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# Analysis for Aging and Operating Experiences of Reactor Vessel Internals

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## 1. Introduction

Reactor Vessel Internals (RVIs) support the fuel assemblies within reactor pressure vessel that have been exposed to neutron irradiation, high temperature, and fast coolant flow. The severe operating conditions can cause degradation of RVI materials by aging. Therefore, the effective aging management and the appropriate regulatory requirements are necessary to maintain the integrity and functionality of RVIs for long-term operation over several decades.

In order to maintain the safety margins throughout overall plant life, this study provides the technical basis to manage the aging of RVIs systematically. The scope of this study includes operating conditions and the aging mechanisms that RVIs potentially would experience during plant operation. The threshold values and screening criteria for each aging mechanisms are also described. In addition, the cases of RVIs failure in the domestic and foreign NPPs are given.

## 2. Operating Conditions

The operating conditions determine the presence of specific aging mechanisms and potential degradation for RVIs.

Exposure to neutron dose ($E > 1.0$MeV) causes decrease of ductility and fracture toughness, and acceleration of Stress Corrosion Cracking (SCC) of materials used in RVIs [1]. There are strong gradients of magnitude of irradiation fluences in the internal structures [2]. The neutron fluence varies also with the azimuth angle in the core. Therefore, there are relatively large uncertainties on the neutron fluence reached to each component and location.

The primary coolant chemistry is important factor related to the aging mechanisms. The main parameters controlling the coolant chemistry are the boric acid, lithium hydroxide, hydrogen concentrations, and the resulting pH level. A minimum pH of 6.9 at 300℃ ($pH_{300} = 6.9$) is required to avoid corrosion of fuel rod cladding. The typical range of $pH_{300}$ for PWR operation is 6.9 to 7.4.

Thermal and mechanical loads are the major applied loads acting on RVIs. Thermal loads are caused by temperature gradients in a component, thermal expansions of different materials, and restricted thermal expansions. They can lead to thermal cycling and fatigue crack initiation. Mechanical loads could be produced by preloads in bolts and coolant flow-generated cyclic forces. The loads are an essential factor to develop SCC. The flow-induced vibrations can lead to fatigue failures and mechanical wear.

The processes used in fabrication of components may induce aging to the finished parts [3]. Welding, bolting, cold working, and casting are four common processes, and each of the processes is associated with stressor for aging. For example, the chromium depletion of austenitic stainless steel induced by welding can make the finished components susceptible to SCC.

## 3. Aging Mechanisms

Aging mechanisms are specific processes that change properties of components with time and use. Degradations by aging are those cumulative changes that can impair the ability of RVIs to function within acceptable criteria [3].

### 3.1 Stress Corrosion Cracking (SCC)

SCC refers to the initiation and growth of crack under following conditions: 1) a tensile stress (both applied and/or residual stresses), 2) a corrosive environment, and 3) a susceptible material [4]. The elimination or reduction of one of these three factors below threshold level prevents SCC. Except cobalt alloy, the austenitic and martensitic stainless steels, and the austenitic nickel alloys are generally susceptible to SCC.

### 3.2 Irradiation-Assisted SCC (IASCC)

Irradiated materials become more susceptible to SCC with an increase of fluence [5]. Although the clear mechanism of IASCC is not yet known, both hardening and radiation-induced segregation could act significant role for IASCC [6]. IASCC was first observed in fuel cladding in 1960s, and then, IASCC failures have been reported for a number of other RVIs [7]. In particular, annealed austenitic stainless steels become susceptible to IASCC when certain criteria are exceeded. Based on laboratory data, threshold value of neutron fluence is $2.0\times10^{21}$n/cm$^2$ ($E > 1.0$MeV) or 3dpa [3].

### 3.3 Wear

Wear is the localized damage and materials loss that results from the relative motion between two metal surfaces in contact [4]. The major cause of wear is flow induced vibration. Mechanical wear has been observed at specific locations in the RVI, especially at the components fabricated by austenitic stainless steel.

### 3.4 Fatigue

Fatigue is the structural deterioration occurred by repeated stress/strain cycles from fluctuating loads and temperatures. When the sufficient microstructural damage accumulates by repeated cyclic loading, macroscopic crack initiate, and then continued cyclic loading can lead to the crack growth. Fatigue behavior is related to stress range, mean stress, cycling frequency, surface roughness and environmental conditions.

### 3.5 Thermal aging embrittlement

Thermal aging embrittlement is caused by the thermally activated movement of lattice atoms over a long period without external mechanical load [2]. It results in a loss of ductility and toughness. The significant factors related to the aging phenomenon are temperature, microstructure, and time. Susceptible to the aging are cast stainless steels, welds of austenitic stainless steels, and some Cr rich martensitic steels.

### 3.6 Irradiation embrittlement

Irradiation embrittlement refers to the loss of ductility and fracture toughness due to exposure to high-energy neutrons ($E > 1.0$MeV). High-energy neutrons displace atoms from their original positions and results in point defects, and those can act as obstacles to dislocation movement. A large reduction in fracture toughness can significantly increase the sensitivity to SCC, IASCC, and fatigue. The screening neutron exposure is conservatively established to be lower at $\geq 1.5$dpa, or $1\times10^{21}$n/cm$^2$ ($E > 1.0$MeV) for wrought stainless steel, and to be lower at $\geq 1.0$dpa, or $6.7\times10^{20}$n/cm$^2$ ($E > 1.0$MeV) for austenitic stainless steel weld metals and casted austenitic stainless steel.

### 3.7 Void swelling

Void swelling refers to the volume changes of materials operating at elevated temperatures, and it produces distortions of structural components [8]. The operation temperature of RVIs is generally low enough to limit the swelling, but locally increased temperature can cause swelling and create local straining. Void swelling particularly prevalent in austenitic stainless steels and nickel-base alloys. For austenitic stainless steel and its welds, the screening dose is to be lower at $\geq 20$dpa, or $1.3\times10^{22}$n/cm$^2$ ($E > 1.0$MeV), and the screening temperature is $\geq 320$℃.

### 3.8 Stress relaxation and irradiation creep

When a component is maintained at a constant load, the time-dependent plastic deformation is defined as creep [8]. If a constant strain is imposed on a component, the time-dependent plastic deformation is a stress relaxation. At elevated temperature, large values of thermally activated creep or stress relaxation can be observed. Irradiation can also enhance the phenomenon. At significant irradiation damage levels, creep and stress relaxation can occur below the temperature within thermal activation range.

## 4. Failure cases

Up to now, the failure cases due to aging have been reported in the RVIs such as core barrel, thermal shield, guide tube support split pin, and baffle-former bolt. Until the early 90's, the majority of failures reported in the RVIs are related to baffle jetting, wear, fatigue, and SCC. These failures significantly decreased by changes of design, materials, heat-treatment process, and introduction of periodic inspection. The representative failure due to aging has been IASCC of baffle-former bolts since 90's. It is considered that the aging mechanisms related to neutron irradiation such as IASCC, void swelling, irradiation embrittlement, and stress relaxation will be observed more often with an increase of operating years of RVIs.

## 5. Summaries

This study deals with the technical information about aging related to the integrity of RVIs. The major environmental parameters determining the specific aging mechanism for RVIs are neutron fluence, primary coolant chemistry, applied load, and fabrication process. The environmental conditions can cause the several aging mechanisms; SCC, IASCC, wear, fatigue, thermal and irradiation embrittlement, void swelling, and stress relaxation/creep for the RVI components. It has been reported that a loss of preload in bolts and springs, materials loss, cracks, dimension changes for the RVI components comes from the degradation results by the above 8 aging mechanisms. Based on the knowledge and experiences, the development of effective aging management program is required for maintaining the functionality of RVIs within acceptable criteria.

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