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

BY

DANIEL JOHN O'GRADY

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Nuclear, Plasma, and Radiological Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2018

Urbana, Illinois

Master's Committee:

Professor Tomasz Kozloski, Advisor
Professor Katherine Huff

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.

Table of Contents

List of Tables

List of Figures

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 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 uneconomic.

1.1 Background and Motivation

In 2016, the U.S. had approximately 7% of its total electricity generation coming from wind and solar power [1]. 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 [2]. 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 [3].

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 [4]. In fact, many of the reactors in France already participate in load-following maneuvers with the help of grey control rods [4]. Grey control rods are similar to standard Pressurized Water Reactor (PWR) control rods but have significantly less rod worth [5]. 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 [4].

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) [4]. This practice, in addition to the response of the local Xenon concentrations, can lead to significant changes in local pin powers throughout the core. Changes in local power can cause fuel to swell or contract, due to thermal expansion [6]. If a utility chooses to ramp down the reactor during times of low demand, or high supply, the fuel pellets will contract. When the decision is made to return the reactor back to full power, the rate at which the power can be increased is limited by the thermal expansion of the fuel pellets [6]. A sudden expansion of the fuel pellet has the potential to exert additional stress on the cladding, commonly referred to as Pellet-Cladding Material Interaction (PCMI). PCMI can lead to fuel failure by PCI, and has been extensively investigated since the early 1970s.

1.2 Pellet Clad Interaction

In the early 1970's a string of fuel failures in Boiling Water Reactor (BWR) led to the first classification of Pellet-Cladding Interaction (PCI) induced fuel failure. Shortly after, PCI induced fuel failures were found in PWR and determined to be an inherent problem in Light Water Reactor (LWR) zircaloy based fuels. To reduce the risk of failure, fuel manufactures made design modifications and began to provide power ramping guidelines [**?**]. These ramp guideline were particularly conservative and focused primarily on BOC power ramps. Since then, PCI has been extensively studied in order to increase the efficiency of reactor operation and minimize the number of fuel failures.

PCI induced fuel failure is the result of PCMI and environmental contributions. PCMI is best described as the material interaction at the pellet-clad interface which creates a stress state on the fuel cladding [**?**]. In the presence of an aggressive local chemical environment, "PCI-SCC", or a , "PCI-", PCMI In the absence of fuel/cladding defects, it is the primary cause of fuel failure during standard operation of a PWR. PCI is a result of fuel

A UO_2 fuel pellets radius is a strong function of power, quantified using the pellet's Linear Hear Rate (LHR), and exposure.

1.3 Conditioned Power

Chapter 2

PWR1

2.1 Plant Description

2.2 Summary of Previous Results

2.3 Load-Follow Operation

Chapter 3

Methodology

3.1 BISON

3.2 MPACT Screening Process

Chapter 4

Results and Discussion

4.1 BISON

4.2 Limiting Pin

Chapter 5

Conclusions

We conclude that graduate students like coffee.

References

[1] U.S ENERGY INFORMATION ADMINISTRATION, "Electricity data browser - Net generation for all sectors," .

[2] F. PARASCHIV, D. ERNI, and R. PIETSCH, "The impact of renewable energies on EEX day-ahead electricity prices," **73**, 196–210.

[3] A. LOKHOV, "Load-following with nuclear power plants," **29**, *2*, 18–20.

[4] A. LOKHOV, "Technical and economic aspects of load following with nuclear power plants," .

[5] F. YOUSEFPOUR and M. B. GHOFRANI, "Improvement of the axial power distribution control capabilities in VVER-1000 reactors," **27**, *10*, 949 − 957.

[6] M. GARTNER and J. LAVAKE, "POWER RAMP TESTING AND NON-DESTRUCTIVE POST-IRRADIATION EXAMINATIONS OF HIGH BURN UP PWR FUEL RODS," pp. 27–38.

Vita

Juan Valdez was born. . . .