AGE60+

Applicability of ageing related data bases and methodologies for ensuring safe operation of LWR beyond 60 years

S. Ortner, P. Styman, A. Fellerman, E. Butcher (NNL)
H. Hein, C. Eiselt (AR-G), M. Brumovsky (UJV)
F. Gillemot (MTA-EK), M. Serrano, (CIEMAT)

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Background

- Information on NPP ageing acquired by wide range of organisations
- Much unpublished, published obscurely / sporadically
- Progress in understanding degradation based on limited, locally-available data
- Progress in predicting degradation during long-term operation is made difficult
AGE60+ Objectives

Progressively

- To encourage European researchers to share data in order to maximise its utility;
- To consolidate available data in readily-accessible formats;
- To utilise selected, accessible data to assess the applicability of current predictive methodologies to cover 60+ years of nuclear power plant operation.
Project Outline

- **Raising awareness and scoping acceptable databases on**
  - Degradation of pressure vessel internal structures
  - Concrete ageing

- **Scoping and population of databases on**
  - Low alloy steel thermal ageing, relevant to RPV embrittlement
  - WWER RPV steel embrittlement

- **Expansion and utilisation of**
  - MnMoNi RPV steel embrittlement database
General

- Cannot do justice to large amount of work performed by colleagues
- High level summary
General

- Report on «The Status And Value Of Databases In Support Of Safe Nuclear Power Generation And Waste Management»
  - Clarified the advantages that have been gained from the production and utilisation of a common database
    - Valid for all technical areas
    - Provided support for discussions with potential sharers of data
  - Identified characteristics required to make a database useful over time
## Project Outline

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Value</th>
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<tbody>
<tr>
<td>For any individual database to be successful, it will require</td>
<td>• Preservation of information</td>
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<tr>
<td>• The existence of a champion</td>
<td>• Preservation of experience</td>
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<td>• Association with a particular technical question or social responsibility</td>
<td>• Ability to address particular issues beyond the capacity of a single organisation</td>
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<td>• Advertisement of the existence of the database to build up a community of contributors / users</td>
<td>• Identification of new aspects to questions</td>
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<td>• Ease of access, including the use of up-to-date software</td>
<td>• Provision of gearing to the efforts of an individual organisation</td>
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<td>• Incorporation of up-to-date information</td>
<td>• The building of a community of users / contributors (across organisations, countries, time)</td>
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<td>• Sufficient size of community involved and level of expertise to provide assurance of appropriate data validation and manipulation, even when data are not made fully public</td>
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<td>For a database to be maintained over time, it will also require</td>
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<td>• A track record in addressing questions</td>
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<td>• Sustained funding</td>
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<td>• Perception of a continuing technical need</td>
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<td>Updating of information and software</td>
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Progress Towards a Concrete Properties Database

- Collaborations / interactions more common in use and degradation of concrete for containment structures than for concrete in association with High Activity Waste treatment
  - AGE60+ provided opportunity to identify area in which new collaborations would add value

- Data and archive samples from extensive physical and chemical testing are owned by government departments or commercial organisations
  - AGE60+ provided “champion” to expand awareness and utilisation of this data/material
Progress Towards a Concrete Properties Database

- Consulted European and North American organisations
  - Waste Management Organisations
  - Contractors
  - Universities

- Positive response received to concept of forming of a network to exchange information
  - Contractual discussions would be required concerning the ownership and use of the information

- Possibly in context of an EU concerted action project
Ageing Of Internals

- Identified many specific questions, and scoped contents of databases required to
  - Produce constitutive models for tensile and fracture toughness
  - Define threshold fluences for IASCC initiation and swelling
  - Develop disposition curves for cyclic and IASCC growth rates
- Collaborations/data compilations exist for many areas of interest (e.g. EPRI)
  - Considered remaining needs
Ageing Of Internals

- **Identified outstanding questions / needs**
  - Lack of high neutron dose data (relevant fluxes)
  - Differences between LWR and FR exposures in hardening and swelling
    - (Neutron spectrum and flux effects subject of part of FIJHOP proposal)
  - Differences between BWR and PWR exposures for IASCC
Ageing Of Internals

- More generally, microstructural data are needed to feed physically-based predictive models (e.g. EURATOM projects PERFORM-60, SOTERIA)
  - Different data needs for semi-empirical or atomistic models
- AGE60+ concludes that key to progress in predictive modelling is development of database structure suited to collating microstructural data.
Thermal Ageing

- Object was to improve the understanding and effective monitoring of thermal ageing of low-alloy steel components by collating appropriate thermal ageing data.
  - Thermal aging, if significant for the RPV vessel, might not be considered adequately in RPV irradiation surveillance programs.
  - Thermal ageing is linked to the issue of neutron flux effect at low fluxes.

- Work performed
  - Reviewed open literature.
  - Contacted organisations for previously unpublished data.
    - NRG, EDF Energy, EDF, AREVA...
Thermal Ageing

Example of Results

- German surveillance Charpy data
- Low Cu/P/Ni RPV steels 7-30y 290°C

No thermal aging embrittlement effects observed, possible slight annealing effect
Thermal Ageing

- **Example of Results**
  - Russian surveillance data
  - VVER-1000 weld material (low Cu/P, high Ni) up to ~23y 310-320 °C)

Significant thermal ageing effect
Thermal Ageing

- “Overview of the current state of the art knowledge on thermal ageing effects and databases for LTO”
  - Databases exist, but not all are accessible for proprietary reasons
  - Prediction of thermal ageing is implemented in several codes (RCC-M/ RSE-M VERLIFE)

- Thermal aging effects in RPV and Pressurizer
  - are unlikely for low Cu/P/Ni materials up to ~320 °C
  - may occur for high Cu materials (> ~0.3 % Cu) at >300 °C
  - may occur for high Ni (>1.35 % Ni) materials at >310 °C

Further long-term data on thermal ageing are needed to ensure LTO of NPPs
WWER Steel Embrittlement

- Enthusiasm for up-to-date database clarified at Workshop set up by AGE60+ partners (database champions)
  - International Workshop on RPV EMBRITTLEMENT AND SURVEILLANCE PROGRAMMES (held Prague, 13-16 October 2015)
- Informal collection of data analysed
**WWER Steel Embrittlement**

- **Comparison of $dT_k$, $dT_0$ for WWER440/V-213C**
  - Charpy transition temperature $T_k$ shifts are lower than fracture toughness $T_0$ shifts
    - Highlights general risks of using surrogate measurement
    - Note that initial values of $T_0$ are lower than those of $T_k$ and absolute values of $T_0$ remain lower $T_k$ within the NPP expected lifetime.
WWER Steel Embrittlement

- Analysis of fracture toughness data
  - Data analysed using Master curve procedure
  - Embrittlement trend curves for 15Kh2MFAA base and weld metals have been proposed and checked on collected data using several criteria.
    - Clean low-Cu/P steels
  - The best suitable ETC are proposed for the further use of prediction radiation embrittlement for LTO
    - First example of ETC for fracture toughness.
WWER Steel Embrittlement

- **ETC for base metals**

\[ dT_0 = 3.988 F^{0.5822} ; \sigma = 15.48 \, ^\circ C \]
**WWER Steel Embrittlement**

- ETC for weld metals

\[
\sigma = 15.17 \degree C
\]

\[
dT_0 = (3.86\times C_p + 11.32\times C_{Cu} + 1.39\times (C_{Mn} + C_{Si}) \times F^{0.632}; \sigma = 15.17 \degree C
\]

**CASE W16**

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**AIC**

**CASE W1**

**CASE W3**

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Consideration of ways in which available database might be improved to enhance prediction of RPV embrittlement

- Factors included in current ETCs
- Measurement uncertainties
- Methods of deriving ETC
MnMoNi Steel Embrittlement

- Factors in ETCs
  - Added yield stress information to many sets
  - Identified yield stress contributions to hardening / embrittlement
  - Identified inadequacy in representing irradiation temperature contribution
  - Added extra data sets
MnMoNi Steel Embrittlement

**Measurement uncertainty - Bootstrapping**

- Improve derivation of $T_{41J}$ from Charpy data sets
- Identify measurement uncertainty
  - Define cause of some outliers (recommendation to SOTERIA)
- Improve measurement methodology
- Reduce scatter in input $\Delta T_{41J}$ measurements to allow small effects (e.g. $\sigma_Y$) to be seen and to optimise descriptions of large effects (e.g. irradiation temperature)
MnMoNi Steel Embrittlement

- **ETC derivation by analysis of raw Charpy data as a whole**
  - Current methodology uses data inefficiently (16-30 measurements produce each $\Delta T_{41J}$ value)
  - Excess emphasis on start-of-life values
  - Current ETCs often disturbed by new data and outliers
  - Fit to all data produced very robust ETC for CMn steel (Magnox RPV and AGR core support structures) embrittlement, very stable against outliers

\[
\hat{C} = C_L + (C_U - C_L) \cdot \left[ 1 + \exp \left( -\left( \frac{T - T_0}{\xi} \right) \right) \right]^{-\nu}
\]

\[
C_U = C1 + C2 \cdot Z
\]

\[
T_0 = g0 + g1 \cdot \sqrt{F}
\]

\[
C_i = \hat{C} (T_i, F_i, Z_i; \Theta) + \varepsilon_i
\]

$\varepsilon \sim N(\hat{C}, \sigma^2)$
MnMoNi Steel Embrittlement

- Reducing prediction uncertainty – Analysis of raw Charpy data as a whole

- First attempts to fit trial function
  - Note change in USE derived at same time as change in $T_0$
  - Extraction of $\Delta T_{41J}$ affected by USE drop as well as $T_0$ shift

- Promising
  - Model clearly needs refining
  - Examination of residuals indicates USE affected by Mn, C, Ni, notch orientation, weld flux
Conclusions

- Small project has been very fruitful
- Raised concept of sharing data / setting up databases related to ageing of concrete.
  - Generally positive response to this first step
- Identified area in which new database would provide opportunity to advance predictive modelling of the degradation of internals
  - Identified information gaps
- Collated, reviewed LAS thermal ageing data
  - Identified materials / conditions for which degradation may be significant during LTO
  - Identified information gaps
Conclusions

- Produced up-to-date database on WWER-440 steel embrittlement.
- Produced new embrittlement trend curves
  - Fluence-dependence of $T_0$ in base and weld metals
- Expanded and utilised database on MnMoNi steel embrittlement
  - Identified factors which influence embrittlement but are not (correctly) described in current ETCs
  - Reduced measurement uncertainty in $\Delta T_{41J}$
  - Suggested improvements to measurement protocols
  - Proof of principle for more robust derivation of ETC
Next steps

- Small project also fruitful in proposed work
  - Form an international network to share information on concrete ageing within the waste management community
  - Consider how to set up a microstructural database (internals)
  - Act on needs for long term thermal ageing data and for high fluence (low flux) PWR data on internals and RPVs
  - Publicise advantages of changing Charpy measurement methodology
  - Reduce $T_{41J}$ uncertainty and identify outliers with bootstrapping and continue with full-Charpy-data analysis
    - Make recommendation to SOTERIA WP3 to use bootstrapping to help identify which outliers are caused by high measurement uncertainty
  - Use the ETC developed in AGE60+ for WWER fracture toughness data
  - Utilise the information from VERLIFE and AGE60+ to move towards use of fracture toughness for RPV integrity assessment in all LWRs
  - Develop ETC for MnMoNi fracture toughness data using robust analysis procedure
Thank you for your attention
Title

- **Title paragraph**
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  - Second
    - Third
    - Fourth