuclide noble gasses, halides, and interhalides [16];

Micro Reactors

Its like a reactor but smol.

1.2 Scope

As a developing design, work has been done on neutronics [6], thermal-hydraulics and autonomous load following [5], and corrosion concerns [17]. However, until now, little to no work has been done on the control system. First and foremost, this work details a multiphysics characterization of the MSNB required to design a feedback controller capable of matching the core power generation to the secondary power demand. In addition to the main control mode of following power transients during normal operation, specific discussion is centered around more dynamic time periods, namely: 1) initial start-up; 2) shutdown, both planned and emergency; and 3) restart;

Chapter 2

Process Control Engineering

2.1 Feedback

2.2 Feedforward

The term ‘Feedforward’ can be used to refer to any element in the control block diagram that exists outside of the feedback loop.

Disturbance Feedforward

Not that useful since disturbance transport delay is on the order of minutes and disturbance dynamics are on the order of milliseconds

Pre-Filter

This could be electronic (less ideal) or physically realized by decoupling

2.3 Time Variance

Fissile depletion - time function parameters or look-up table to gain-schedule and turn the time variant system into a shift invariant system.

In addition to the relatively slow time variance of fissile fuel depletion during steady-state critical operation, there are specific times in a MSNB’s expected operational life-cycle that exhibit a higher degree of time variance: 1. Start-up; 2. Shut-down; and 3. Re-start.

Start-up

Black-start may need to deal with thawing salt - main concern is fission product neutron poison build-up (discuss the burnable poison stuff)

Shut-down

Planned shut-down

Emergency Shutdown/SCRAM(must be passive)

Decay heat and keeping the salt liquid for restart

Re-start

^{135}Xe stripper

Chapter 3

Reactor Characterization

3.1 Reactor Design selection

3.2 Neutronics Modeling

3.3 Process Simulation

Chapter 4

Controller Design

4.1 Reactor Transfer Function

4.2 Tuning Methodology

Chapter 5

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6.1 Limitations

6.2 Future Work

6.3 Summary Remarks

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Appendix A

Test

Code 1: Hello!

```
    print("Hello World") #comment
    try:
        a=2/x
    except ZeroDivisionError:
        print('undefined')
```

Inline codes like `import numpy`

Code 2: F strings

```
x = 4
print(f"The numeral four: {x}")
#comment
```

Appendix B

What

Straight Cash Homie