INVESTIGATION OF PELLET CLAD INTERACTION DURING LOAD-FOLLOW OPERATION IN A PRESSURIZED WATER REACTOR USING VERA-CS

BY

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THESIS

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Abstract

This is a comprehensive study of caffeine consumption by graduate students at the University of Illinois who are in the very final stages of completing their doctoral degrees. A study group of six hundred doctoral students. . . .

To Father and Mother.

Acknowledgments

This project would not have been possible without the support of many people. Many thanks to my adviser, Lawrence T. Strongarm, who read my numerous revisions and helped make some sense of the confusion. Also thanks to my committee members, Reginald Bottoms, Karin Vegas, and Cindy Willy, who offered guidance and support. Thanks to the University of Illinois Graduate College for awarding me a Dissertation Completion Fellowship, providing me with the financial means to complete this project. And finally, thanks to my husband, parents, and numerous friends who endured this long process with me, always offering support and love.

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List of Abbreviations

CA	Caffeine Addict.
CD	Coffee Drinker.

List of Symbols

τ	Time taken to drink one cup of coffee.
μg	Micrograms (of caffeine, generally).

Chapter 1

Introduction

In the United States (U.S.), nuclear power generation has high fixed costs and low variable costs. As a result, utilities have traditionally sought to operate nuclear stations at full power from Beginning of Cycle (BOC) to End of Cycle (EOC). More recently, the deregulation of the energy market and the emergence of intermittent renewable energy sources have caused load-follow operation to become a more attractive option for nuclear generation.

The deregulation of the energy market has forced utilities to compete against each other to sell electricity within a region. The beneficiary of this competition are the customers, who are guaranteed fair prices for electricity and will not be footing the bill for an inefficient/uneconomical utility project. Nuclear stations, with low variable costs and high fixed costs, have typically been able to economically compete within deregulated markets because the typical plant lifetime of at least 20 years allows owners to spread out the fixed costs. Recently, the low price of natural gas and government subsidized renewable energy sources, such as wind and solar, have made nuclear stations appear inefficient.

1.1 Background and Motivation

In 2016, the U.S. had approximately 7% of its total electricity generation coming from wind and solar power [**?**]. This share is likely to increase as the U.S. continues to move away from fossil fuels and towards a "greener" energy future. As a result of this increase, in combination with the deregulation of the energy market, the price of electricity has become volatile. At certain times, the price of selling electricity within a region can even become negative, due a sudden increase in renewable energy output and a low market demand [**?**]. In some areas, negative electricity prices are further increased due to the fact that large generating facilities would rather sell at a loss to avoid decreasing their power level. This preference is caused by the high capital cost and relatively low variable costs of large generating facilities [**?**].

Nuclear stations are typically one of these large generating facilities. As a result of the large construction costs and the fixed number of staff members that must be on site at all times, most utilities prefer to keep

a reactor at full power, as it is easiest to maintain constant power. If instead of remaining at full power, a nuclear station operated in load-following mode, could this increase the efficiency of the plant? During load-follow operation, a nuclear station will vary its power output in response to the anticipated demand to better suit the market needs, stabilizing the price of electricity. Theoretically, the current operating plants were all designed with the maneuverability to respond to such change in demand [**?**]. In fact, many of the reactors in France already participate in load-following maneuvers with the help of grey control rods [**?**]. Grey control rods are similar to standard Pressurized Water Reactor (PWR) control rods but have significantly less rod worth [**?**]. The low rod worth allows them to be used for reactivity control without putting significant stress on the surrounding fuel. In the U.S., grey rods are not present in PWR, increasing the complexity of load-follow operation [**?**].

To participate in load-follow operation in the U.S., a PWR can use the critical boron concentration to modify the power level while making minor control rod insertion to manage the core Axial Offset (AO) [**?**]. This practice can lead to significant changes in local power levels throughout the core. Significant changes in local power can cause fuel to swell or contract, due to thermal expansion [**?**]. If a utility chooses to ramp down the reactor during times of low demand, or high supply, the fuel pellets will contract allowing the cladding to slowly creep down. When the decision is made to return the reactor to a higher power level, the rate at which the power can be increased is limited due to the thermal expansion of the fuel pellet [**?**]. If enough time has passed at low power and the cladding has crept down on the fuel pellet, a sudden expansion of the fuel pellet has the potential to cause fuel failure. As a result, studies must be performed on the maximum power ramp rate to determine if load-follow operation introduces a significant risk to all fuel rods.

In this study, the market conditions under which it is economic for a PWR to perform load-follow power maneuvers were investigated. As a baseload energy source, current market conditions are causing the premature shutdown of some nuclear power plants [**?**]. If load-follow power maneuvers are possible for these plants, they can become more competitive in their local market, possibly allowing them to remain in operation without government intervention. Although, improving the economics of a nuclear reactor is a strong driving force for this study, it is also important to improve the compatibility of nuclear power with renewable energy sources. In the absence of energy storage, a complete shift away from fossil fuels will require renewable energy sources, and hopefully nuclear power, to provide all of the energy on the grid. If it can be proven that traditional PWRs can safely and economically respond to the changes in renewable energy output, the shift away from fossil fuel can be expedited. In addition, nuclear power working together with renewable energy sources can positively impact the public's opinion on nuclear power.

1.2 Literature Review

Chapter 2

PWR1

Chapter 3

VERA-CS

Chapter 4

Results and Discussion

Chapter 5

Conclusions

We conclude that graduate students like coffee.

Vita

Juan Valdez was born....