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Nondestructive Evaluation (NDE) System for the Inspection of Operation-Induced Material Degradation in Nuclear Power Plants

Machine learning for non-destructive estimation of neutron-induced embrittlement of reactor pressure vessel steel

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www.nomad-horizon2020.eu

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 755330.

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2. Specimens and measurement methods
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Nuclear power in the EU

- Nuclear power is the most important source of low-carbon electricity in the EU
  - 25 % of all electricity
  - 50 % of low-carbon electricity
- European nuclear reactor fleet is growing old
  - Most of the reactors were built in the 1970s and 1980s
- We must understand material degradation phenomena for safe long-term operation of nuclear power plants

Charpy impact test (ISO 148)

- Ductility of metals with BCC crystal structure is a function of temperature
- Standardized method to determine ductile-to-brittle transition temperature (DBTT)
- A set of specimens is measured in varying temperatures
  - Pendulum energy loss as a function of a specimen's temperature is determined

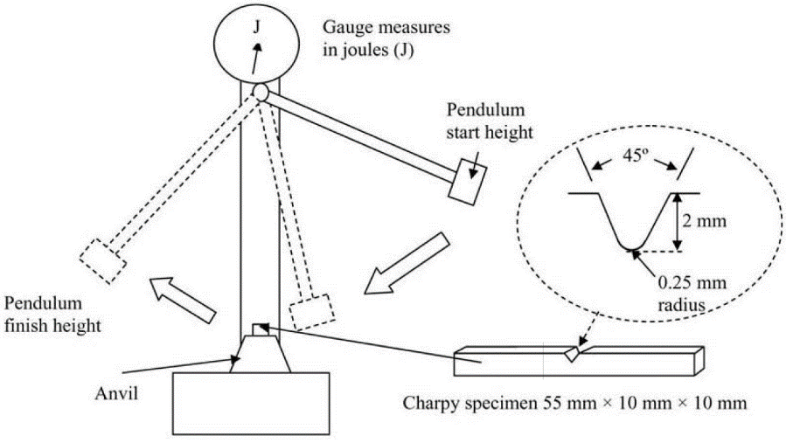


Image: S.E. Hughes. A Quick Guide to Welding and Weld Inspection. Quick Guides (ASME Press) Series. Matthews Engineering Training, 2009.

Neutron-induced embrittlement and DBTT

- Due to neutron irradiation, the reactor pressure vessel (RPV) becomes more brittle as the reactor ages
  - The embrittlement restricts the lifetime of the entire power plant
- Embrittlement can be measured through the DBTT
- The DBTT changes due to neutron radiation
  - Radiation leads to increased DBTT
  - RPV becomes brittle in higher temperatures

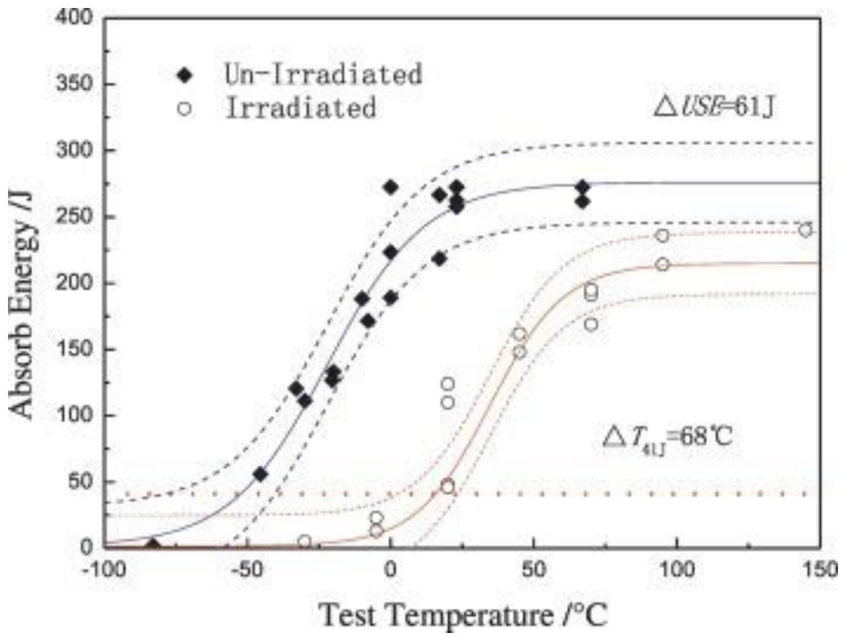


Image: Lin et. al, (2017), Engineering Failure Analysis

2. MEASUREMENT METHODS AND SPECIMENS

Specimens and irradiation

- 157 Charpy samples (ISO 148): both irradiated and non-irradiated
  - Six different steel alloys commonly used in RPVs: 15Kh2MNFA, 18MND5-W, 22NiMoCr37, A508-B, A508-Cl2 and HSST-03
- Several different irradiation conditions emulated actual pressurized water reactor operating conditions
  - Irradiation temperature ranged between 100 - 305 °C
  - Neutron fluence ranged between 1.55 - 9.36 · 10^{19} n/cm^2
- In total 22 different steel alloy – irradiation temperature – neutron fluence combinations

Applied measurement methods

- Six NDE methods were used to measure 29 different parameters related to electric, magnetic and elastic material properties
  - Electric (resistivity, Seebeck coefficient, eddy current impedance loop shape)
  - Magnetic (Barkhausen noise, magnetic permeability)
  - Elastic (sound velocity)

- ISO 148 Charpy impact test was used to determine the DBTT destructively

3. PREDICTION MODELS AND RESULTS

NOMAD Simulated customer case

- Data set used for building the models is strongly grouped by material and irradiation conditions

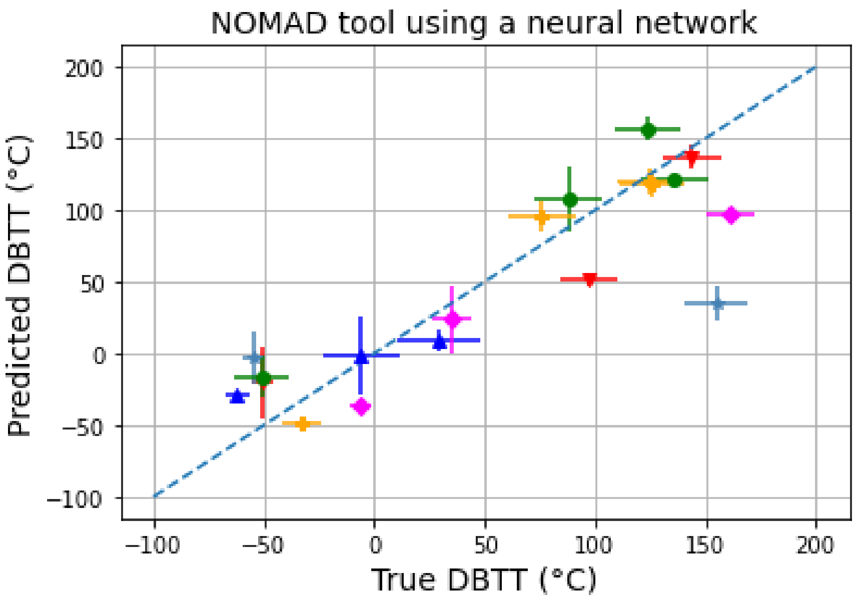
- The method must simulate an actual customer case:
  - A customer brings a set of Charpies with same and known material irradiated in same but (more or less) unknown conditions. Customer wants to know the DBTT.

- Models should be able to adapt to new data groups
  - Leave One Group Out cross-validation was applied
  - A build-in splitter class in scikit-learn

- Feature space dimensionality was reduced – only the most important NDE parameters were selected.

Neural network

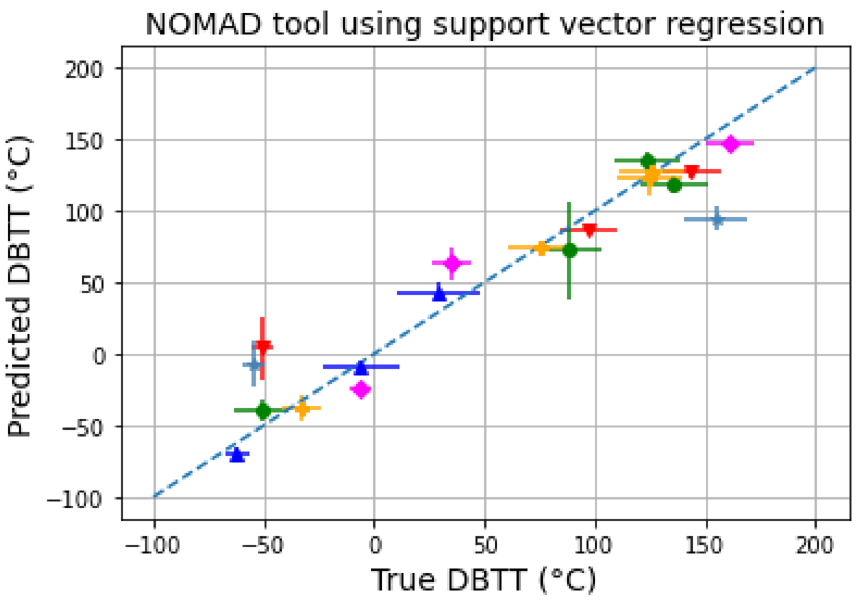
- A feedforward neural network with two dense hidden layers
- Neural networks need a lot of hyperparameter tuning
  - Easy to overfit
- Results are not terrible
  - One steel alloy in particular is predicted poorly



	Test	Train
RMSE	40.9 °C	12.5 °C
MAE	31.3 °C	8.5 °C
R^2	0.65	0.97

Support vector regression

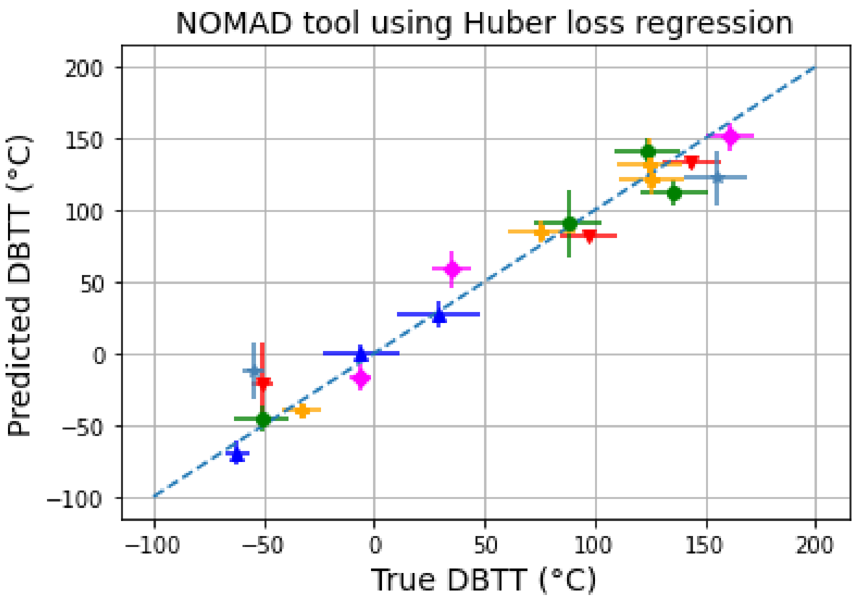
- Support vector regression with a 3rd degree polynomial kernel
  - Data is scaled between 0 and 1
  - The model has several hyperparameters
- The model predicts the DBTT with sufficient accuracy



	Test	Train
RMSE	27.3 °C	12.5 °C
MAE	19.0 °C	6.4 °C
R^2	0.85	0.98

Huber loss regression

- Linear regression with normalized data and an outlier-robust loss-function
- The model has no user-selected hyperparameters
- The model predicts the DBTT with excellent accuracy



	Test	Train
RMSE	22.2 °C	14.9 °C
MAE	15.9 °C	9.7 °C
R^2	0.92	0.97

4. CONCLUSIONS

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Conclusions

- Several non-destructively measurable parameters change when steel is under neutron irradiation
  - These parameters can be used to build a regression model that predicts embrittlement

- Several regression algorithms were tested
  - Simple linear Huber loss regression gives excellent results

<u>It is possible to estimate the neutron-induced embrittlement of RPVs in a non-destructive fashion.</u>

Conclusions

- The demonstrated approach has potential for predictive maintenance and degradation monitoring:
  1. Non-destructively and accurately measured properties that are known to correlate with material degradation
  2. Destructively measured material properties
  3. Using modern regression methods to build a predictive model using both non-destructive and destructive data.

- At the moment, there are several project preparations for the next Euratom project call based on the same approach.

NOMAD Acknowledgements

Project partners:

- Fraunhofer Institute for Nondestructive Testing, Germany
- The Belgian Nuclear Research Centre
- Swiss Association for Technical Inspection
- European Research and Project Office GMBH, Germany
- Coventry University, UK
- HEPENIX Technical Service Ltd., Hungary
- Hungarian Academy of Sciences – The Centre of Energy Research
- Paul Scherrer Institute, Switzerland
- TECNATOM, Spain

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