*Transactions of the Korean Nuclear Society Autumn Meeting*
*Gyeongju, Korea, October 25-26, 2012*

# Overview of Long-Term Operation and Reactor Pressure Vessel Thermal Annealing

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## 1. Introduction

Thermal annealing can be applied to reactor vessel to recover the fracture toughness of reactor vessel materials of nuclear power reactor where neutron radiation has reduced the fracture toughness. 10CFR Part 50 Appendix G rule require the demonstration of an adequate margin of safety for reactor vessels. These rules are based upon calculation procedures which comply with the procedures specified in the ASME Code, Appendix G [1].

Since the reactor vessel beltline region is subjected to neutron radiation embrittlement, the actual margin of safety can change with time. 10CFR Part 50 Appendix G identifies thermal annealing of the reactor vessel beltline region to recover fracture toughness properties of the material. Further, 10CFR Part 50 Appendix G specifically requires that the reactor vessel be capable of being thermally annealed if $RT_{NDT}$ exceeds 94°C (200°F).

This paper reviews status of Long-Term Operation in overseas and domestic nuclear industry, thermal annealing experience in overseas, and recovery of material properties that can be achieved by thermal annealing for domestic nuclear power plant.

## 2. Long-Term Operation

### *2.1 Status of License Renewal in U.S.*

Among the 104 units, 73 units have received license renewal allowing operation up to 60 years in U.S. 9 units entered their 41st year of operation. It is expected that all plants will apply for the first license renewal period. A late 2007 survey of senior executives from 23 of the 26 U.S. nuclear operating companies revealed that more than 95% of those interviewed had given some or a lot of thought to long term plant operation, and more than 85% felt operation past 60 years was somewhat or very likely.

### *2.2 Long-Term Operation Issues in Overseas and Domestic Nuclear Industry*

Recognizing the many technical challenges confronting nuclear plant operation to 60 or 80 years and beyond, Long-Term Operation (LTO) Project was launched in U.S. Long-Term Operation is provide technical basis for extended nuclear plant operation to 80 years and beyond by identifying and overcoming key technical barriers. Issues to be addressed in all area for LTO were presented in LTO project and shown in Table 1. Totally, 17 primary issue and 43 sub issue were identified. Of these issues, LTO project has been actively working on 17 issues up to now.

Table 1: Long-Term Operation Issues

| | Primary Issues | Sub Issues | Ongoing Work |
|---|---|---|---|
| 1 | Primary system metal aging | 12 | 4 |
| 2 | Concrete aging | 3 | 2 |
| 3 | SSC monitoring, diagnostic and prognostics | 3 | 2 |
| 4 | Digital I&C modernization and enhanced | 2 | 2 |
| 5 | Fuel design and performance | 4 | 1 |
| 6 | Risk informed safety analysis | 5 | 2 |
| 7 | Environmental interface | 1 | - |
| 8 | Integrated life-cycle-management | 3 | 2 |
| 9 | Cable aging | 1 | 1 |
| 10 | Underground equipment aging | 2 | - |
| 11 | NDE technology advancement | 1 | - |
| 12 | Design, licensing and configuration improvement | 1 | - |
| 13 | Equipment qualification improvement | 1 | - |
| 14 | Coating | 1 | - |
| 15 | Integrated DB for aging mechanisms | 1 | - |
| 16 | Welding technology | 1 | - |
| 17 | Potential life limiting issues | 1 | - |
| | Total | 43 | 17 |

Among the 17 primary issues, the area of “primary system metal aging” contains 12 sub issues. Table 2 shows the LTO issues, specifically, in the area of “Primary system metal aging”. As indicated in Table 2, 7 sub issues including “reactor pressure vessel thermal annealing” were prioritized as “High”. Detailed study on these high priory issues should be performed in consideration of subsequent continued operation (CO) beyond design life.

Table 2: Primary System Metal Aging Issues of Long-Term Operation

| | Detailed Sub Issues | Cat. | Priority |
|---|---|---|---|
| 1 | Environmental SCC of Ni alloy | A | H |
| 2 | Environmental SCC of stainless steel | A | H |
| 3 | IASCC of austenitic and cast stainless steel | A | H |
| 4 | RPV embrittlement from long term fluence | A | H |
| 5 | Surveillance capsules with fluence of 60-plus years | A | H |
| 6 | Expansion of MDM and IMT | B | H |
| 7 | Determination of RPV cold over-pressurization life limits | A | L |
| 8 | Advanced alloys and fabrication methods for RVI replacement | B | L |
| 9 | Environmental effect on fracture resistance of Ni lloy | B | M |
| 10 | Environmental effects on fatigue life | B | M |
| 11 | Irradiation-induced creep of reactor internals | B | L |
| 12 | Thermal annealing of reactor pressure vessel | B | H |

[Note] A: Life limiting, B : Life cycle management. C: Modernization, D: Enabling technology

## 3. Thermal Annealing

*3.1 Thermal Annealing Experience in Overseas*

The US Code of Federal Regulations (CFR) identifies thermal annealing of the reactor pressure vessel beltline region to recover the fracture toughness properties. It has been demonstrated that annealing of irradiated RPV materials restores the mechanical properties [2]. Annealing of 15 WWER-440 RPVs in the Russian Federation, Armenia, Bulgaria, Slovakia and Finland was carried out successfully. There are seven WWER-440 RPVs still in operation after annealing. However, thermal annealing has not been implemented for operating nuclear power plant in U.S.

*3.2 Preliminary Study on the Thermal Annealing for Domestic Operating Nuclear Power Reactor*

There are two methods of thermal annealing an embrittled reactor pressure vessel: wet and dry. Full recovery of material properties can be obtained by dry annealing. Based on the previous studies and regulatory guide, the extent of fracture toughness recovery as a function of annealing time and temperature was predicted for domestic neutron embrittlement-sensitive reactor pressure vessel materials. To predict $RT_{NDT}$ and USE after annealing, input data and several assumptions were provided. As shown in Fig. 1~2, optimal thermal annealing condition is considered as 850$^{o}$F for annealing temperature and 168 hours for holding time. The evaluation result indicates that percent recovery of $RT_{NDT}$ and USE reach up to 82% and 100%, respectively.

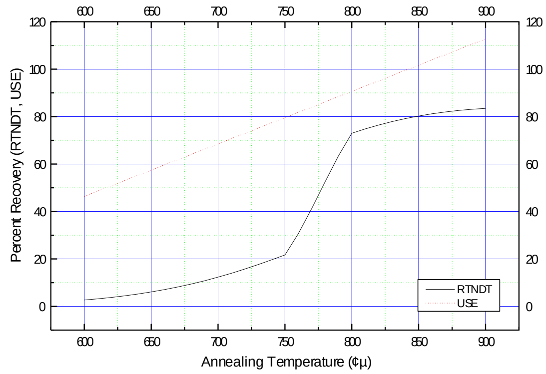


Fig. 1 Percent Recovery of $RT_{NDT}$ and USE as a function of annealing temperature

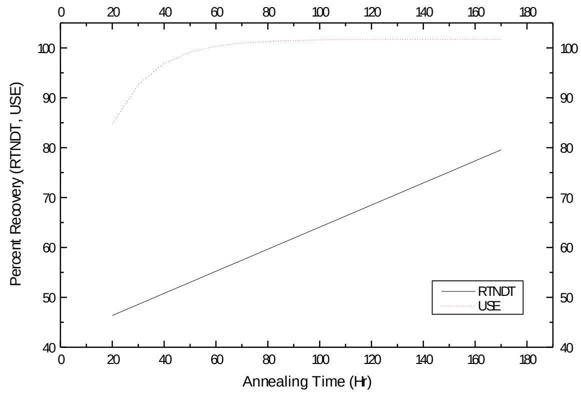


Fig. 2 Percent Recovery of $RT_{NDT}$ and USE as a function of annealing time

## 4. Conclusion

Thermal annealing can be viewed as available options and considered as the last option to address irradiation embrittlement of reactor pressure vessel for continued operation. In this regard, it is necessary to conduct detailed study of reactor pressure vessel thermal annealing focusing on its implementation in the near future reflecting the current circumstance of domestic nuclear industry.

## REFERENCES

[1] Regulatory Guide 1.162, Format and Content of Report for Thermal Annealing of Reactor Pressure Vessel, US Nuclear Regulatory Commission, 1996.
[2] Thomas R. Mager, Thermal Annealing of an embrittled reactr vessel:feasibility and methodology, Nuclear Enginering and Design 124, 1990.