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AMES Thematic Network on Ageing (ATHENA)

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Final report

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Key action: Nuclear fission
Area: Operational safety of existing installations

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Contents

1. Object

The present document constitutes the final report for the three years of activity of the ATHENA thematic network (11/2001-11/2004). It covers the technical as well as the administrative and project management aspects. It constitutes the contractual deliverable N° 16 of the contract FIR1-CT2001-20170.

The reports referenced in this document and the technical presentations made at the different workshops are available on CIRCA (http://www.forum.europa.eu.int/Public/irc/jrc/Home/main).

2. Summary

The ATHENA thematic network was the main project of the AMES (Ageing Materials European Strategy) European network in the Fifth Euratom Framework Programme (FP5). The objectives of ATHENA (AMES Thematic Network on Ageing) were to summarise the state of the art and edit guidelines on important issues like:

- The definition of the technical areas of cooperation and activities needed to be in place to ensure a reliable remaining lifetime assessment of a VVER reactor pressure vessel
- The master curve and its applications
- Annealing of VVER-440 reactor pressure vessels, re-embrittlement models validation after annealing and other open issues in embrittlement of VVER type reactors
- Understanding of irradiation embrittlement (effect of chemical composition and irradiation variables on embrittlement rate in reactor pressure vessel steels)
- Synergy between ageing mechanisms (mainly thermal ageing).

The working method was to entrust the evaluation of these issues to a critical mass of experts working in sub-groups (work packages), mainly by means of workshops. The main idea was to optimise the use of existing information obtained in different frameworks (European R&D projects, national projects, TACIS-PHARE, bilateral cooperation projects), since the limited funding of the project did not allow new research work. The project was rather successful in gathering existing information that was unpublished and property of the ATHENA participating organisations. The results obtained in the different work packages and the recommendations for future work are summarised in the next paragraphs.

3. Technical results of the different work packages

3.1. Work Package 2: Linking AMES strategy to Eastern Europe (EPLAF)

EPLAF (European Plant Lifetime and Ageing Forum) was created in 1997, under the auspices of the Directorate-General for Energy of the European Commission (now DG TREN), in order to foster communication and dialogue between different European industrialists involved in Eastern Europe, Russia, and the Ukraine in bilateral or multilateral projects related to the assessment of ageing and remaining lifetime of VVER nuclear power plant components.

The main aim of the forum is to define, in the most effective way, the additional needs, purpose, activities and expected results from further assistance and future co-operation projects to be developed together with the Eastern colleagues. This is being done taking benefit from the combined experience of the participating industrial experts.

The first activity of the forum was the drafting of 'Action Plan N° 1'. This document describes in a logic sequence of ten steps the full spectrum of technical areas and activities needed to be in place to ensure a reliable remaining lifetime assessment of a VVER reactor pressure vessel. Action Plan N° 1 was updated in the frame of ATHENA thematic network. It represents an agreed perspective of European experts in the field and was discussed and approved with Russian and Ukrainian colleagues during joint meetings held in Moscow [M10] and Kiev [M11]. The final Action Plan N° 1 is based on analysis performed by EPLAF of different ongoing bilateral and multilateral European projects in the field of RPV ageing assessment. Through this plan, some understanding has been gained of the extent to which current or past programmes of work meet the needs of a comprehensive study of ageing phenomena. This includes identification of areas where further projects should be defined. For this purpose, projects already identified with present-day knowledge of the experts involved are broken down to allow the further specification of detailed activities which should be incorporated into future programmes.

As a result, this document will be of use to both Eastern and Western bodies responsible for developing assistance programmes or for the definition of co-operation projects.

The following topics are covered in the document:

- Item 1: collection, evaluation and incorporation of data in databases on material characterisation
- Item 2: provision of relevant materials
- Item 3: development of an accepted system of metal properties characterisation
- Item 4: study of different factors in steel embrittlement behaviour
- Item 5: non-destructive monitoring of pressure-vessel material degradations
- Item 6: annealing and re-embrittlement
- Item 7: embrittlement formulas/curves
- Item 8: impact on structural integrity assessment
- Item 9: impact on design and operation

- Item 10: training.

The action-plan document is deliverable D4.

3.2. Work Package 3: Master-curve implementation for fracture toughness assessment

3.2.1. Objectives and summary

The general objective of WP3 was to integrate the information available on master curve (MC) applications and experience in European countries, including CEEC partners, obtained in different frameworks. This work led to the definition of a common European position on the use of the master curve documented in the deliverable [D18]. In addition, a workshop type event was organised for WP3 to clarify the application and the encountered open issues of the MC (MASC workshop "Use and application of the master curve for determining fracture toughness", held 12-14 June 2002 on the ferry between Helsinki and Stockholm [D7]).

The following issues were emphasised in WP3:

- Using the master curve in special applications like irradiated materials with high neutron fluence, materials susceptible to intergranular fracture or materials showing exceptional lower-shelf or transition behaviour
- Introduction of appropriate modifications and extensions proposed and needs for further modifications
- Links between different applications like ageing of materials and structural integrity assessments
- Applications related to the structural integrity assessment:
  - reference curves
  - acceptable failure probability
  - size adjustment (statistical)
  - constraint adjustment.

Master curve a jeho aplikacia - recommendation- Thermal(1/2)

3.2.2. General on the master curve

The master-curve procedure for determining the fracture toughness of ferritic steels in the transition range is described in ASTM E 1921-02. The standard covers base and weld metals with yield strengths from 275 to 825 MPa. As a general condition for applicability the material should behave in accordance with the statistical cleavage fracture model which means among others "macroscopically uniform" mechanical properties. Ferritic structural steels, both normalised and quenched and tempered grades, normally follow this assumption to the extent that no applicability limitations for non-homogeneity exist. For such steels the standard MC procedure is generic without additional analyses. This means also that, assuming that the requirements set for the test and analyses procedures are fulfilled, the determined standard T_0 temperature and tolerance bounds may be regarded as conservative without additional margins or adjustment. If the assumptions of the cleavage fracture model are not satisfied or they are only partly satisfied, the MC approach can usually still be applied if the material-specific behaviour is considered in the model. As a statistical model the basic MC approach is compatible and allows consideration of different material-specific characteristics.

3.2.3. Procedures for material-specific data

In general, the dependence of materials fracture toughness on temperature in the transition range is not sensitive to characteristics like the mechanical properties and microstructure. As a consequence of this feature, a similar fracture toughness versus temperature dependence, as it is assumed in the basic master-curve model, can be used in most cases. Even measures decreasing the toughness of the steel, like special heat treatments or neutron irradiation, do not generally degrade the consistency of the measured fracture toughness versus temperature behaviour with that predicted by the model.

Typical cases where the master-curve method should, however, be adjusted or modified or the method should not be applied are as follows:

- Inhomogeneous materials or materials with a dual or multi-phase microstructure consisting of phases with different properties. These cases can usually be estimated with the master curve by adopting a modified scatter band model for fracture probability or in certain cases by introducing the bi-modal distribution model.
- Materials which are susceptible to grain boundary fracture may exhibit fracture behaviour which do not follow the master-curve prediction if the proportion of grain boundary fracture is high.
- The fracture behaviour outside the standard temperature region ($-$ 50 °C < $T\text{-}T_0$ < 50 °C) will often, but not always, follow the master-curve model. In certain cases these extrapolations may be used, although this option is not included in the ASTM E 1921-02 standard. Deviations from the predicted behaviour are often associated with special situations which should be recognised before the extrapolation.

3.2.4. Guides for applying the master curve

The standard master-curve estimation method has been included in several integrity assessment guides compiled for general steel and/or weld structures or certain specific applications. These procedures may include, besides the standard procedure, tools for analyzing abnormal material conditions possibly encountered in specific cases, which makes these guides more universal than the ASTM E 1921 standard. A typical example is the SINTAP procedure, developed for assessing steel structures, which includes a sub-routine type guide for analysing inhomogeneous steels using the MC approach. This MC extension has recently been expanded further to cover also welded structures, which may show distributed, bimodal type fracture behaviour. Corresponding generic guidelines have recently been developed also under the IAEA coordinated research project titled “Surveillance Programme Results Application to RPV Integrity Assessment”. This IAEA guide is intended specifically for the fracture toughness testing using small, surveillance size specimens and for applying these results using the MC approach for RPV structural integrity assessments.

3.2.5. Recognised open issues

Some issues needing clarification were discussed in the MASC conference [D7], dealing mainly with (1) the standard procedure, (2) the limits of acceptability of the MC, and (3) the codification aspect. These conclusions are given below.

3.2.6. Conclusions

In conclusion, the master-curve method has proven to be a robust engineering method, superior to the previously used methods of assessing brittle fracture propensity. The standard (ASTM E 1921-02) master-curve procedure is applicable for most structural steels without significant open issues. Minor revisions including the inclusion of a formula for estimating the multi-temperature median K_{Jc}-temperature dependence were proposed. For further research, the following topics are recommended:

- Description for general master-curve estimation procedures should be developed further for applications like the regulations of reactor pressure vessels.
- The limitations of the master-curve approach should be studied further and guides compiled for their use.

3.3. Work Package 4: Annealing and re-embrittlement issues

Annealing of a reactor pressure vessel embrittled by neutron irradiation constitutes the only known technique to restore the initial material properties, to an extent that depends on the annealing conditions and on the materials. This technique has been widely used in VVER-440/V-230-type reactor pressure vessels.

A very important related issue is the one on re-embrittlement behaviour of the material after the annealing. In this respect, there is an obvious link with Work Package 5 on radiation embrittlement understanding.

A vast amount of information on annealing and re-embrittlement is available in the European countries where such annealing operations have been performed, and this topic was also investigated in various TACIS projects. There are also a number of experiments carried out on “Western”-type RPV steels as well as results from annealing of embrittled vessels and of demonstration experiments. However, this information remains fragmented and Work Package 4 aimed at integrating the existing information and identifying the areas where additional research is necessary.

The five main tasks in WP4 were:

- Collection of all available data on annealing and re-embrittlement of VVER- and PWR-type steels

- Analysis of all collected data
- Review and analysis of applied annealing techniques and recommendations for their further improvement if necessary
- Collection of requirements from regulatory bodies and comparison of lifetime procedures applied
- Proposal for necessary research and development activities for full understanding of the process and for reliable assessment of behaviour of annealed RPVs.

Based on papers presented during WP4 meetings and on discussion of the participants as well as on existing literature and literary surveys, an extensive state-of-the-art report was produced [D19], with the following contents:

- Introduction: radiation embrittlement and its consequences on RPV lifetime. Survey of international/national projects
- Annealing effects on radiation embrittlement
- Re-embrittlement rate and models
- Testing and sampling
- Annealing technology
- Regulatory requirements to RPV annealing and lifetime evaluation
- Assessment of lifetime of annealed RPVs
- Recommendations for future research and development activities in the field of annealing and re-embrittlement of RPVs.

The conclusions and recommendations of the state-of-the-art report can be summarised as follows:

A large amount of work was performed to define and explain the effect of annealing for recovery of radiation damage in RPV steels, both for PWR and VVER-440 types of reactors. The results showed that only dry annealing can be effectively applied for substantial recovery of RPV material properties. This work served as a basis for the definition of thermal regimes (475 °C – 100 to 150 h) for successful annealing of 13 RPVs of VVER-440/V-230 type.

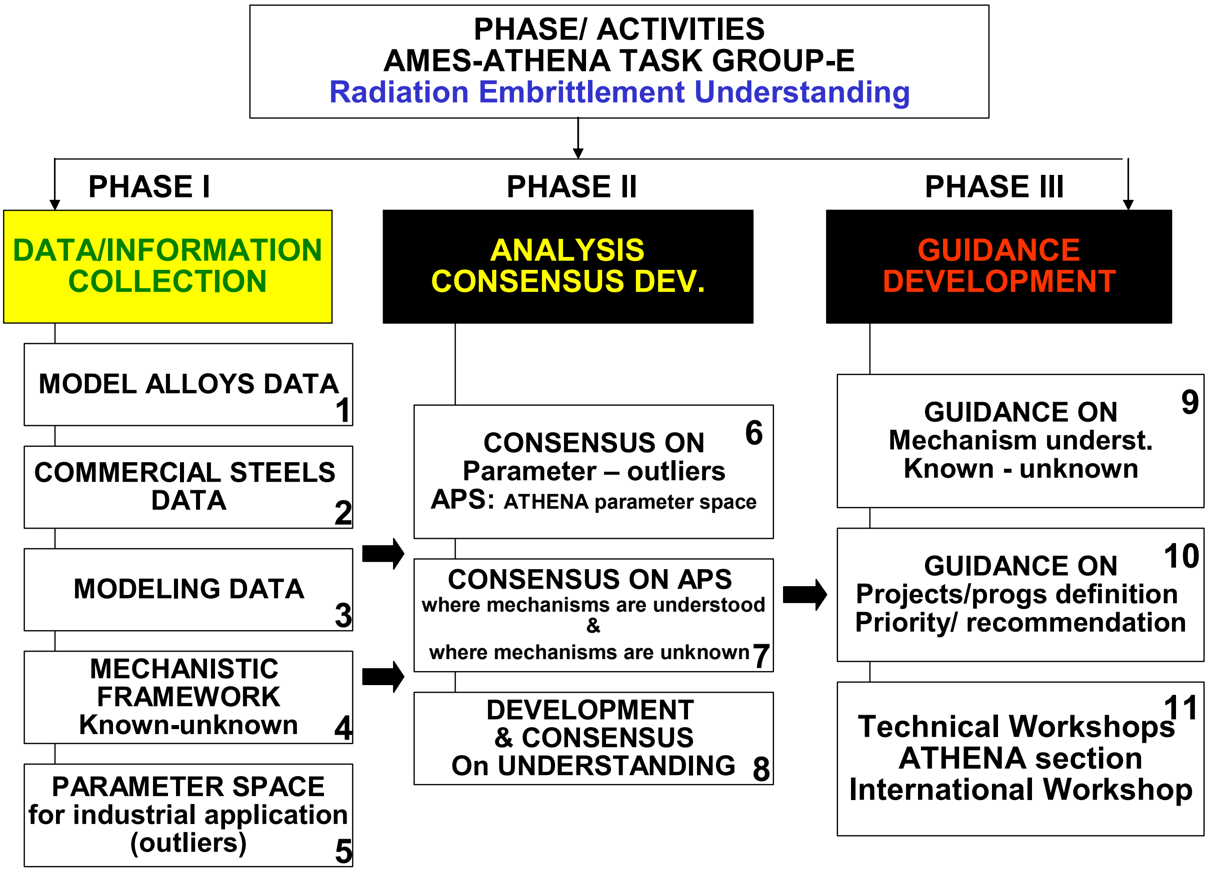
Additionally, many projects have been concentrated on the evaluation and explanation of re-embrittlement of RPV materials irradiated after annealing. Models for evaluation of the re-embrittlement rate in VVER-440 materials have been proposed and tested with limited experimental data. More general validation of re-embrittlement models, based on studies of mechanical properties as well as on changes in material microsctructure, is still needed. RPV materials behaviour during re-irradiation after annealing should be adequately monitored, e.g. by surveillance specimen programmes with actual or surrogate materials, and/or by sampling from inner RPV surface in uncladded vessels, Use of fracture toughness data for RPV lifetime evaluation is recommended in addition to traditional approaches.

In order to increase accuracy in prediction of RPV lifetime after annealing and decrease extra-conservatism, the future work should be concentrated on:

- Better understanding of re-embrittlement mechanisms (hardening and non-hardening components)
- Development of improved models for RPV materials re-embrittlement assessment also considering behaviour of upper shelf both in Charpy impact and in static fracture toughness tests
- Acquisition of more experimental data focused on further validation of improved models
- Preparation of regulatory documents for conducting and evaluation of VVER RPV annealing.

3.4. Work Package 5: Radiation embrittlement understanding

The activities of ATHENA Work Package 5 can be broken down in three phases as shown below.



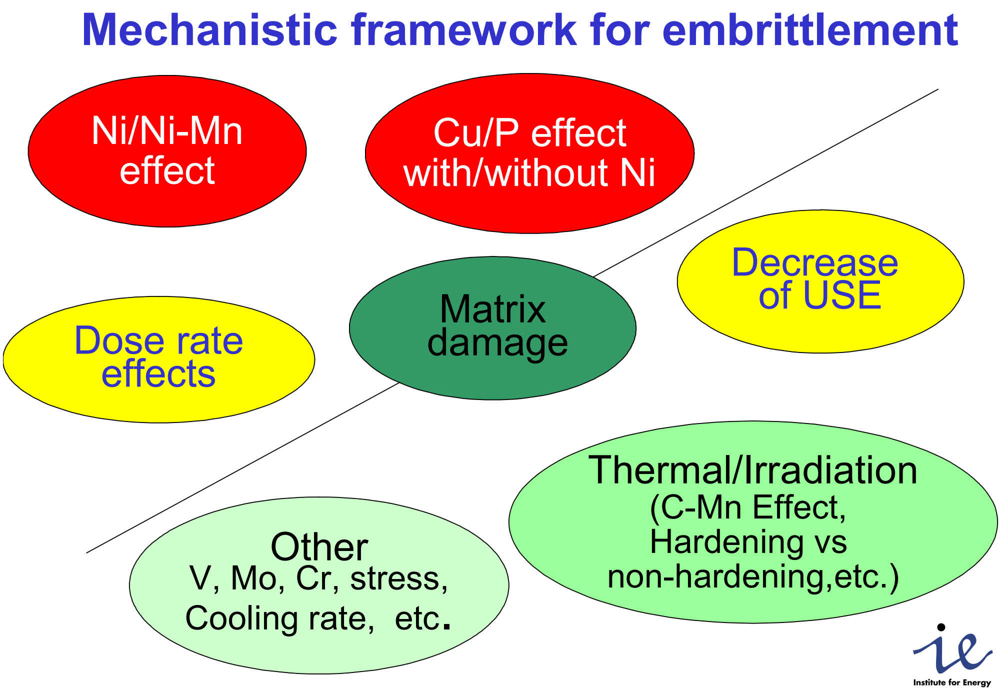
3.4.1. Model alloys

A report on model alloys was produced [D9]. The report describes the data available from different sources, the running projects, a discussion of these results and conclusions. A separate report [D22] evaluates the similitude between model alloys and commercial steels and describes the irradiation programme performed on model alloys and model steels as a tool to understand the role of each individual element and possible synergisms. It was shown that the response of model alloys is largely similar to the commercial RPV steels, even if the DBTT shifts are larger. Such similitude is encouraging for the continuation of studies on model alloys.

3.4.2. Mechanistic framework for irradiation embrittlement understanding

Several WP5 workshops, and particularly the Madrid workshop [M5] (19 September 2002) led to the definition of the mechanistic framework for embrittlement understanding.

Six elements have been distinguished and proposed as given in the following figure:



Presentation of the results in electronic format

Due to the vast amount of information generated in WP5 (Radiation embrittlement understanding) and WP6 (Ageing mechanisms – influence and synergism), and in order to make this information easily accessible using modern tools, it was decided to present the results in electronic format (website). Due to the strong links between WP5 and WP6, the two work packages are integrated in a common structure. For each element of the mechanistic framework, a top-level summary introduces the subjects, summarises the state of the art and open issues, and provides links to the second level where each specific mechanism or technical issue are addressed more in details in presentations made at the workshops.

This presentation makes it very easy to make links between related topics and allows the reader to have rapidly an overview of the topics, while leaving the details accessible for specialists interested in specific issues.

This website can be accessed at the following address:
http://safelife.jrc.nl/ames/projects/athena/athena.php.

3.4.3. Techniques for irradiation embrittlement understanding

A consensus document on techniques for radiation embrittlement understanding was produced [D20], including a list of techniques, their description and potential. The main techniques for radiation embrittlement understanding are:

- Parametric studies with model alloys in material test reactors: The parametric study of the response to neutron irradiation of model alloys is a fundamental tool to understand the role of each elements and possible synergisms
- Re-evaluation of surveillance database: Over the years, hundreds of surveillance specimens have been examined and tested. The results can be used to develop trend curves
- Use of reference materials (irradiation at different temperatures and at different fluence rates)

Irradiation ageing pat elevated temperatures / PAS application

"Radiacie versus temperature "

- Micro-structural investigation and techniques: A number of techniques have emerged as sufficiently mature to be reliably applied to provide the necessary information of irradiated commercial RPV steels. These are:
  - transmission electron microscopy (TEM)
  - field emission gun scanning transmission electron microscopy (FEGSTEM)
  - small-angle neutron scattering (SANS)
  - atom probe field-ion microscopy (AP-FIM)
  - scanning auger electron spectroscopy (AES)
  - positron annihilation.

3.4.4. Critical evaluation and recommendation for an experimental matrix of required projects, required facilities and materials

A consensus document on critical evaluation and recommendation for an experimental matrix of required projects, required facilities and materials was produced as a deliverable of this work package [D21]. This report critically reviews and recommends future projects in the field of mechanism-understanding evaluation and recommendation for an experimental matrix of required projects, facilities and materials.

- **Realistic welds project**: The objectives are to study radiation embrittlement of different welds simulating real VVER-1000 reactor pressure vessel ones. The chemical composition of the ferritic steels varies around the reference industrial one in order to perform a parametric study of the influence of nickel and manganese contents on the sensitivity to neutron irradiation.

- **Model steels**: In order to study the influence of Mn, Mn-Ni, Mn-Ni-Si on irradiation embrittlement, the JRC has defined and procured a set of model steels, starting from a same base composition and adding the elements of interest. The matrix, initially foreseen to represent VVER steels, was extended to PWR steels. This programme is a logic complement of the previous one on realistic welds.

- **Development of reference materials for VVER-1000**: The surveillance programmes of LWR-type power reactors include, in many cases, standard reference materials in addition to actual-pressure vessel steels. These specimens are supposed to serve as a reference by comparing the radiation embrittlement of the plant-specific material to the reference material, and to detect anomalies in the radiation environment of the surveillance capsules. A correlation monitor material for the VVER-1000s, well characterised in terms of irradiation behaviour, is needed in order to determine the reliability of accelerated data for the validation of RPV surveillance data.

- **Novel techniques and methods development:** A review of different projects for the development of the techniques targeted to mechanisms understanding and ageing assessment and monitoring is presented:

  - dynamic toughness and dynamic master curve
  - micro-structural investigation and techniques
  - multiscale modelling.

- **RPV cladding:** The mechanical and physical properties of the cladding are different from those of the base steel of the vessels. It is necessary to develop projects to investigate cladding properties for elastic-plastic assessment for PTS analysis.

- **Investigation of irradiation-stress effects:** Recent data have shown a possible effect of stress in radiation embrittlement when characterised by the transition temperature shift. The effect is anyhow rather small and if it exists it is probably within the scatter of the transition temperature shift.

- **Investigation of EOL RPVs:** Several RPVs (e.g. Novovoronezh, Greifswald units 1-8) and Magnox units, etc. which reached their end of life have been shut down and are being already dismantled. The trepans cut from these units can provide key information on long-term ageing of thick-walled structures.

RPV recovery annealing

- **Re-embrittlement:** Re-embrittlement after annealing is an issue especially relevant for RPV of VVER-440/V230. All VVER-440/V230 RPVs were annealed because of extremely high rates of radiation embrittlement of the core welds. The re-irradiation embrittlement kinetics after annealing determines practically the RPV lifetime.

- **Dosimetry and flux-effect studies:** The surveillance specimens are generally located in higher dose rate and different spectral regions away from the reactor pressure vessel wall. In addition, the spectra inside of the wall are different from those at the vessel surface. The influence of dose rate and spectrum on embrittlement remains an open issue.

- **Temperature of VVER surveillance specimens:** Standard surveillance programmes for VVER-440/V213- and VVER-1000/V320-type reactors did not contain any suitable temperature monitor. Thus their specimen temperature was not known. To clarify this situation, several experimental programmes with direct specimen temperature measurements by thermocouples or melting monitors have been realised and confirm that the irradiation temperature of the specimens is sufficiently close to the RPV irradiation temperature.

- **Knowledge management:** Existing experts in the field of materials research are ageing and close to or even at retirement age, and as manufacturing of new plants is very limited now there is little demand for replacing them and thus no need for huge education of new specialists in this field. Thus, there is a danger that the knowledge gathered by several generations during past times will be lost. Several projects are proposed for the collection, summation, analysis, and proper expertise of all accessible and available literature in the field of embrittlement (mainly radiation damage) of VVER RPV materials together with information about RPV material properties.

- **Non-destructive techniques:** The potential of the various ND techniques for ageing assessment and monitoring have been recently demonstrated in the AMES-NDT project (FP4) and the follow-up round-robin shared-cost actions GRETE (FP5). The round-robin trials performed on fatigued stainless steel specimens and irradiated ferritic steel specimens have successfully identified NDT techniques with good potential for monitoring these degradation processes in certain materials in operating plants. However, assessment of the industrial feasibility of these NDT techniques requires further systematic studies of the capability and reliability of these techniques under conditions which more accurately reflect the industrial environment.

3.5. Work Package 6: Ageing mechanisms – influence and synergism

The overall objective of WP6 was to evaluate the mechanisms of hardening and non-hardening embrittlement in the thermally dominated regime and the transition to the irradiation-dominated regime. The mechanisms under consideration are:

- Hardening: precipitation, clusters
- Non-hardening: segregation
- Strain-ageing/warm pre-stressing.

The variables are temperature, time, dose and dose rate.

WP6 conducted a review of the position and present knowledge in respect of each of four materials categories (C-Mn steels, PWR steels, VVER steels, cladding), in order to identify the materials, irradiation and thermal parameters of interest, and to identify activities that were required in order to close out issues of concern. This review is summarised in the next sections.

3.5.1. C-Mn steels

In C-Mn submerged-arc weld surveillance specimens exposed at 392/360 °C, the observed non-hardening embrittlement was due to intergranular fracture resulting from an increase in grain boundary phosphorus segregation. Theoretical modelling, validated by an accelerated irradiation experiment, showed that surveillance irradiations are thermally controlled. Thus time at temperature is the appropriate parameter for predicting the shifts. A dose dependent trend curve was therefore replaced by one where shifts are determined by time at temperature. The database extended to more than 35 years of in-service exposure.

For C-Mn plate and weld materials given a simulated post weld heat treatment and thermally aged to produce copper precipitation, the time to peak hardening decreased with higher ageing temperature. Peak hardening was not reached after 9500 h at 350 °C. For high copper materials, peak hardening occurred before 3000 h at 400 °C. There is reasonable comparison with some Russell-Brown model predictions. Further work to permit more precise prediction of copper hardening effects under thermal ageing was discussed.

In a new accelerated irradiation experiment, long-term thermally aged submerged-arc welds showed irradiation-induced increases in yield stress considerably lower than predicted by the appropriate Magnox trend curve. This may be a joint effect of removal, during the thermal ageing, of copper and free nitrogen that would otherwise have affected the irradiation-induced hardening. The aged welds showed irradiation-induced increases in DBTT considerably lower than predicted by the appropriate Magnox trend curve, despite a large increase in intergranular fracture. Interpretation requires knowledge of the effects of yield stress and intergranular fracture on DBTT, and of how shifts due to thermal ageing and irradiation are combined. This was identified as a task for the future, and these results should be compared with those from the irradiation of temper-embrittled IAEA model steels.

embritlment for welds and HAZ - thermal age

Reviewing the whole area, it is observed that, when present, submerged-arc welds show the highest embrittlement (ΔT) shifts due to thermal ageing, but in upper shelf operation the fracture toughness and tensile properties of plate are usually lower than those of weld. Good information is available on precipitation and segregation in C-Mn steels in the thermal ageing and irradiation-controlled regimes, and there is a reasonable understanding of factors affecting the likely changeover point from irradiation to thermally-dominated embrittlement (temperature, dose, dose rate).

In conclusion, for C-Mn steels, there is a reasonable database on thermal ageing under conditions relevant to Magnox reactors, extending to very long times (> 35 years). Intergranular fracture can be important, and there is reasonable modelling understanding of this phenomenon and how it is potentially affected by relevant parameters (temperature, time, dose, dose rate). Data are not available for model validation across the whole of this parameter space, but there is good agreement in those high temperature areas where there are data. It is not well understood why under appropriate conditions irradiation-enhanced phosphorus segregation does not appear to occur in Magnox C-Mn submerged arc welds.

3.5.2. 'Western' steels

"Fracture toughness decrease after thermal aging"

.The known occurrences of thermal ageing embrittlement in coarse-grained HAZ (temper embrittlement) or simulated coarse grained materials are generally linked to phosphorus segregation and intergranular fracture. They have been observed in accelerated ageing at higher temperature (450 °C), but may be an issue for long term behaviour (40 years) in normal RPV operating conditions. Some data show that the occurrence of brittle intergranular fracture induced by temper embrittlement is dependent on the microstructure of the RPV steel. Higher cooling rates during quenching lead to lower initial transition temperatures but also to higher sensitivity to temper embrittlement. The reason is not understood, and it is not known at what long time in-service exposure conditions (temperature and neutron irradiation) it will occur.

Atypical behaviour has been seen in some surveillance materials, suggesting a possible synergism between thermal ageing and irradiation embrittlement. Some isolated observations of thermal embrittlement exist, but significant uncertainties are associated with some of those observations.

Most data, both in the literature and presented at the WP5 workshops ([M5], [D24]), suggest no significant thermal embrittlement for RPV steels in the temperature range of interest for up to 100 000 h (and 209 000 h at the slightly lower temperature of 283 °C). Modeling predicts that thermal ageing (due to copper precipitation) is unlikely to be observed at 290 °C in less than 10 years, unless the copper content is 0.35 % or greater. For a matrix copper content of 0.25 %, significant thermal ageing may not be observed at 325 °C for times less than 50 years. Some German data on materials from other components, notably pressurisers, show a significant effect of thermal ageing on both impact and tensile properties, but for high Cu materials that are different from RPV steels.

Thermal ageing of the high-purity low-Cu MnMoNi RPV steel used at Sizewell 'B' for 62 300 h at 325 ºC appears to increase the upper shelf energy. This observation has a parallel in the JRQ data.

In summary, most data suggest no significant thermal embrittlement for RPV steels in the temperature range of interest (290-300 °C) for up to 100 000 h (and 210 000 h for 282 °C). Mechanical property changes reported in the literature or gathered in the framework of the Athena project are limited and without consistent trends. There are isolated reports of limited DBTT shifts in some specific materials (10 to 30°C) and some isolated observations of thermal embrittlement in pressuriser materials at temperatures above 325 °C (70 °C max at 325 °C in 160 000 h), but for high-Cu material (≈ 0.6 %). The potential for thermal embrittlement of "Western" RPV steels for times up to 40 years may therefore be considered as low, but cannot be entirely dismissed on the basis of the available data.

The topic of a possible effect of irradiation under stress on the embrittlement was discussed, based on some Ukrainian results which seem to indicate an effect (apparent systematic effect of stress in increasing T_0). The number of tests is however too limited to draw firm conclusions and this effect might also simply be due to the normal scatter. Trepans cut from vessels withdrawn from service, which were by definition irradiated under stress, show no abnormal behaviour. And the stress alone, in the absence of crack, does not seem to play a role. It was found very difficult to design a conclusive (representative) test on cracked material. There are too few data, but available information and understanding suggest that it is not a big effect with a high priority.

3.5.3. VVER steels

" Irradiaiton Embritlment at elevated temperature " (Thermal ageing-1/2/no.1)

Some data on accelerated ageing of VVER forging to times up to 2500 h at 350 °C show considerable non-hardening embrittlement despite low levels of phosphorus. This should be investigated further by SEM. The same data showed a considerable reduction in upper shelf energy with ageing, which again needs explanation.

Charpy transition shift data on several materials over a range of ageing temperatures are available. Although the 100 000-h results show little shift, it is notable that there are maxima in the observed shifts at shorter times for an exposure temperature of 350 °C, suggestive of a hardening effect exhibiting over-ageing. This feature needs investigation.

There are thermal ageing surveillance specimens in the VVER 440 which will be withdrawn and examined in the future.

3.5.4. Stainless-steel cladding materials

The VVER cladding is a welded structure with a relatively high amount of delta-ferrite and the general behaviour of cladding is similar to that of ferritic steels, with a well defined brittle-ductile transition, unlike forged stainless steel. Charpy shifts under irradiation are limited and smaller than for base and weld metals, but the upper shelf energy and ductile tearing resistance may be considerably reduced.

It is necessary to have reliable irradiated clad properties, so as to facilitate elastic-plastic analysis and thus underwrite longer lifetime.

Some data is also available on US type 308 clad. Thermal ageing exposures up to 50 000 h at 343 °C had little effect on the tensile properties, but increased the ductile-to-brittle transition temperature and reduced the upper-shelf energy level. The magnitude of these changes increased with increasing ferrite content and with increasing aging time. 12 % ferrite weld showed Δ TT of 60 °C and USE decrease of 34 % after ageing for 50 000 h. In addition, both J_{Ic} and the tearing modulus of the 8 and 12 % ferrite welds were significantly decreased by ageing at 343 °C for 50 000 h. Spinodal decomposition and G-phase precipitates associated with dislocations were observed in the ferrite of aged material. A reversion heat treatment (1 h at 550 °C) improved the impact behaviour, but did not give full recovery. Spinodal decomposition is the primary reason for the observed embrittlement due to ferrite hardening, but G phase also contributes.

Some results on French cladding in four conditions – as received, thermally aged (10 000 h at 400 °C), irradiated (approx. 6 x 10^{19} ncm^{-2} at 290 °C), and thermally aged and irradiated – do not show important differences in tensile and impact properties.

3.5.5. Recommendations for further work

The main recommendations for further work are summarised below. More details can be found in [D24].

- For C-Mn steels, the effects of yield stress and intergranular fracture on DBTT and the issue of how shifts due to thermal ageing and irradiation are combined still needs investigation.

- For C-Mn steels, it is important to understand what the controlling fracture event is. (Why is it possible to get significant IGF without apparent extra embrittlement shift?) PISA should consider this issue.

- For Western steels, it would be very useful to have 320 °C irradiation data. An effort is required to collate and review such information as is available.

"to monitor thermal degradation"

- For VVER steels, some 2500 h thermal ageing results appeared to show considerable non-hardening embrittlement despite low levels of phosphorus. It also appeared unlikely that in CrMoV steel this effect would arise from desegregation of carbon, and it was agreed that it should be investigated further by SEM. This still needs investigation.

- For VVER steels, several materials aged up to 100 000 h over a range of ageing temperatures showed little shift, but there seems to be maxima in the observed shifts at shorter times for an exposure temperature of 350 °C, suggestive of a hardening effect exhibiting over-ageing. This feature needs investigation.

3.6. Documents produced

3.6.1. Deliverables

The deliverables produced in the framework of this thematic network are listed below. All required deliverables have been produced.

[D1] TIERSDI/4BA/4361/000/00: Project management report for the period 11/2001 to 04/2002 (T0 to T0+6 months)

[D2] “WP6: Initial position statement – included in [D10]

[D3] TIERSDI/4BA/4640/000/00: Project management report for the period 11/2001 to 11/2002 (T0 to T0+12 months)

[D4] TIERSDI/4NT/4636/000/00: WP2 (EPLAF): “Action plan, terms of reference and list of projects”

[D5] Listing of all projects carried out under TACIS, PHARE, bilateral agreements, multilateral agreements, and other miscellaneous arrangements relating to VVER RPV ageing management – This listing is included in the action-plan document [D4]

[D6] WP2: Updated terms of reference of the EPLAF document (included in the action-plan document [D4]).

[D7] TIERSDI/4NT/4634/000/00: Summary and proceedings of the MASC 2002 Workshop: "Use and application of the master curve for determining fracture toughnesss"

[D8] TIERSDI/4NT/4638/000/00: WP4: 1st annual report (minutes of the first workshop), NRI report, M. Brumovsky.

[D9] TIERSDI/4NT/4633/000/00: "Report on model alloys", JRC report, L. Debarberis and F. Gillemot

[D10] TIERSDI/4NT/4637/000/00: "WP6: Summary of the initial workshop" BNFL report M/RS/EXT/REP/0311/02, C. Bolton

[D11] TIERSDI/4BA/4879/000/00: Project management report for the period 11/2001 to 05/2003 (T0 to T0+18 months)

[D12] TIERSDI/4BA/5012/000/00: Project management report for the period 11/2001 to 11/2003 (T0 to T0+24 months)

[D13a] TIERSDI/4NT/4635/000/00: "Summary and proceedings of the WP2 (EPLAF) workshop in Moscow – 14 October 2002" (Report EPLAF/M(02)/October2002/Issue, F. Sevini)

[D13b] TIERSDI/4NT/4995/000/00: "Summary and proceedings of the WP2 (EPLAF) workshop in Kiev – 19 May 2003" (Report EPLAF/M(03)/Issue 0, F. Sevini)

[D14] WP6: Joint project proposals (part of [D24])

[D15] TIERSDI/4BA/5152/000/00: Project management report for the period 11/2001 to 5/2004 (T0 to T0+30 months)

[D16] TIERSDI/4NT/xxxx/000/00: Final report (present report)

[D17] TIERSDI/4NT/5140/000: WP2 – Action Plan N° 1 for cooperation on technical issues of embrittlement and annealing of VVER reactor vessels

[D18] TIERSDI/4NT/5230/000: WP3: "Master-curve implementation for component assessment"

[D19] TIERSDI/4NT/5231/000/00: WP4: Final report on the annealing and re-embrittlement effects in RPV steels

[D20] TIERSDI/4NT/5325/000/00: WP5: Consensus document on techniques for radiation embrittlement understanding, including a list of techniques, their description and potential.

[D21] TIERSDI/4NT/5235/000/00: Critical evaluation and recommendations for an experimental matrix of recommended projects, required facilities and materials.

[D22] TIERSDI/4NT/5326/000/00: WP5: Report on similitude between model alloys and commercial steels

[D23] WP5: Summary of final workshop (included in [D25])

[D24] TIERSDI/4NT/5269: ATHENA WP6: Ageing mechanisms – influence and synergism. Summary of final workshop

[D25] TIERSDI/4AR/5229/000/00: Proceedings of the final ATHENA conference in Rome

3.6.2. Miscellaneous – progress reports

[1] TIERSDI/4NT/4662/000/00: ATHENA Thematic Network – Scientific Report 11/2001-11/2002

[2] TIERSDI/4NT/5083/000/00: ATHENA Thematic Network – Scientific Report 11/2001-11/2003

[3] TIERSDI/4BA/4361/000/00: Project management report for the period 11/2001 to 5/2002 (T0 to T0+6 months) (Deliverable 1)

[4] TIERSDI/4BA/xxx/000/00: Project management report for the period 11/2001 to 5/2002 (T0 to T0+12 months) (Deliverable 3)

[5] TIERSDI/4BA/4879/000/00: Project management report for the period 11/2001 to 5/2002 (T0 to T0+18 months) (Deliverable 11)

[6] TIERSDI/4BA/5012/000/00: Project management report for the period 11/2001 to 11/2003 (T0 to T0+24 months) (Deliverable 12)

[7] TIERSDI/4BA/5152/000/00: Project management report for the period 11/2001 to 5/2002 (T0 to T0+30 months) (Deliverable 15)

[8] "AMES Thematic Network on Ageing", presentation at the FISA 2003 conference