Evaluation of mechanical properties for heat affected zone in WWER-1000 RPVs based on surveillance test data

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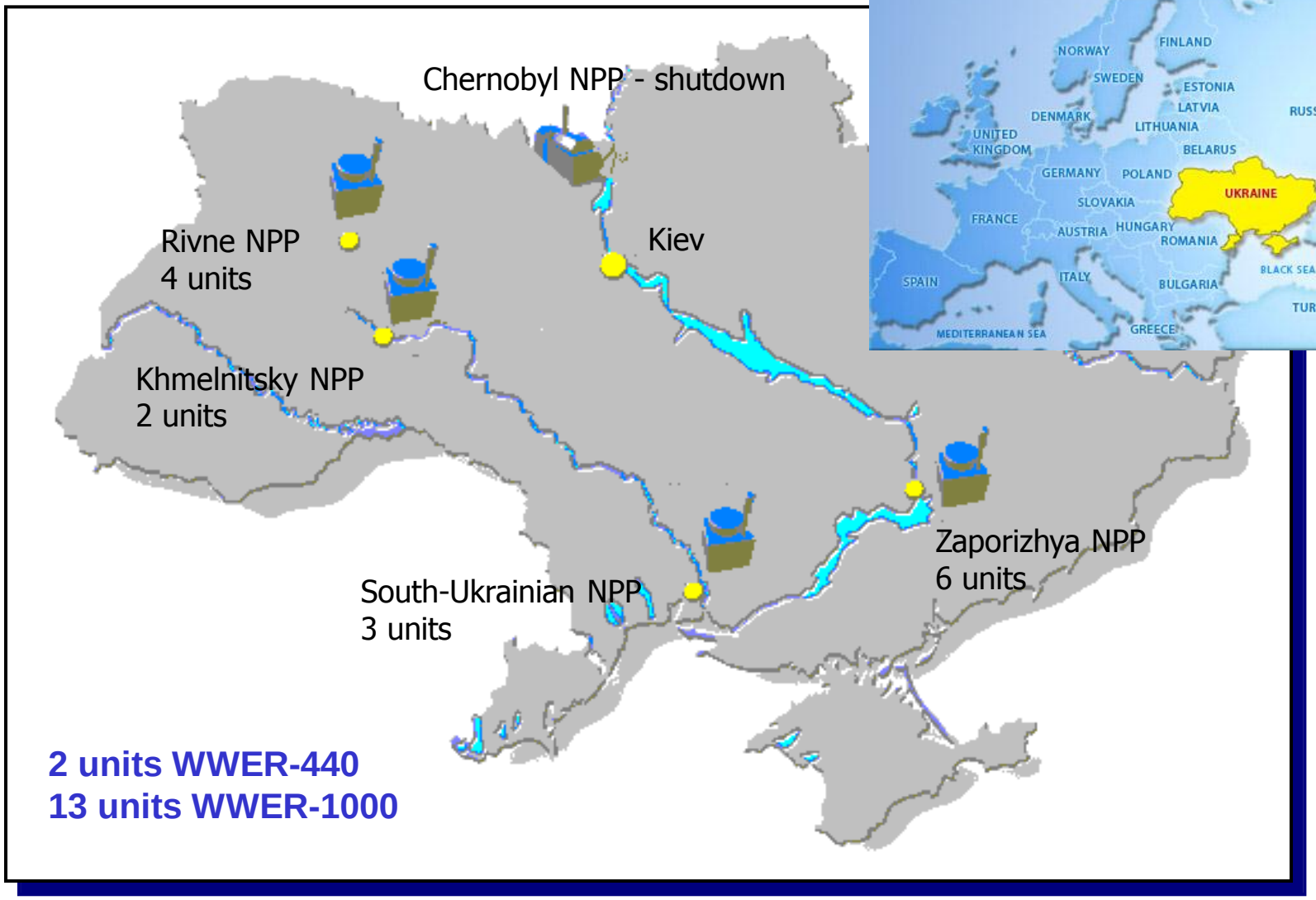
Location of Ukrainian NPPs



Introduction

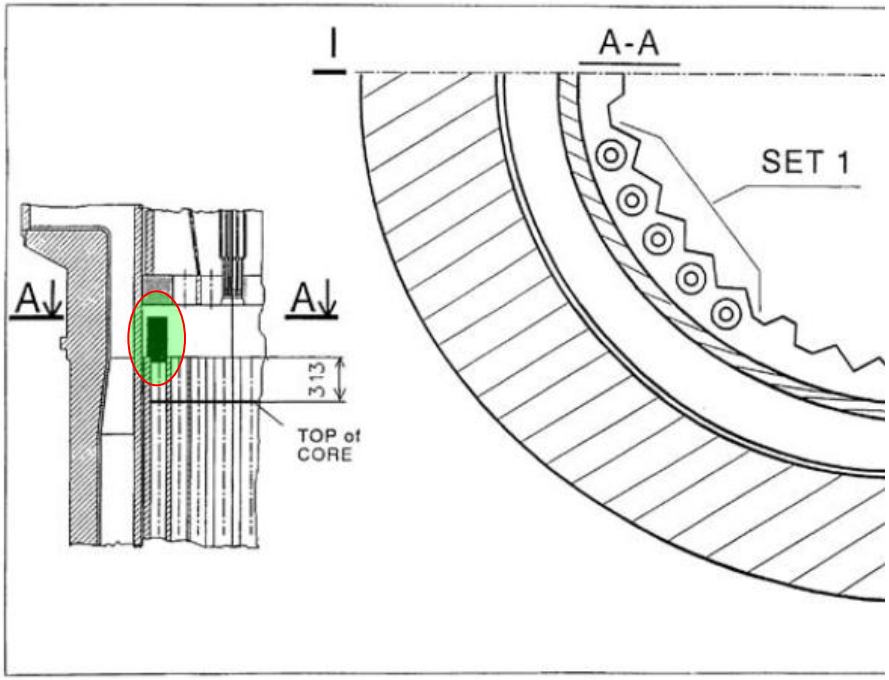
- One of the main topics of the periodical inspections is an evaluation of RPV metal degradation due to the operation factors (neutron irradiation, coolant temperature, etc.). Radiation embrittlement is considered as a key phenomenon in the RPV material degradation. To estimate the embrittlement effect the surveillance program is fulfilled for the specific nuclear power plant
- Specimens made of base, weld and heat affected zone metal are included in nomenclature of the surveillance program for WWER-1000 type reactor. Tension, Charpy impact and fracture toughness specimens are used to estimate the changes in the mechanical properties of RPV materials (yield strength increase, transition temperature and fracture toughness curve shift due to irradiation, etc)
- An experience has shown that HAZ metal in un-irradiated and irradiated condition reveals a high scatter in the test data for Charpy curve. not allow to determinate the radiation shift of transition temperature reliably so HAZ metal is not considered in the analysis of RPV material embrittlement
- In this study surveillance test data for HAZ metal has been analyzed in view point of radiation hardening and embrittlement in comparison to base and weld metal

Materials and test methods

- WWER-1000 RPV materials for nine NPP units operated in Ukraine were included in the analysis (HAZ surveillance test data are available). RPVs were manufactured by Izhora and Atommash (Russia)
- Base metal has medium Ni and Mn, low Cu and P content (except one RPV with 0,12 % wt)
  - Manganese 0,35 – 0,54 % wt
  - Nickel 1,1 – 1,26 % wt
  - Copper 0,05 – 0,12 % wt
  - Phosphorus 0,007 – 0,01 % wt
- Charpy impact test data is applied to evaluate radiation embrittlement
  - Standard Charpy V-notch specimens 10 x 10 x 55 mm
- Tension test data is used for estimation of radiation hardening rate
  - Round specimens with reduced diameter of 3 mm and a gauge length of 30 mm

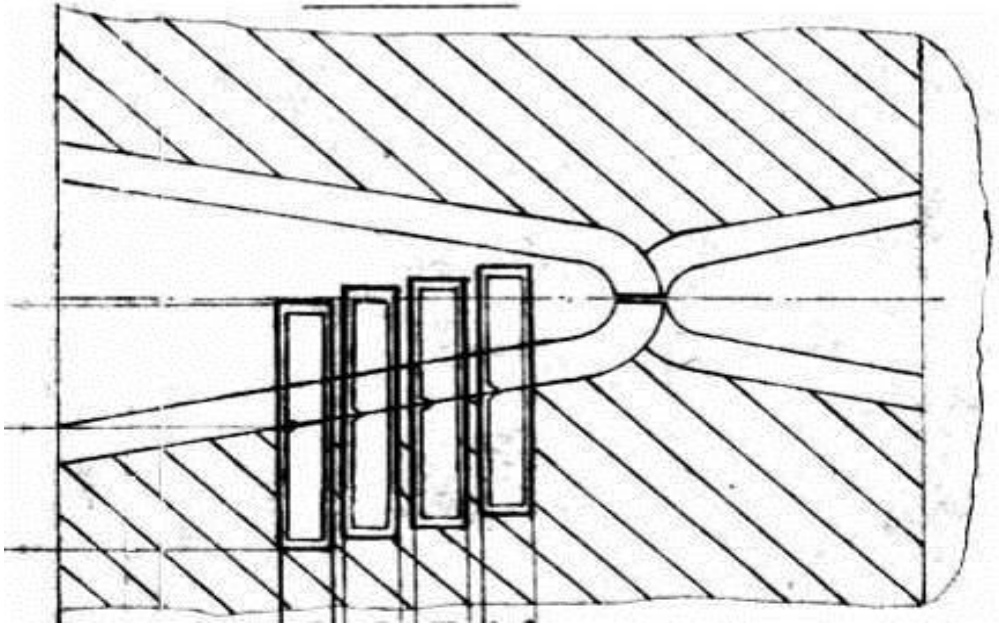
Irradiation condition

- Specimens were irradiated in the standard surveillance capsules and position
  - Max neutron fluence (E > 0,5 MeV) $68{,}7 \cdot 10^{22}$ m^{-2}
  - Neutron flux ~ 10^{15} $m^{-2} \cdot s^{-1}$
  - Irradiation temperature ~ 300°C
  - Maximum lead factor 3,5



WWER-1000 surveillance set position

CVN specimens for HAZ metal

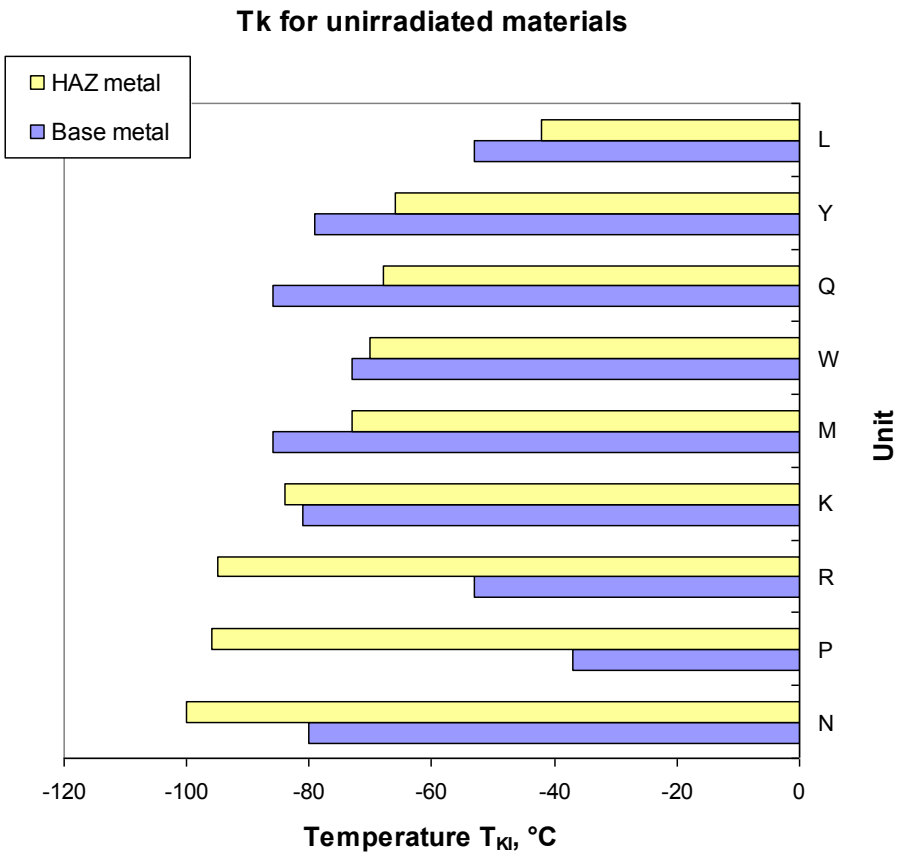


Cutting layout of HAZ specimens with T-S orientation

- In fact specimens are cut with different position of Charpy V-notch relative to base and welds (closer to or further from fusion line)
  - Difficult to estimate transition temperature reliably because of high scatter in the Charpy impact test data

Temperature T_{KI} for HAZ and base metal in un-irradiated condition

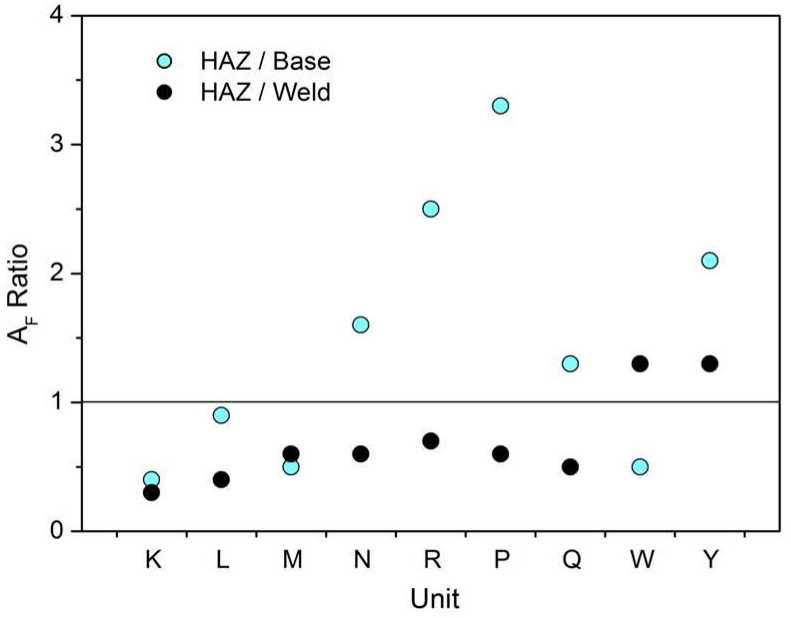
- In order to compare the ductile to brittle transition temperature of RPV materials the Charpy impact test data have been analyzed
- Transition temperature T_{KI} (corresponds to 47 J) for un-irradiated materials is low enough
  - - 86 to - 37 °C for base metal
  - - 100 to - 42 °C for HAZ metal
- In most cases the initial T_{KI} temperature for base metal is lower or comparable to that of HAZ metal



Charpy V-notch specimens – surveillance test data

Radiation embrittlement rate for HAZ relative to base and weld metal

- Comparison of HAZ with base metal and welds with regards to radiation embrittlement using A_F coefficient (functional equivalent for CF chemistry factor)
- For all reactor pressure vessels the radiation embrittlement rate for HAZ metal is lower than for base and/or weld metal with the exception of one RPV
- For Y unit reactor pressure vessel the susceptibility of HAZ metal to neutron irradiation is higher in comparison to base and weld metal
  - most probably related to a comparatively high content of copper (0,12 % wt.) and phosphorus (0,01 % wt.)

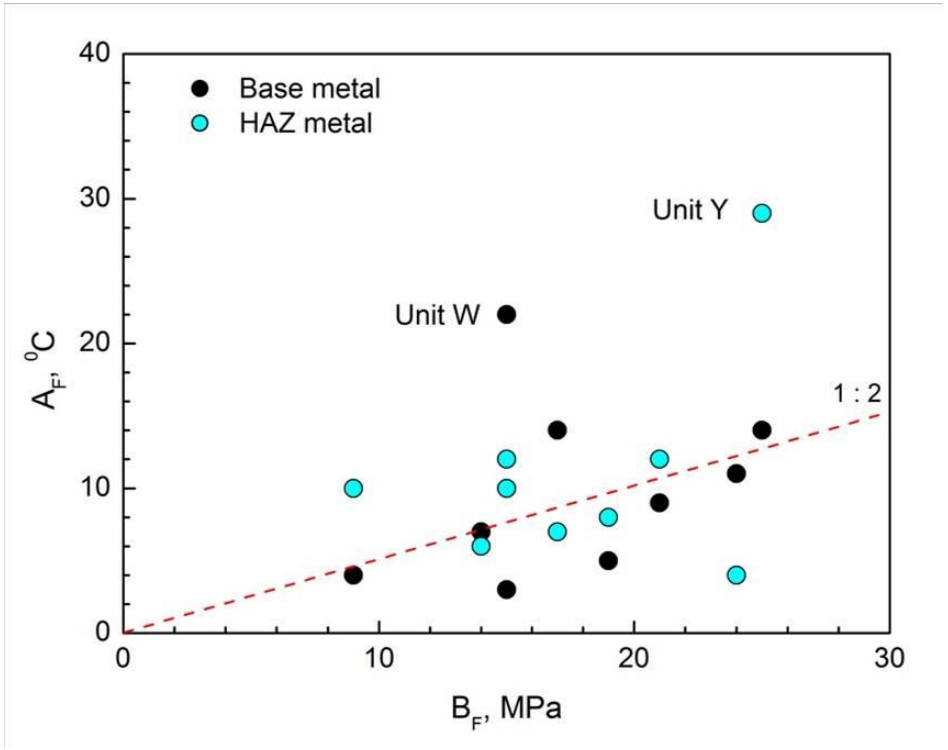


Ratio of A_F coefficients for RPV materials

(i.e. $\frac{A_F^{HAZ}}{A_F^{Base}}$ and $\frac{A_F^{HAZ}}{A_F^{Weld}}$) is used

Radiation hardening to embrittlement correlation for HAZ and base metal

- B_F and A_F coefficients have been applied to evaluate the increase of yield strength and the transition temperature shift respectively (PNAE G-7-002-86)
- Radiation hardening model
  - $\Delta R_{p0,2} = B_F \cdot F^{1/3}$
  - B_F is radiation hardening coefficient and F is fluence in the terms of 10^{22} m^{-2}
- Radiation embrittlement model
  - $\Delta T_F = A_F \cdot F^{1/3}$
  - A_F is radiation embrittlement coefficient
- Relation between yield strength increase and transition temperature shift due to irradiation results in a factor of 0,6 in average
  - close to a known empirical correlation $\Delta T_{41J} = 0{,}7 \cdot \Delta R_{p0,2}$ for pressure vessel steels



- For unit Y heat affected zone metal the high embrittlement rate is not consistent with radiation hardening

Conclusions

- In the most cases the initial T_{KI} temperature for base metal is lower or comparable to that of HAZ metal
- For all reactor pressure vessels considered in this study the radiation embrittlement rate for HAZ metal is lower than for base and/or weld metal with the exception of one NPP unit that most probably related to comparatively high content of copper and phosphorus in the RPV shell
- An unusual high embrittlement of HAZ metal for one WWER-1000 RPV is observed that does not comply with the radiation hardening rate considering the known empirical correlations between the transition temperature shift and increase in yield stress
- HAZ metal seems to be not the limiting material in the case of WWER-1000 RPV metal with low Cu and P