Advanced High-Fluence Low-Flux RPV Mechanical Property Models for Extended Life

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Program: RC-8: Materials Research Pathway: Characterization and Modeling of the High Fluence Effect On Reactor Pressure Vessel Steels.

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ABSTRACT:

The proposed work will further develop accurate models of the mechanical property changes under extended life conditions in reactor pressure vessel (RPV) steels. The RPV, which is permanent component of light water reactors (LWRs), is subject to neutron irradiation hardening and embrittlement. Thus, accurate embrittlement predictions are critical to LWR life-extension. Embrittlement is primarily caused by irradiation hardening $\Delta\sigma y$, and is manifested by an increase in the ductile to brittle transition temperatures (ΔT). Hardening is caused by the formation of nano-scale precipitates and various solute defect complexes, which act as obstacles to dislocation glide, and is directly relatable to ΔT. In the low to intermediate fluence (ϕt) stage of irradiation at $< \approx 4\times10^{19}$ n/cm2, the primary hardening features in typical RPV steels are Cu-rich precipitates. At higher ϕt Mn-Ni-Si precipitates grow slowly but result in enormous hardening and embrittlement. In spite of the deep understanding of embrittlement that has been developed over several decades, predictive ΔT models must still be empirically calibrated by service relevant databases. However, the surveillance database supporting current US regulatory embrittlement models is primarily limited to low to medium ϕt, which is less than half that experienced during 80 year extended life of many plants, and current ΔT regulatory models do not include the effect of Mn-Ni-Si precipitates. Accelerated test reactor irradiations, which can easily reach high ϕt, show that current models systematically and significantly underpredict embrittlement at high ϕt. However, the higher ϕ used in accelerate tests has a potentially strong effect on the embrittlement rates that is not fully established. Therefore, quantitative embrittlement models remain an open challenge.

This objective of this work is to develop new data, databases, physical understanding, and accurate models of the mechanical property changes under extended life conditions in reactor pressure vessel (RPV) steels. The work will integrate data from decades of development at University of California, Santa Barbara with international databases, as well as expanding on this data through additional studies. Data includes hardness measurements and extensive microstructural characterization with atom probe, (small-angle) x-ray scattering, transmission electron microscopy, and Resistivity-Seebeck coefficient measurements on an extraordinary range of compositions and irradiation conditions. Molecular kinetic Monte Carlo and mesoscale cluster dynamics modeling will be used to understand key missing physics of precipitate sink effects and associated influence of flux on hardening. The databases and understanding will inform a new generation of refined reduced-order physics-based models for $\Delta\sigma y$ and ΔT under LWR life-extension conditions. The physics-based models will be complimented by machine learning and coupled machine learning – physics analysis to explore proposed trends and data limitations. The results will be disseminated through an aggressive outreach effort targeting relevant industry, regulators, professional organizations, and the international community.

This work will create the most complete RPV embrittlement database in the world, providing a uniquely valuable international resource. The physics- and data-based models will yield new fundamental insight on the role of precipitates as sinks as well as critical engineering scale guidance for life extension, a major concern for the nuclear industry. These data and models will be disseminated through a targeted effort to engage the essential members of the RPV community.