Thermal Annealing: A Fresh (80+) Look at Old (40+) Issue

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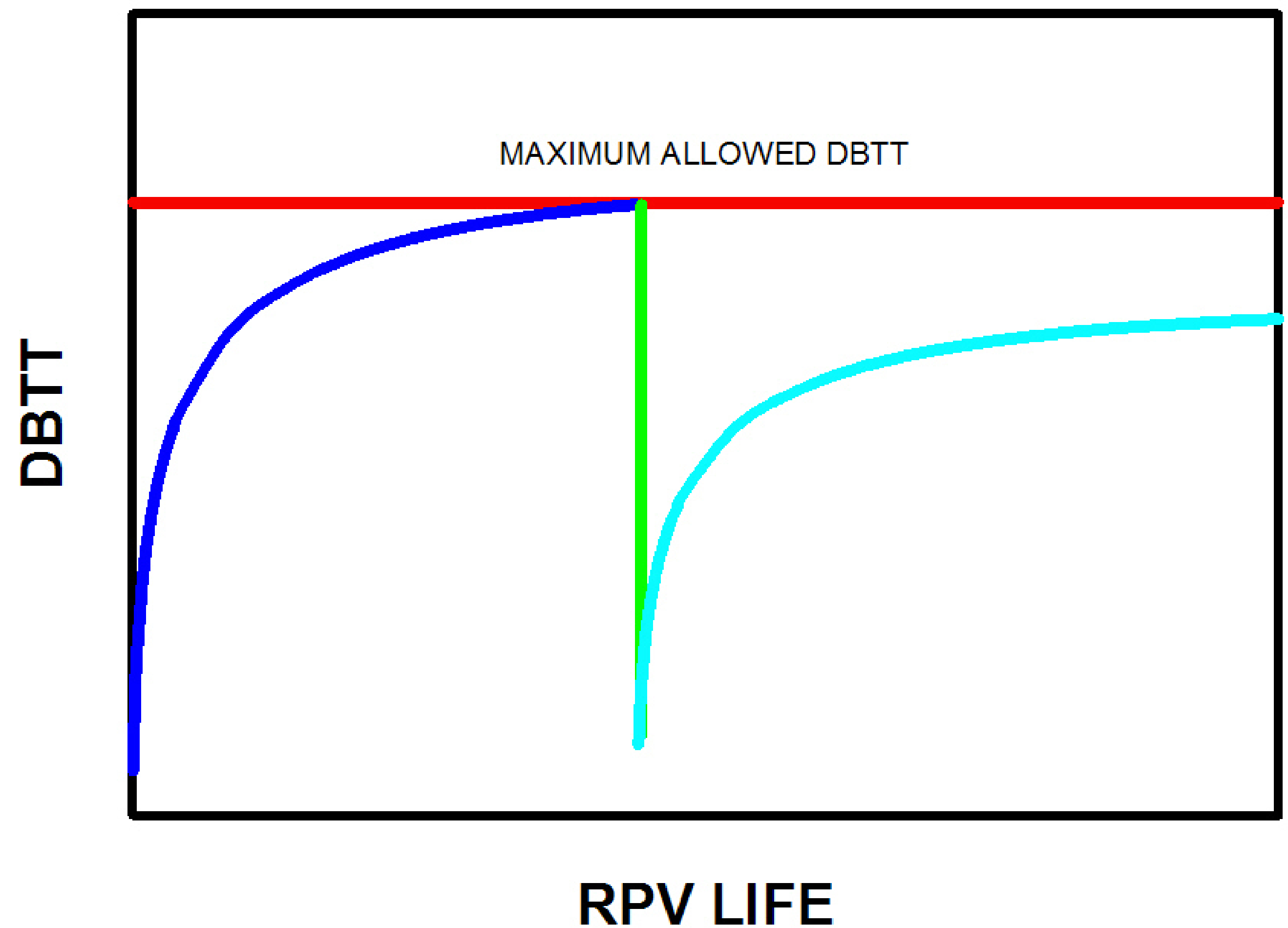
What is or is not RPV Thermal Annealing?

- 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 (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 the resulting fine scale microstructure is different
- Re-irradiation response can be different due to the different starting microstructure
- Thermal annealing is the only option that can, to some degree, recover the irradiated beltline region transition temperature shift and recover upper shelf energy properties lost during radiation exposure and, thus, extend RPV service life
- The degree 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

RPV Thermal Annealing



Vessel Annealing – Wet Annealing

- Two basic types of anneals
  - Wet anneal
  - Dry anneal
- Wet anneal is performed at temperatures ≤ 650°F (343°C)
  - Wet annealing is not as complicated from an engineering viewpoint because the primary water temperature is controlled by pump heat up to the vessel design temperature of 650°F (343°C)
- Wet anneals have been successful on two test reactors, SM-1A (US Army, Alaska, 1967) and BR3 (Belgium, 1984); they operated near 260°C for short time after the wet anneals
- EPRI performed research (TR-106001, Dec. 1995) to support wet annealing on Yankee Rowe.

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Vessel Annealing – Dry Annealing

- 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 using the dry anneal process are quite complex and may need plant-specific evaluations to assure that other areas of the plant (e.g., concrete) are not harmed by the high annealing temperatures
- 850°F (454°C) is regarded as an optimum “dry” annealing temperature

Most of the Annealing Recovery Work was done in the 80’s – 90’s

- In the 1980’s a study at Idaho National Laboratory assessed annealing feasibility for US RPVs including alternative heating methods
- In 1995 a study was conducted to determine if thermal annealing of the reactor vessel in Westinghouse 3 and 4 loop plants would be feasible
  - Thermal and stress analyses determined that stress, temperature and dimensions of the vessel and its associated components remain within acceptable limits
  - Conclusion: there are no major technical impediments to thermal annealing the vessels studied
- EPRI performed research (TR-106001, Dec. 1995) to support annealing on Yankee Rowe related materials
- In the 1990’s research on the effects of annealing recovery of irradiated RPV steels were performed at ORNL and UCSB as part of NRC Heavy Section Steel Irradiation (HSSI) Program

Marble Hill Demonstration Project

- In the 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
- Objectives
  - Demonstrate engineering feasibility of annealing system
  - Determine component thermal/stress response
  - Benchmark 3-D stress analysis models
  - Provide information to resolve regulatory concerns
  - Provide realistic cost data regarding equipment costs, modeling, etc.
- Marble Hill annealing demonstration was successful

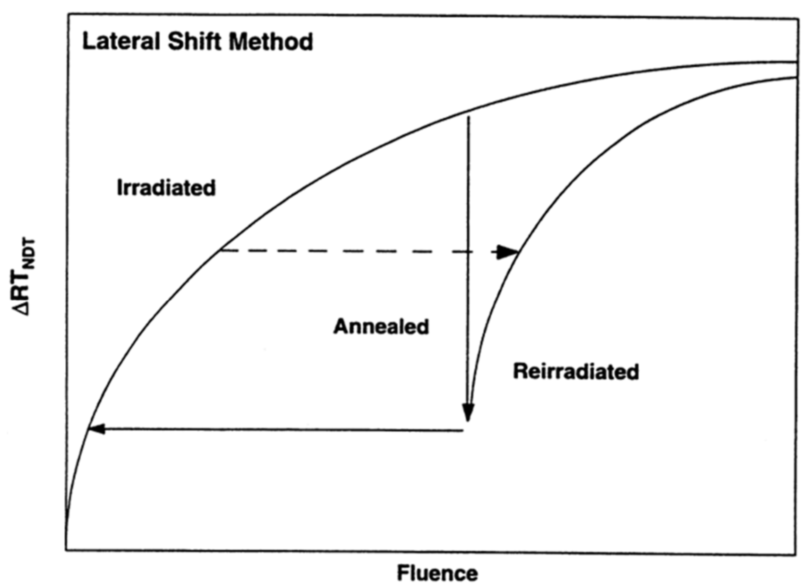
Why the Demonstration? – Palisades NPP

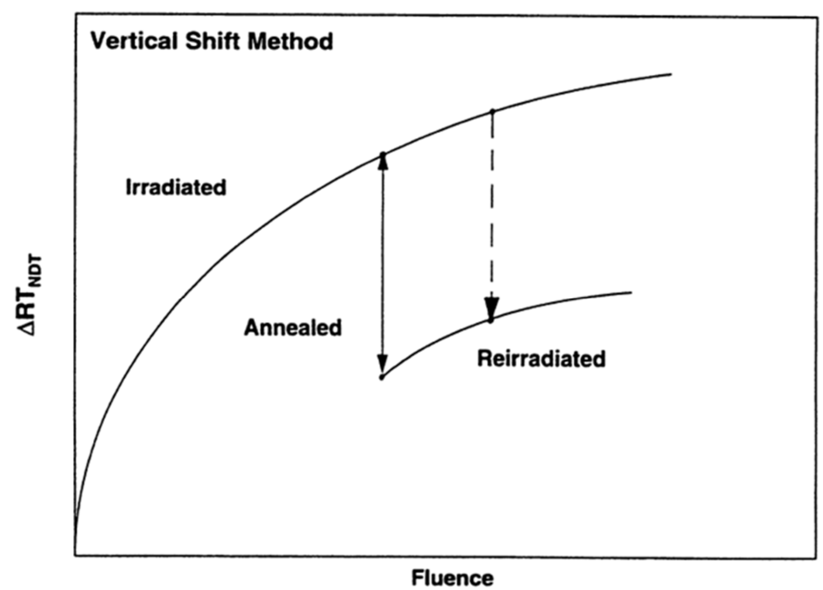
- Palisades was limited to operate until 1999 based upon PTS concerns for the most-limiting beltline weld metal heat
- This resulted in a plan to anneal in 1998 to recover properties and continue operation to at least 2011 and hopefully beyond
- Additionally, a supplemental surveillance program to assess material recovery and re-embrittlement trends for all beltline welds and the surveillance plate material was developed
- The annealing was canceled due to revised fluence estimates

US Rules, Regulations, and Guidance

- Annealing Rule in 10 CFR Part 50.66
- Annealing Rule and Regulatory Guide 1.162 contain references to NUREG/CR-6327
  - Predictive model for annealing recovery utilizing microhardness and CVN data to cover a broad range of annealing conditions
  - Model incorporates annealing time and temperature and neutron irradiation dose rate (flux)
- 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
- ASTM E 509 provides an expanded guidance on thermal annealing and the necessary supplemental material surveillance programs
- ASME Code Case N-557 “In-Place Dry Annealing of a PWR Nuclear Reactor Vessel (Section XI, Division 1)”

Methods Used to Predict Re-Embrittlement





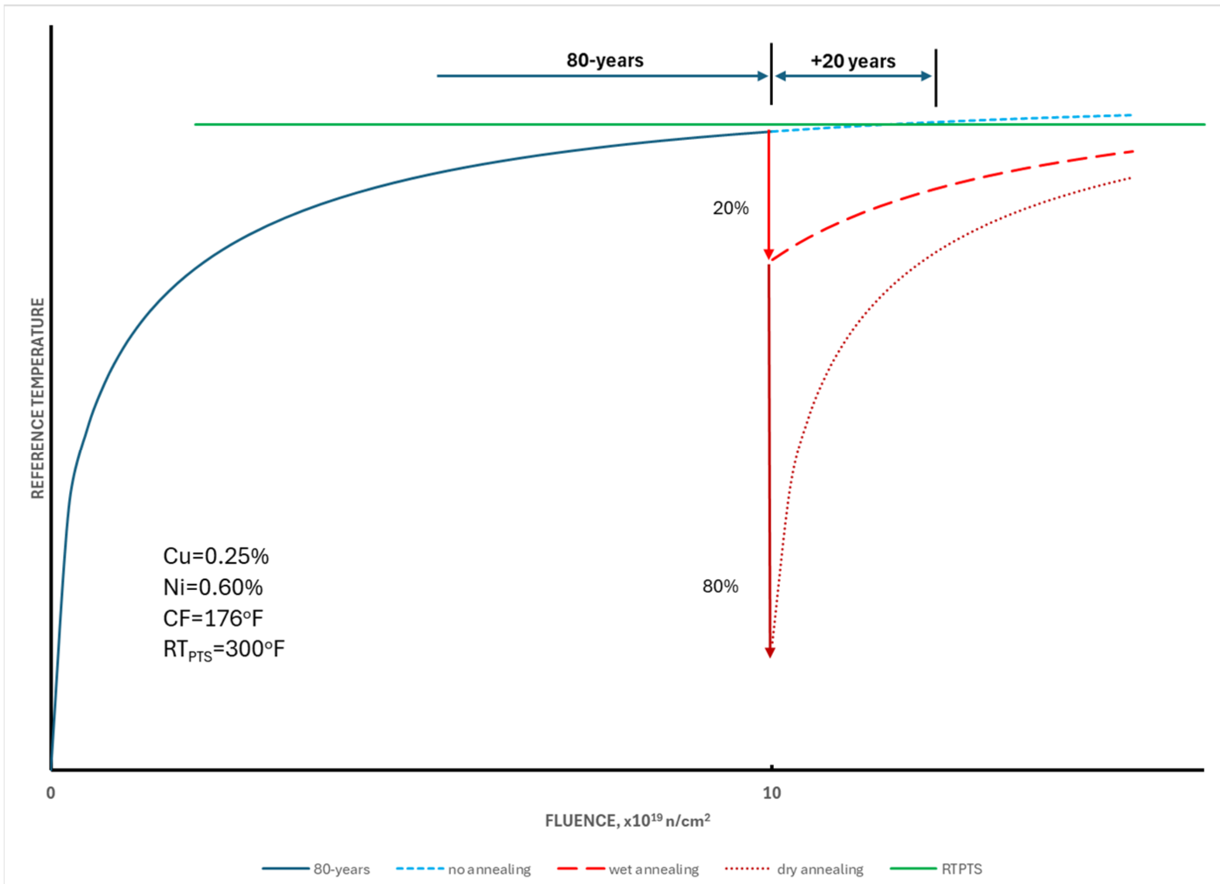
Why Do We Need Fresh Look at Annealing?

- A large amount of annealing data were accumulated by the end of 1990's to develop models that describe the recovery of mechanical properties after annealing, Those were mostly microhardness, Charpy, and Atom-Probe measurements.
- The majority of these data were generated from Test Reactor Irradiation experiments with Cu-bearing materials irradiated to fluences that were an order of magnitude lower than those that would be experienced by the beltline RPV materials after 80 years.
- As a result, this annealing model used in Codes and Regulations is based on data where annealing was aimed to recover embrittlement caused mainly by Cu-rich clusters.
- **Embrittlement of 80-year neutron-exposed beltline RPV materials will be dominated by Ni-Mn-Si clusters and no systematic studies have been performed so far to address thermal stability of these clusters at annealing conditions considered in 1990's.**

Why Do We Need Fresh Look at Annealing?

- The effectiveness of the annealing is <u>not</u> determined by percentage of recovery. The rate of <u>re-embrittlement</u> (or how long one can safely operate annealed RPV) <u>is the true measure</u> of effectiveness of annealing. Unfortunately, only a limited amount of re-irradiation experiments were performed in 1990's.
- Methods of annealing need to be reevaluated for 80-years-old plants as well
- High-temperature dry annealing will provide a high percentage of recovery and more likely another 80-years of RPV operating life. But it is complicated and expensive. Do we need to operate plant beyond 100 years?
- Low-temperature wet annealing will not recover as much DBTT shift as dry annealing. But it is relatively easy to perform, and it might be just enough to operate old reactors until new and more advanced energy sources become mature enough to replace the old plants.

Case Study



80-years
+20 years
20%
80%
Cu=0.25%
Ni=0.60%
CF=176°F
RTPTS=300°F
REFERENCE TEMPERATURE
0
10
FLUENCE, x10^19 n/cm^2
80-years
no annealing
wet annealing
dry annealing
RTPTS

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Sustaining National Nuclear Assets

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