



The Development of Reactor Pressure Vessel Thermal Annealing Evaluation Program for NPP Lifetime Management

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ABSTRACT

In terms of plant safety, the reactor pressure vessel is one of the most critical pressure boundary components in a nuclear power plant. Irradiation embrittlement is one of the primary degradation mechanisms for the reactor pressure vessel, therefore, the effects of irradiation damage should be considered in determining the overall lifetime of the reactor pressure vessel. Thermal annealing of a reactor pressure vessel is considered to be the best option for assuring vessel integrity when nil-ductility temperature and upper shelf energy do not satisfy regulatory limits. To implement thermal annealing for a reactor pressure vessel, the prediction of the percent recovery of mechanical properties and the subsequent reembrittlement rate should be performed in advance. These predictions should consider plant specific information and the thermal annealing process. Therefore, an integrated thermal annealing evaluation program with respect to the nuclear power plant's lifetime management is a useful tool. In this paper, a thermal annealing evaluation program that can be used for evaluating recovery percent of material properties and the post-annealing reembrittlement trend and it's resulting affect on the vessel's lifetime is introduced, and a sample application to a nuclear power plant is illustrated.

1. INTRODUCTION

The primary degradation mechanism for reactor pressure vessels is irradiation embrittlement due to the neutrons from uranium fuel in the reactor core. The neutron irradiation changes the material properties of the vessel's steel, specifically it's ductility and it's fracture toughness. A reduction in fracture toughness due to irradiation is referred to as embrittlement. This embrittlement usually affects the vessel beltline wall closest to the reactor fuel. There are three basic operational issues affected by radiation induced embrittlement of the reactor pressure vessel; heat-up and cool-down P-T limits, pressurized thermal shock and upper shelf energy. For an older plant, low upper shelf fracture mechanics analysis and detailed plant-specific PTS analysis may be required to demonstrate acceptable safety margins throughout the operation period. In addition to these activities, a comprehensive embrittlement management strategy is required for maintaining reactor pressure vessel integrity in relation to nuclear power plant lifetime management. To proceed with this strategy effectively, a practical methodology should be established in advance for preparing for plant lifetime

extension. Thermal annealing is considered to be the best option and thus an integrated program and engineering approach are necessary to evaluate the feasibility of thermal annealing. Although thermal annealing has not been yet applied to commercial operating PWR plants except the VVER units, a quantitative evaluation of embrittlement recovery due to thermal annealing and the subsequent reembrittlement trend is required to assess the feasibility of continued operation. In this paper, an integrated thermal annealing evaluation program that can be used for evaluating recovery percent, material properties in post-annealing, reembrittlement trend, and vessel lifetime is introduced and the application to a nuclear power plant is illustrated.

2. IRRADIATION EMBRITTLEMENT MANAGEMENT

To develop remedial measures for mitigating effects of irradiation embrittlement, various methods such as fuel management, neutron shielding, pre-stressing and thermal annealing can be viewed as available options in a nuclear plant embrittlement management program. The fuel management and neutron shielding are options available for reducing fluence accumulation in the reactor pressure vessels[1]. The prestressing e.g. with a memory band mechanically wound on the outside surface has been suggested as a potential method for preventing PTS failures[2]. The thermal annealing is the last option for considering the nuclear plant life extension. These irradiation embrittlement management options in terms of implementation timing are shown in Fig. 1.

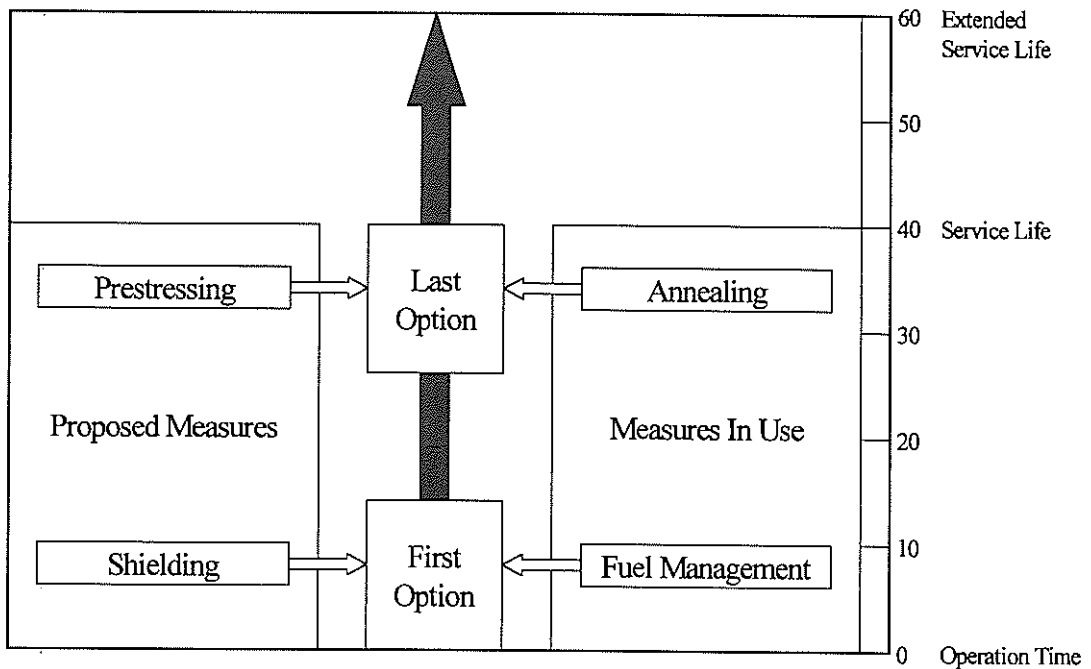


Fig. 1. Irradiation Embrittlement Mitigation Options

3. REACTOR PRESSURE VESSEL THERMAL ANNEALING

Thermal annealing is a heat treatment wherein the reactor pressure vessel beltline material is heated above the normal operating temperature and maintained at that temperature about 1

week[3]. This heat treatment effectively relieves the embrittlement damage to the steel's microstructures and restores the ductility of the material to nearly its unirradiated level[4]. Many metallurgical studies have been performed on reactor pressure vessel materials that show that thermal annealing can recover the fracture toughness properties of the reactor pressure vessel. However, limited information is currently available on the rate of reembrittlement of reactor pressure vessel materials following a thermal annealing treatment. If reembrittlement occurs quickly for a given material and annealing time/temperature combination, the economic benefits regarding continued operation could be less than desired [5]. Therefore, knowledge of the embrittlement recovery and reembrittlement rate is important to optimize the annealing condition and to provide for maximum material property recovery. In this respect, it is required to develop a tool for evaluating the data in terms of recovery and reembrittlement rate and assisting engineers in plant aging research and embrittlement management.

4. THERMAL ANNEALING EVALUATION PROGRAM

A thermal annealing evaluation program has been developed to assist users in assessing the effects and effectiveness of thermal annealing on reactor pressure vessel materials. This program is operated on a PC based Microsoft Windows 95 or 98 operating system.

4.1 BASIC EQUATION

According to regulatory guide 1.162, "Format and content of report for thermal annealing of reactor pressure vessels", percent recovery of $RT_{NDT}(R_t)$ and percent recovery of $USE(R_{USE})$ are evaluated using Eq. (1) and (2), respectively[6,7]. Once the value of R_t and R_{USE} are determined from the surveillance data or calculation, the post-annealing reference temperature(RT_{NDT}) and upper shelf energy(USE) are evaluated. According to lateral shift method, reembrittlement for the RT_{NDT} and USE of the post-annealing operating period is evaluated using Eq. (3) and (5), respectively.

○ RECOVERY PERCENT OF $RT_{NDT} : R_t$

$$R_t = [0.5 + 0.5 \tanh\{(a_1 T_a - a_2) / 95.7\}] \quad (1)$$

Where, Φ : neutron flux (n/cm^2 -s)
 T_i : irradiation temperature ($^{\circ}F$)

○ RECOVERY PERCENT OF USE : R_{USE}

$$R_{USE} = \{[1 - 0.586 \exp(-t_a / 15.9)] \times [0.570 \Delta USE_i + (0.120 T_a - 104) Cu + 0.0389 T_a - 17.6]\} \times \{100 / \Delta USE_i\} \quad (2)$$

Where, ΔUSE : unirradiated mean USE - mean USE after irradiation
 t_a : annealing time (hr)
 T_a : annealing temperature ($^{\circ}F$)
 Cu : copper contents of material (wt%)

○ REEMBRIITLEMENT OF RT_{NDT}

$$RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT} + M \quad (3)$$

$$\Delta RT_{NDT} = (CF)(f + f_i)^{0.28-0.11\log(f+f_i)} \quad (4)$$

Where, $RT_{NDT(u)}$: reference temperature of the material in the unirradiated condition

M : margin term to account for uncertainties

○ REEMBRITTEMENT OF USE

$$C_v USE = C_v USE_{(u)} \times [1 - D/100] \quad (5)$$

$$D = (100Cu + 9) \cdot (f + f_s)^{0.2368} \quad \text{base metal}$$

$$D = (100Cu + 14) \cdot (f + f_s)^{0.2368} \quad \text{weld metal} \quad (6)$$

$$D = 42.39 \cdot f^{0.1592} \quad \text{upper bound}$$

Where, $C_v USE_{(u)}$: upper shelf energy of the material in the unirradiated condition

4.2 PROGRAM DESCRIPTION

This thermal annealing evaluation program can be used for predicting percent recovery of material properties and the embrittlement trend after annealing. Specific plant information such as thermal annealing implementation timing, vessel geometry and initial material properties is required for predicting thermal annealing recovery and the reembrittlement trend. This program is composed of a plant information management module, data management module, and evaluation module. The configuration of each module is shown in Table 1. Also, the system flow within the application is shown in Fig. 2.

Table 1. Configuration of the Thermal Annealing Evaluation Program

| Main Module | Description | Remark |
|-------------------------------------|--|--------|
| Plant Information Management Module | Beginning of Operation / EOL Vessel Geometry Data Operation Time Temperature of Irradiation(°F) | |
| Data Management Module | Fluence Data Surveillance Data Material Data(Welds Metal, Base Metal) | |
| Evaluation Module | Prediction of Recovery(RT_{NDT} , USE) Prediction of Reembrittlement(RT_{NDT} , USE) | |

The plant information module as shown in Fig. 3 is composed of plant specific data such as vessel geometry, material data, operation time. Likewise, the plant data management module is composed of fluence and surveillance data. Finally, the thermal annealing evaluation module predicts the recovery percent and the reembrittlement trend for the vessel materials by applying the thermal annealing condition as shown in Fig 4. In order to utilize the thermal annealing evaluation program, it is necessary to specify the thermal annealing conditions, that is, annealing parameters which include annealing zone, chemistry factor(CF) evaluation criteria, annealing temperature and time, and timing of thermal annealing. The annealing zone can be selected as either base metal or weld

metal. Chemistry factor, CF is calculated using the surveillance data or Reg. Guide 1.99 Rev. 2 in accordance with the availability of surveillance data. If the surveillance data is available, CF can be calculated by using the existing surveillance data. Otherwise, CF is calculated by using the Cu and Ni contents according to the Reg. Guide 1.99, Rev. 2. Also, annealing temperature and annealing time are specified and a point of time for the annealing implementation is considered.

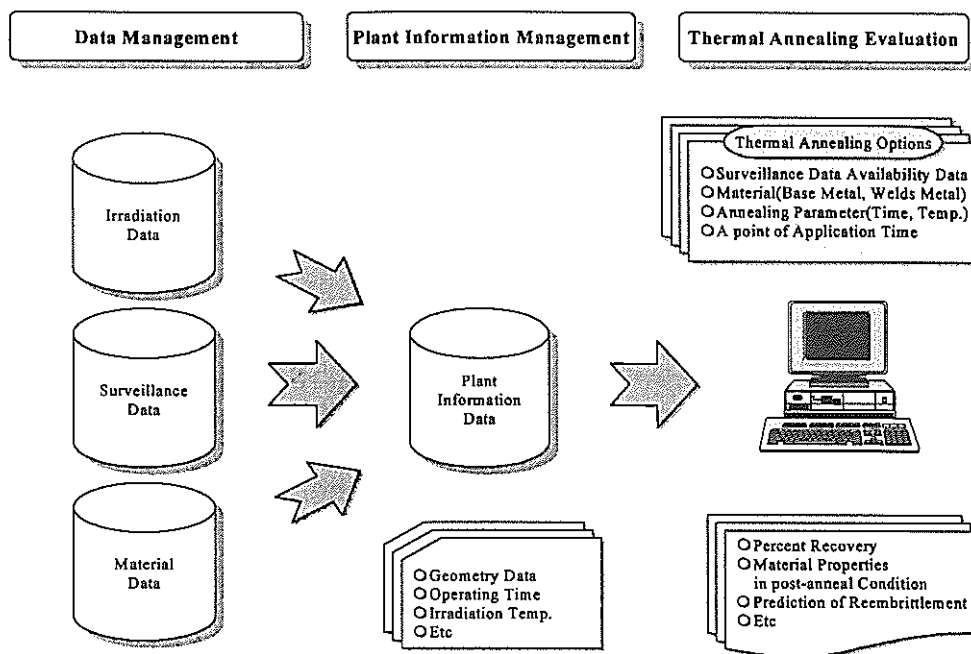


Fig 2. System flow within Application

4.3 PROGRAM APPLICATION

With respect to plant lifetime management, the thermal annealing evaluation program is applied to a domestic (Korean) nuclear power plant to predict percent recovery of material properties and the reembrittlement trend. To predict RT_{NDT} and USE after annealing by using this program, geometry input data package of the nuclear power plant and several assumptions are provided. The assumptions for the evaluation are shown in Table 2. The thermal annealing parameters are considered as optimal conditions which are 850°F for annealing temperature and 168 hours of annealing time. The evaluation result indicates that percent recovery of RT_{NDT} and USE reach up to 82% and 100%, respectively. Fig. 5 and Fig. 6 show the percent recovery of material property as a function of annealing parameter. Thus, it is possible to utilize these results for assessing reactor pressure vessel integrity in relation to the plant life extension. In addition, by using this program, reembrittlement trends of material properties can be easily predicted as shown in Fig 7 and Fig. 8. Based on the post-anneal material properties and reembrittlement trends, it can be judged that continued operation of additional 20 years is feasible after thermal annealing implementation, with 40 years of operating before annealing. Therefore, for this nuclear power plant, it is feasible to perform thermal annealing as a last option for mitigating irradiation embrittlement.

Table 2. Thermal Annealing Condition and Percent Recovery

| Parameters | Condition | Percent Recovery |
|---------------------------|--|---------------------------------------|
| Base Metal | SA-508 Class 1 | RT _{NDT} : 82% USE : 100% |
| Weld Metal | Linde 80 | |
| Annealing Timing | 4.114 x 10 ¹⁹ n/cm ² | |
| Annealing Temp. | 850 °F | |
| Annealing Time | 168 Hr | |
| Initial RT _{NDT} | -10 °F | |
| Irradiation Temperature | 550 °F | |
| Cu Content | 0.29 % | |
| Initial USE | 78 ft-lb | |
| Irradiated USE | 35 ft-lb | |

5. CONCLUSION

Thermal annealing can be viewed as a part of an irradiation embrittlement mitigation program as part of plant lifetime management. To implement thermal annealing on an operating nuclear power plant, a practical engineering tool is required to evaluate the feasibility. In this regard, a thermal annealing evaluation program has been developed to predict and evaluate the recovery percent of material properties and the reembrittlement rate after annealing. Results of a sample application of this program are presented on the basis of sample data for a domestic nuclear power plant. This program can be used as a tool to assess the feasibility of plant lifetime extension and the annealing response for a reactor pressure vessel. Finally, the evaluation program will be upgraded in the near future in order to improve its function.

REFERENCE

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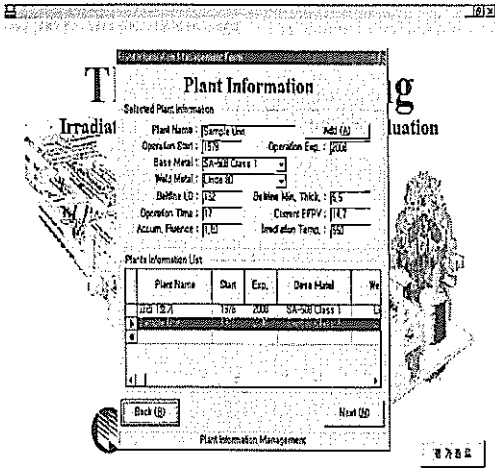


Fig. 3. Plant Information

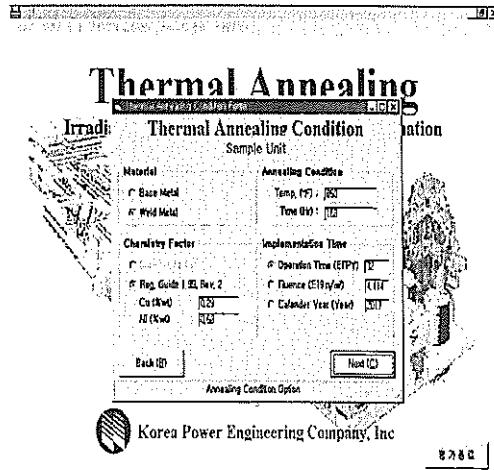


Fig. 4. Thermal Annealing Condition

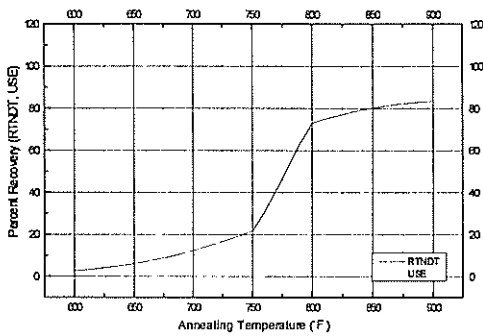


Fig. 5. Percent Recovery of RT_{NDT} and USE as a Function of Annealing Temperature

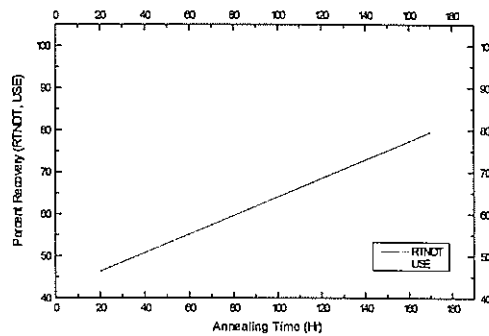


Fig. 6. Percent Recovery of RT_{NDT} and USE as a Function of Annealing Time

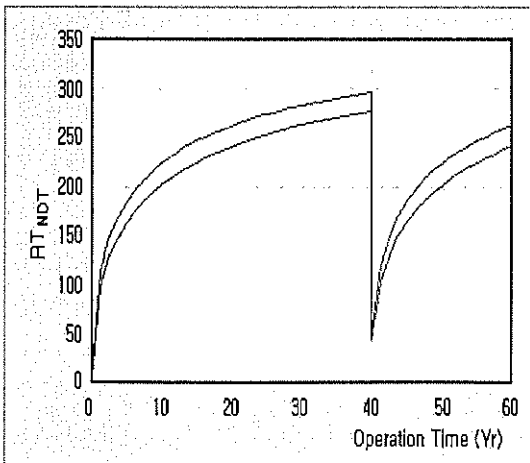


Fig. 7. Reembrittlement Trend of RT_{NDT}

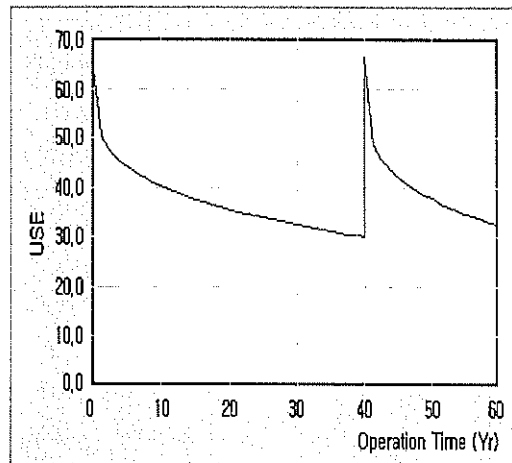


Fig. 8. Reembrittlement Trend of USE