CHAPTER I

INTRODUCTION

Since the early 1950s, nuclear fission technology has been explored on a large scale for electric power generation and has evolved into the modern nuclear power plants. Nuclear electric power generation is ideally suited to provide large amounts of power while minimizing the overall environmental impact. Estimates show that nuclear generated electricity can be cost competitive with other sources of generation. Since that time, nuclear power has increased its share of worldwide electricity production. However, electricity markets in the U.S., Europe and elsewhere are becoming increasingly competitive and nuclear power has to prove that it can compete with other methods of generation. This can be achieved by operating nuclear power plants as many years as possible, as efficiently as possible, and with as low cost as possible.

Power plant electricity generation costs are usually broken down into three major categories: capital, fuel, and operating and maintenance. One way of reducing cost is therefore to increase the burnup of the fuel by higher enrichment. This strategy has been going on in many plants for several years. Such an option in nuclear power plant management gives rise to more demand for fuel, longer operational cycles and higher fuel burnup.

Modern nuclear power plants operate under high fuel burnup conditions, so that the fuel core performs with higher duty for greater fuel residence times. This results in the fuel being exposed to increased levels of chemicals in the coolant such as lithium and boron, giving rise to high crud build-up on fuel cladding, higher cladding oxidation than predicted by previous models, and in some cases, the axial offset anomaly (AOA) (Kondratova and Lister, 2000).

AOA is an unexpected shift of axial power distribution towards the bottom of the core during reactor operation. The flux depression is caused by the concentration of soluble boron in crud deposits on the fuel cladding surfaces in the upper half of the reactor core (NRC Information Notice 97-85, 1997). Experience demonstrates that there are three factors required for AOA to occur: (1) sufficient boron and lithium in the coolant, (2) corrosion products in the coolant that deposit as crud on the fuel cladding, and (3) sufficient local fuel rod power level to sustain nucleate boiling.

Pressurized water reactors (PWR) are a type of nuclear reactor that experiences AOA; both boron and lithium are not applied in other type of reactors. There are two major systems utilized to convert the heat generated in the fuel into electrical power for industrial and residential use. The primary system transfers the heat from the fuel to the steam generator, where the secondary system begins. The steam formed in the steam generator is transferred by the secondary system to the main turbine generator, where the energy in the steam is converted into electricity. After passing through the low-pressure turbine, the steam is routed to the main condenser. Cold water, passing through the tubes in the condenser, removes heat from the system and condenses the steam. The condensate is pumped back to the steam generator for reuse.

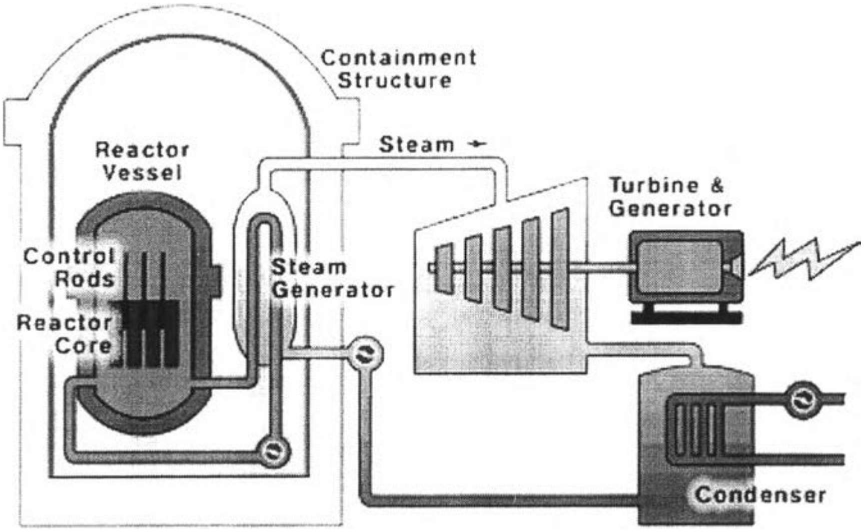

Figure 1.1 Typical Pressurized Water Reactor.

In PWRs, the coolant chemistry, in both primary and secondary systems, must be closely controlled for good plant operation. PWR primary coolant chemistry reflects a balance between three main goals: (1) minimizing corrosion, (2) optimizing fuel performance, and (3) reducing the radiation field. Current chemistry parameters for primary coolant in PWRs are typically those shown in Table 1.1 (Rahn *et al.*, 1984; Millett and Wood, 1998). Lithium-7 has been recommended for the alkalisation of the primary coolant because of its favorable nuclear properties. Boron, in form of dissolved boric acid, is used in conjunction with the absorber rods to control the chain reactions.

In PWRs, the principal primary-system corrosion products are nickel ferrite and magnetite (Rahn *et al.*, 1984; Lambert *et al.*, 1986). It was found that the presence of bubbles in subcooled boiling condition can lead to an overconcentration of corrosion products and consequently results in crud deposition (Najibi *et al.*, 1997). In addition, the solubility of Fe- and Ni- based oxide is lowest in the range of nuclear plant operating temperatures (Lambert *et al.*, 1986). After crud deposition, boron incorporated with lithium is thought to be buried inside the crud (NRC Information Notice 97-85, 1997), the resulting species having retrograde solubility at high temperatures (Cohen, 1980). Therefore, boron hideout would not be measured and detected after shutdown.

Table 1.1 PWR water chemistry

Lithium-7 hydroxide	2.2-3.5 ppm ^{7}Li
Hydrogen	2.2-4.5 ppm
Oxygen	0.1 ppm (max)
Chloride	0.15 ppm (max)
Boric acid	0-4000 ppm B
pH_{300}	6.9-7.4

Since the middle of the 1980s, zinc addition has been implemented in BWRs, and shown to have a beneficial effect in term of radiation field reduction (EPRI NP-6975-D, 1990; Lister *et al.*, 2002; Uruma *et al.*, 2004). It is understood that zinc competes with cobalt, a major activity source, to incorporate in spinel oxide films. Zinc addition at the level of a few ppb effectively swamps cobalt which is generally at the ppt level. Also zinc displaces cobalt from some spinel lattices. This results in the reduction of activated cobalt, and, consequently radiation dose rate in the plant. Since most of the oxide film in PWRs is of a spinel type, it is believed that zinc addition should have a beneficial effect in PWRs as well. However, the effect of zinc addition on corrosion product deposition on Zircaloy-cladding surfaces is unclear.

In this work, the PWR primary coolant conditions were simulated to study the deposition of corrosion products on a heated surface. The effects of pH and zinc addition were investigated. Associated with crud deposition, boron hideout return was also studied. A subcooled boiling condition, controlled by the Zircaloy-4 cladding heating cartridge, was imposed inside an autoclave. The concentration of lithium and boron were controlled to achieve the desired pH. Nickel ferrite was synthesized and represented as crud in the experimental loop.

Boron hideout was also of interest. To study this phenomenon, a neutron-based technique is attractive since boron has a high absorption cross-section for thermal neutrons. In addition, probing with neutron can be nondestructive; therefore, it can be employed while the experiment is running. However, the sensitivity of the technique must be proven before applying to the experimental loop. Hence, the feasibility of the techniques was reviewed, and a neutron technique was tested in static and room temperature environments with the same geometry of autoclave as in the experimental loop.