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Study of Aging Mechanisms for Structural Materials within SAFELIFE Project

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Изучение механизмов старения конструкционных материалов в рамках проекта SAFELIFE

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Рассмотрен комплекс исследовательских программ EURATOM, направленных на изучение механизмов старения и методов устранения повреждений конструкционных материалов корпусов реакторов. Данный комплекс предусматривает разработку неразрушающих методов исследования теплового старения и мониторинга радиационного охрупчивания материалов, усовершенствование программы испытаний с использованием образцов-свидетелей для реакторов типа ВВЭР-440, дозиметрии, а также применение различных механизмов разрушения для оценки структурной целостности АЭС. В частности, проект ATHENA позволил обосновать модель повторного охрупчивания после отжига и выявить зависимость скорости охрупчивания от химического состава корпусных сталей. Кратко изложены основные достижения действующих программ EURATOM, а также задачи следующего этапа исследований в рамках проекта SAFELIFE.

Ключевые слова: старение, радиационное охрупчивание, сети, контроль старения.

1. **Background of the AMES Network**. The AMES (Aging Materials Evaluation and Studies) network was set up in 1993 to bring together the organizations in Europe having the greatest expertise on nuclear reactor materials assessment and research on aging management [1].

The aims of the general strategy was to understand the influence of various embrittlement mechanisms; develop new techniques; improve the dosimetry aspects; improve the prediction of irradiated material fracture toughness.

The information coming from the running projects is as much as possible integrated with the results from different programs (EU-funded, national, TACIS-

PHARE), enabling the definition of a common European position on these issues. An overview of AMES projects throughout FP4 is given in [2] and [3].

Hereby follows a short description of the status of the presently running projects carried out by institutes' members of the AMES network.

ATHENA (coordinator R. Gerard, Tractebel). In order to optimize the fulfillment of its strategy, in November 2001, the AMES Steering Committee started ATHENA, a thematic network organized in task groups on technical issues:

- Master Curve implementation for fracture toughness assessment
- Annealing and re-embrittlement issues
- Radiation embrittlement understanding
- Thermal aging, stress/strain aging and other aging mechanisms: influence and synergism.

These task groups have the aim of improving the co-ordination and synergism on well-identified R&D topics concerning material degradation.

The objectives of ATHENA (AMES Thematic Network) are:

- To entrust the evaluation of specialized problems to a critical mass of experts, that cannot be present in the Steering Committee;
- To create links with nationally-funded projects on the same or on complementary topics and valorize as such these in-kind contributions;
- To coordinate with projects on similar issues that are carried out in the framework of the Tacis and PHARE programs. The task groups provide an opportunity to share this information. In this way, some of the tasks carried out in the framework of the R&D projects can be re-oriented in order to obtain additional and/or complementary information on the same materials. It enhances the scientific and industrial co-operation with the partners of Eastern and Central Europe, Russia and Ukraine;
- To introduce links with American and/or Asian institutions that work on similar issues and can participate on an in-kind basis. This raises the stake of European contributions on a global level.

This cross-fertilization between projects represents the greatest added value of ATHENA. The thematic network will greatly enhance the return of different programs (European R&D projects, national projects, Tacis-PHARE, bilateral co-operation projects). Besides the key participants identified in the ATHENA contract, the "work packages" are open to a wide participation on an in-kind basis, which should ensure an improved feedback on the real needs of the European industry.

REDOS (coordinator A. Ballesteros, Tecnatom). Follow-up to FP4 MADAM, the scope of this project is the accurate determination and benchmarking of radiation field parameters, relevant to the reactor pressure vessel monitoring. Neutron exposure of the reactor pressure vessel (RPV) and reactor internals is one of the key factors that should be quantified reliably when assessing their lifetime. Irradiation embrittlement is the most important damaging in the RPV lifetime evaluation.

Despite improvements in the calculation of the neutron field parameters with the corrected cross section values, remarkable discrepancies exist between the calculated and measured values, especially in ex-vessel position. To resolve these difficulties and discrepancies, the experimental and computational techniques should be combined.

PISA (coordinator C. English, AEA Technology). This project (Phosphorus Influence on Steel Aging) has the objective of improving the understanding of irradiation embrittlement by segregation of phosphorus to internal grain boundaries and reducing the impact of brittle intergranular failure mechanism on the properties of the reactor pressure vessel.

The range of the RPV steels considered includes the Mn–Mo–Ni steels employed in European PWRs, the mild steels used in UK Magnox RPVs, and the steels employed in WWER-440.

The approach employed to achieve this objective is to improve predictability through developing improved physical understanding of both the segregation process and any resultant change in the mechanical properties. The necessary understanding will be developed through focused experimental investigations of irradiated steels and model alloys, with associated modeling studies.

The project foresees three irradiations, respectfully, at the temperature 200°C and fluence $5 \cdot 10^{18}$ n/cm^2; 290°C and $5 \cdot 10^{18}$; 290°C and $18 \cdot 10^{18}$. Two irradiations have already been completed. Post-irradiation examination is in progress, and will have to determine the microstructural and mechanical property changes in steels and model alloys. Finally, the development of improved mechanistic understanding will be primarily achieved through modeling of the segregation process and the effect of such segregation on the mechanical properties.

COBRA (coordinator A. Ballesteros, Tecnatom). This project tackles the open issue of the uncertainty in the measurement of the correct irradiation temperature to which WWER-440 reactor surveillance capsules are subjected [4]. Non-homogeneous neutron and gamma flux distribution determines the temperature gradient along the capsule and possible overheating as compared to the real conditions of the reactor pressure vessel. The latter phenomenon would produce nonconservative surveillance data.

Melting temperature monitors have shown uncertainties in assessing the temperature in the interval from 272 to 292°C.

Hence a special direct temperature measurement system by thermocouples has been implemented in Kola NPP in order to prove the feasibility of the solution to the problem. The consortium includes Russian, Armenian, and European institutions.

The obtained results show that the irradiation temperature of the surveillance specimens is about 272°C, hence it is possible to get conservative RPV surveillance results.

FRAME (coordinator M. Valo, VTT). This project is concerned with fracture mechanics based trend curves for PWR and WWER RPV materials. The scope is to validate the use of the Master Curve approach, as compared to the conventional one involving the increase of the ductile-to-brittle transition temperature assessed by Charpy impact testing.

Cleavage-initiation fracture toughness is the property needed in structural safety analyses of the reactor pressure vessel. However, this property is not measured directly for the irradiated (neither for the annealed or re-irradiated) material condition, instead a correlative embrittlement estimation based on the

Charpy-V test is used. It is difficult to quantify the uncertainties inherent in the current estimation, and hence, the assumed uncertainties are addressed by the use of a conservative fracture toughness reference curve and by added margins. Charpy-V impact toughness is in many respects a clearly different material property than fracture toughness. Hence, the current understanding of embrittlement may be a biased one.

In the FRAME project, fracture toughness-based embrittlement models will be created and they will be critically compared with the published Charpy-V based models.

Fracture toughness-based trend curves do not exist nowadays, because the required databases are non-existing or are insufficient in size. Trend curve development is in essence mathematical fitting of candidate functions to measured irradiation shift data. Approximately twelve different materials are included in the test matrix. The irradiation in HFR LYRA rig is successfully carried out and the post-irradiation testing campaign is about to start.

GRETE (coordinator EdF). The project is the follow-up to AMES-NDT, which was dedicated to aging monitoring of non-irradiated materials. The object of GRETE is a round robin exercise on nondestructive techniques to assess and monitor the degradation of reactor pressure vessel steels due to neutron irradiation and thermal fatigue of piping. The techniques studied are based on thermo-electric and magnetic effects. The results will be of interest for RPV surveillance programs, because a validated non-destructive measurement of surveillance specimens could provide an alternative to destructive testing and therefore allow sparing of surveillance samples.

Nondestructive Techniques for the characterization of neutron irradiation damage are: Automated ball indenter; Magnetic Barkhausen Noise; Micromagnetic measurements; Nonlinear Harmonic Analysis of Eddy Current signals; Thermo-electric power measurements.

For the characterization of fatigue damage: Magnetic Barkhausen Noise; Micromagnetic measurements; Nonlinear Harmonic Analysis of Eddy Current signals; Fluxgate, Giant Magnetic Resistor, Superconducting Quantum Interference Device; Ultrasonic Scattering or Backscattering. Analyses of the results and elaboration of conclusions are in progress.

2. **AMES in the 6th FWP**. In the context of the European Research Area, there is a need for integrating the activities on NPP Plant Life Management into a common structure dedicated to the evaluation of open issues, elaboration of new activities, and efficient utilization of available resources.

JRC-IE, starting from the experience accumulated since 1993 with the operation of NESC, ENIQ, and AMES networks is presently elaborating a strategy to optimize common plans for FP6 in different areas, and launch the SAFELIFE network in September 2003, which will cover the issues of NPP PLIM so far tackled in a scattered way by individual European networks.

The invaluable expertise and differentiated background of the present networks will be kept by reconsidering their role as Expert Groups. This will ensure that all different issues will be considered when planning new activities, especially in the context of the Network of Excellence dedicated to PLIM or new proposals for Integrated Projects (Fig. 1).

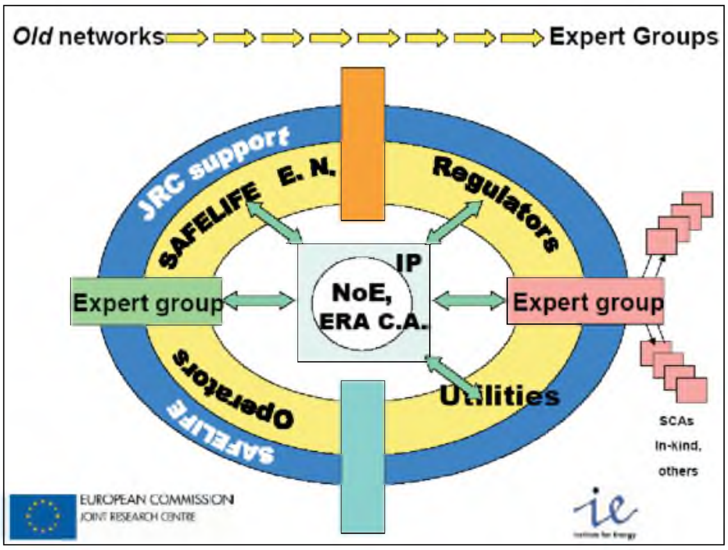

Fig. 1. Evolution towards an integrated approach to NPP PLIM in the EU.

The Expert Groups will act as review bodies advising on the contents of new project proposals.

3. **SAFELIFE and Plant Life Management of Aging NPPs in Europe**. An integrated approach to R&D activities on generic issues for plant life management of aging nuclear power plants is required to support European needs for sustainability and for Safe & Secure Supply (3S) of electrical power. To meet this challenge, the European Commission's Joint Research Centre proposes to form a Network focused on structural integrity for plant life management of key components, covering the main R&D disciplines involved and considering all nuclear power plant designs, both western and eastern. This is intended to provide a long-term structure capable of addressing generic issues related to accident prevention, plant performance and risk informed methods, and to harness the efforts of the leading European R&D. In addition, it can provide support for a rationalized EU approach to plant decommissioning and related waste management issues.

The initiative will be based on the successful established European Networks: AMES, NESC (network for the evaluation of structural components), ENIQ (European network for inspection qualification) and on new ones such as NET (neutron evaluation techniques) and AMALIA (Assessment of Materials Aging under the effect of Load and IASCC) operated by the JRC Institute for Energy.

SAFELIFE composition

- members of the European Networks AMES, NESC, ENIQ, NET, and AMALIA;
- members of running DG-RTD Thematic Networks and Shared Cost Actions in this area;
- representatives as appropriate from other European and international organizations.

SAFELIFE network objectives are the following:

- Establishment of a long-term structure to improve the focus and effectiveness of the European R&D for plant life management for key reactor components in aging nuclear plants.
- Development and funding possibilities of major "integrated" project proposals at trans-national and EU level consistent with the European Research Area principles.
- Strategic planning and management of R&D actions in this area
- Promote harmonization of the best practice for improved European codes and standards.
- Organize training and professional development in advanced procedures and to maintain engineering competence for safe and economic operation of nuclear plants.
- Link and co-operate with all key international and national organizations.
- Optimize access to existing data, facilitate data exchange, and support effective dissemination and technology transfer.

Conclusions. Evolving from the 4th and 5th EURATOM Framework Program approach based on in-kind and co-financed initiatives promoted by its Steering Committee, AMES has reached important results and built a wide consensus on important issues related to neutron embrittlement of the reactor pressure vessel [5].

With the start of the 6th Framework Program and the introduction of new instruments like the Integrated Projects and the Network of Excellence, there is a need for a broader and more efficient integration of activities and resources in the spirit of the European research Area.

AMES and other European nuclear networks operated by JRC-IE will therefore evolve into Expert Groups of a more expanded new initiative on NPP Plant Life Management called SAFELIFE, which will be promoted by JRC and built on the experience acquired with the operation of the present networks.

In this way, SAFELIFE could constitute the basis for the future Network of Excellence on PLIM of nuclear power plants in the EU.

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Резюме

Розглянуто комплекс дослідних програм EURATOM, що спрямовані на вивчення механізмів старіння та методів усунення пошкоджень конструкційних матеріалів корпусів реакторів. Даний комплекс передбачає розробку неруйнівних методів дослідження теплового старіння і моніторинга радіаційного окрихчування матеріалів, удосконалення програми досліджень із використанням зразків-свідків для реакторів типу ВВЕР-440, дозиметрії, а також застосування різних механізмів руйнування для оцінки структурної цілісності АЕС. Зокрема, проект ATHENA дозволив обгрунтувати модель повторного окрихчування після відпалу та виявити залежність швидкості окрихчування від хімічного складу корпусних сталей. Коротко викладено основні досягнення діючих програм EURATOM та задачі наступного етапу досліджень у рамках проекту SAFELIFE.

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