Reactor Pressure Vessel Aging at Extended Operation - Thermal Annealing of Reactor Pressure Vessels

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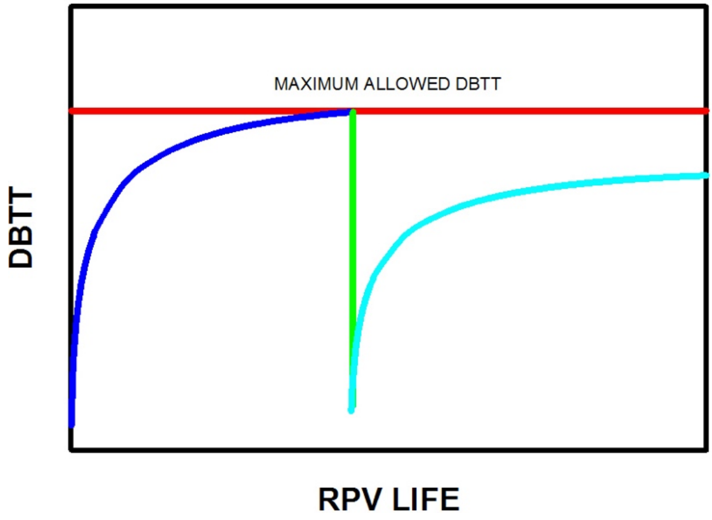
Subsequent License Renewal Has Been Driven by Ability of Critical Materials to Satisfy Current Regulatory Requirements

- For Turkey Point Units 3 and 4, the circumferential beltline RPV weld is the critical component and it has passed acceptance, **by mostly, applying the Master Curve RT_{To} rule.**
- It is anticipated that most Units applying for SLR will use similar approach as well.
- While this is the very valuable approach, **once this margin is used up, the NPP will not be able to extend its operation**.
- The only technology that has been demonstrated (internationally and in the US) to extend the life of the RPV and the life of the NPP is thermal annealing.



What is and is not RPV Thermal Annealing?

- It is **not a traditional metallurgical anneal** at temperatures up to about 1000^{o}C
- **It is a localized area heat treatment of the RPV** (at lower temperatures between 340^{o}C and 500^{o}C) and for a long holding time (up to 168 h)
- **Material mechanical properties are partially or fully recovered, but resulting fine scale microstructure is different**
- Re-irradiation response can be different due to the different starting microstructure

Vessel Annealing

- Thermal annealing is the only proven option that can recover irradiated beltline material transition temperature shift and recover upper shelf energy properties lost during radiation exposure and extend RPV service life
- The beltline region is heated to 340 to 560°C
- Amount of mechanical property recovery is function of:
  - Difference between the irradiation and thermal anneal temperatures
  - Time of annealing
  - Material chemistry
  - Degree of pre-existing irradiation damage

Vessel Annealing – Wet Anneal

- Two basic types of annealing
  - **Wet anneal**
  - Dry anneal
- Wet anneal is performed at temperatures < 650°F (343°C)
- Reactor coolant water is generally heated by the RCPs
- Wet annealing is not as complicated from an engineering viewpoint because primary water temperature is controlled by pump heat up to the vessel design temperature of 343°C
- Wet anneals have been successful on two test reactors, SM-1A (US Army, Alaska, 1967) and BR3 (Belgium, 1984) and they operated near 260°C for a short time after annealing

Vessel Annealing – Dry Anneal

- Dry anneals are performed at higher temperatures than wet anneals
  - Use air as the heating medium inside of radiant can
  - Electric-resistance heating source
- Dry annealing requires removal of core internal structures and primary water so that a radiant heating source can be inserted near the vessel wall to locally heat the embrittled beltline region
- **Engineering difficulties of dry anneal process are quite complex and may need plant-specific evaluations to assure that other portions of the plant (eg., concrete) are not harmed by the high annealing temperatures**

US Vessel Annealing Recovery Results

Annealing recovery test results on US RPV steels found:

- Annealing at 850°F (454°C) resulted in complete recovery of USE, and 75% or more recovery of the Charpy 41 J transition temperature shift
- Annealing at 343°C provided significantly less benefit
- **EPRI report TR-106001, Dec. 1995 reported results of some irradiation embrittlement and re-annealing studies for Yankee Rowe related materials**
  - Annealing at 454°C resulted in recovery of 80-100% of the transition temperature and 100% recovery of the USE
  - Annealing at 343°C resulted in about a 40% recovery in transition temperature

Marble Hill Demonstration Project

- In 1990's a joint DOE/industry-sponsored Annealing Demonstration Project (ADP) was conducted at the Marble Hill facility (a partially completed Westinghouse plant) to demonstrate feasibility
  - Nozzle-supported four loop Westinghouse design vessel -- canceled plant (unirradiated vessel)
  - Indirect gas-fired heating method was chosen
  - DOE funding lost after demonstration was completed, but **EPRI funded writing the Marble Hill report (EPRI TR-104934) and a final NRC report (NUREG/CR-6552) was also later published**

Midland Demonstration Project

- Skirt-supported Babcock & Wilcox-design vessel
- Electric resistance heating method (Russian technology and experience)
- Project approximately 50 percent complete when DOE funding eliminated
- Electric resistance heater fabricated and tested, but never shipped to the US from Russia
- **Demonstration was never completed**

Guidance for Thermal Annealing

- **10 CFR 50.66, “Requirements for thermal annealing of the reactor pressure vessel”**
  - Permits thermal annealing of LWRs
  - Requires a plan for conducting the thermal annealing be submitted at least three years before fracture toughness criteria are exceeded
  - Reg Guide 1.162 describes the format and content of an acceptable Thermal Annealing Report (TAR) and addresses the metallurgical and engineering issues that need to be addressed in an application to perform a thermal annealing

Concluding Remarks

- **Technology exists and has been proven for performing thermal annealing on VVER-440/1000 and PWR RPVs in the beltline region**
- Decision to anneal may involve more than technical or cost issues
  - Even if thermal annealing is not technically needed, a decision to anneal could benefit extended long term operation
    - **Guarantee that the fracture toughness properties are improved**
    - **Re-embrittlement rate should be reduced**