SOTERIA is an on-going H2020 project which proposes a comprehensive research approach in order to enable nuclear power plant operators, as well as regulators, to better understand and thereby predict the ageing phenomena occurring in reactor pressure vessels and internal steels to ultimately ensure a safe long-term operation of existing European nuclear power plants.

The SOTERIA approach is based on an end-user perspective and has planned the set-up of simulation-oriented experiments aiming to validate models at different scales.

*The **sixth edition of the SOTERIA newsletter** contains a summary of the technical progress of the different work packages since November 2018, when the newsletter #5 was issued. In addition, there is a section devoted to the dissemination activities, with the forthcoming Final Workshop, the last End-User Group Meeting and the participation of SOTERIA in the NUGENIA Forum 2019.*

Remember that all the publications and presentations prepared by the SOTERIA team members since project start are available on our public website, as well as further information.

We would also like to remind that the SOTERIA End-User Group is still open to equipment manufacturers, vendors, and operators (if interested, please contact Julien Vidal at julien.vidal@edf.fr).

The SOTERIA project partners

Progress in radiation effects on microstructural evolution of RPV and internals under different levels of fluence and flux (WP2)

Neutron and ion irradiated stainless steel has been examined by TEM. The ion irradiation has been performed at IBC, 3 MeV Tandetron with 8 Mev Fe-ions at two different fluxes. Preliminary results show that features other than faulted loops are observed at the material ion irradiated at low flux, similar appearance for the high flux damaged microstructure. Neutron irradiated materials (BOR60) shows faulted and unfaulted loops, and cavities.

Ion irradiated model alloys were examined to analyse the role of Ni on radiation damage formation at high fluence levels. Results shows the formation of dislocation loops, dislocation lines and cavities enriched in Ni, and second-phase precipitates displaying a FCC lattice and containing 25at.%Ni.

Post irradiation annealing (PIA) has been performed on a model alloy with chemical composition representative of RPV steels (Fe-1.1Mn-0.7Ni-P) neutron irradiated at 300°C. The post irradiation annealing was performed at 400, 500 and 600°C. APT examination reveal that the neutron irradiation produces a high number density of Mn, Ni and P rich clusters. PIA at 500 and 600°C result in the dissolution of these clusters whereas they remain stable during PIA at 400°C.

Progress in evaluating uncertainties in fracture toughness measurement on irradiated RPV steels and mitigation approaches (WP3)

The work on effects of initial materials inhomogeneities on microstructure and mechanical properties of RPV steels at irradiated state for LTO was completed by issuing a dedicated deliverable. The influence of specimen size, specimen orientation and irradiation embrittlement on the scatter of the fracture toughness, the distribution of the cleavage initiation size and the reference temperature T_0 was investigated by testing of miniature 0.16T-C(T) specimens for reasons of effective use of the available irradiated specimen materials. For all investigated materials there is an influence of the orientation (L-T, L-S and S-T) of miniature 0.16T-C(T) specimens on T_0 which varies within a span of 2 standard deviations.

The effects of additional uncertainties in RPV surveillance data have been studied as well with the aim of quantifying their impact on the total uncertainty and scatter and to improve the use of surveillance data from an end-user perspective of view. Among others the flux effect (i.e. effect of lead factor), the fluence distribution of single specimens within one specimen set, the potential effect of neutron spectrum, the existence of any potential new effects not included in the Embrittlement Trend Curves (ETC), like late blooming irradiation embrittlement, non-hardening mechanisms etc., effects of testing conditions and methods for evaluation of test results, and potential thermal ageing effects during irradiation were considered. The interaction of uncertainties has been analysed to quantify the effects from the point of view of reasonable conservatism.

The effect of the fluence distribution of single specimens within one specimen set for A533B and A508 steels on the uncertainty of transition temperature shift dT_k determined from notch impact testing is shown in Figure 1.

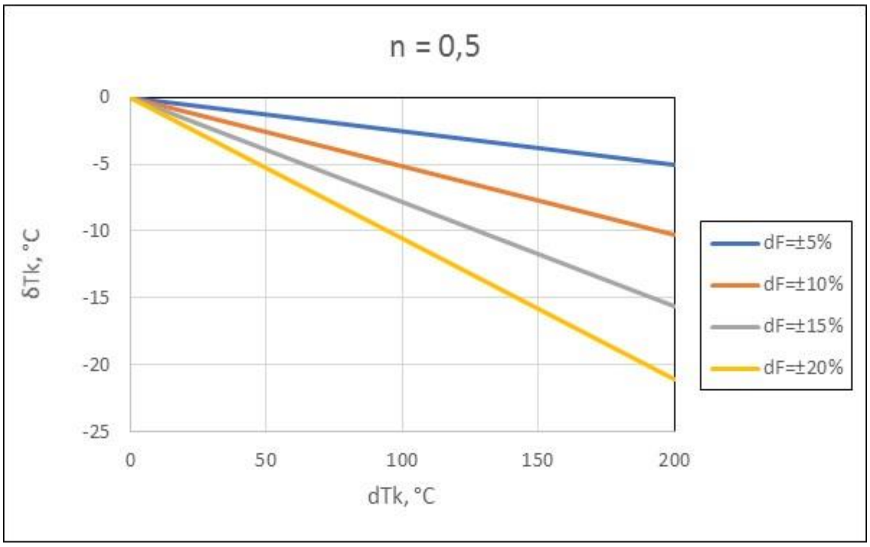

Figure 1 – Effect of the different maximum scatter of neutron fluence in individual specimens in a surveillance set on the difference in transition temperature for different level of embrittlement (dTk) and constant slope of Embrittlement Trend Curve (n=0.5)

Progress in environmental effects on IASCC susceptibility of reactor internals (WP4)

WP4 progress is summarized next:

- ***Irradiation effects on microstructural evolution in proton-irradiated 316L SS:*** Detailed characterisation of neutron-irradiated and proton-irradiated alloys have confirmed that irradiation-induced defects (loops and "black spots") as well as very fine cavities can readily form during neutron and proton irradiation (dependent on dose and irradiation temperature) and that nanoscale irradiation-induced solute redistribution (segregation and clustering) can impact the alloy's SCC susceptibility. Still to complete: FEGSTEM-EDX analyses of Grain Boundaries (FIB) and Post-SCC characterisation of proton-irradiated 316L to assess nature and depths of cracks.

- ***SCC testing of cold-worked & proton irradiated 316L SS:*** None of all tested specimen with loads up to 800 MPa and test durations up to 2000 h showed any cracked grain boundaries in SEM investigations. Some pronounced oxidation was observed along grain boundaries in particular for heat treated specimen. Significantly different oxidation behaviour for specimens having different surface treatments and heat treatment conditions. No significant difference between oxidation of differently loaded specimen was observed (so far – further microscopy work ongoing). Oxidation clearly depends on the actual grain orientation. Still to complete: Further loading and unloading of specimens will be performed to check grain boundary cracking under loading (at different load levels), further investigations on grain boundary oxidation, FIB cuts along grain boundaries and detailed comparison of loaded/unloaded specimen oxidation behaviour (in particular at grain boundaries).

- ***Effects of the environment on the oxide properties:*** Studying the effect of environment, the higher the crystallites size is observed, thicker the outer oxide layer is formed on the surface. Auger Spectroscopy indicates that the different environments produce variations in the structure and chemical composition of the oxide layer: (I) Samples tested in high Li environment shows a thicker outer layer (Fe rich) than reference sample. (II) Cr/Fe ratio is higher in high B environment. (III) NiFe ratio is higher in high B& high Li environment. Oxide films formed in these environments are different in thicker, composition and morphology. Cr is not present in surface oxide in low B/Li ratio environment. NiFe2O4 and Fe2CrO4 oxide compositions are the most likely. Cr(OH)3 is detected in the surface. A Ni rich spinels (NiCr2O4) appears in surface in 2000B-10Li condition. The characterization analysis is nearly completed except some final examinations by TEM.

- ***IASCC testing of reactor internals:*** O-ring specimen radioactivities have been assessed for making the required handling plan for work permit. A new diamond saw has been nuclearized and put into hot cell. Carried out diamond-sawing trials on mock-up O-ring material. TEM specimen electropolishing equipment has been decontaminated and is awaiting clearance measurements before moving to new facility. Tools and procedures are functioning for safe cutting of hot O-rings. Because the hot cells are new, new equipment needs to be nuclearized before installation, and existing equipment from old facilities have to be decontaminated before moving into new facilities. This is time-consuming, as safety is first. Loading of the specimens remotely has been demonstrated. The new autoclave and high-temperature recirculation loop function well. The plan to saw one of the O-rings shorter to produce three simultaneous stress levels has been delayed while nuclearizing the diamond saw and deploying it in the hot cell. Decision has been made to initiate the first autoclave run with only two lengths if sawing cannot be done soon. At least a second autoclave run (high hydrogen conditions) is also intended.

- ***IASCC testing of proton irradiated 316L SS:*** The Validation Test successfully demonstrated the methodology of using the 4 point bend testing to produce SCC initiation in a specimen with a surface damaged or irradiated layer. Direct current potential drop (DCPD) was not sensitive enough to detect the cracking (supported by FEA model). Test 1 used the same methodology as the validation test. Evidence of SCC initiation was observed on the proton irradiated surface during post-test characterisation. Baseline test for comparison to be undertaken in the next stages of the programme. Test 2 – Proton-irradiated specimen 2, Stage 1 loading to 80% of bulk yield stress, hold ~100 hours, Stage 2 loading to yield point of proton-irradiated layer, hold ~1000 hours. Test 3 – Baseline (un-irradiated) material with CW surface layer. Stage 2 loading parameters dependant on Test 3 outcome. Does radiation-induced hardening alone initiate SCC? 2 further proton-irradiated specimens remain for additional SCC testing.

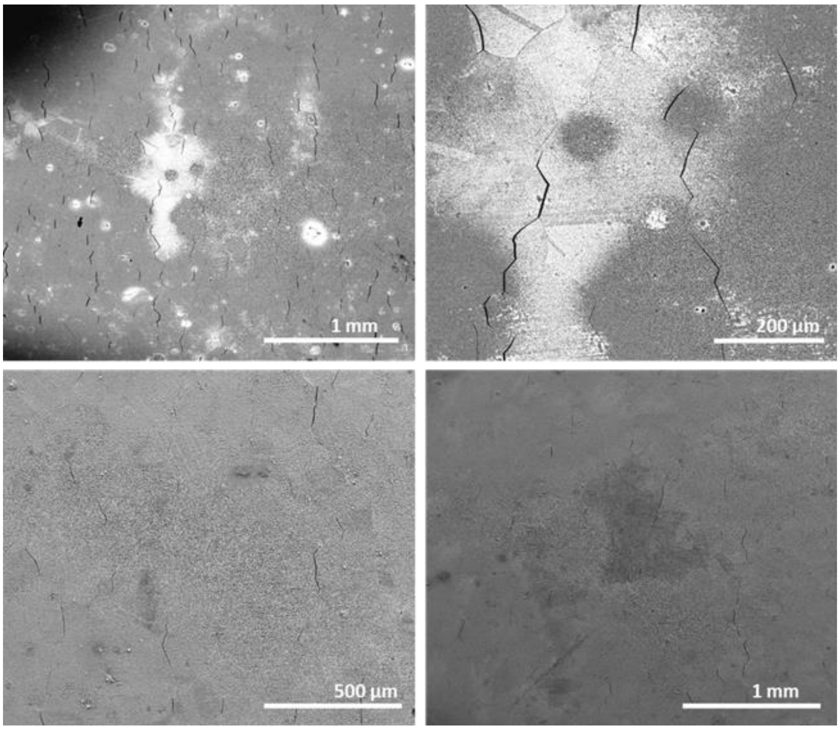

Figure 2 – SEM images showing IASCC on the proton irradiated 316L SS specimen surface post-4-point-bend SCC testing.

- ***He effects in the LWR regime:*** A report has been issued and no further action is required.
- ***Effect of He bubbles on grain boundary (GB) weakening:*** Irradiations, TEM and SEM investigations, slow strain rate tests (SSRT) and nanohardness tests have been completed. A deliverable is under preparation.

- ***Cr diffusion:*** This study cannot explain the higher Cr depletion profile observed in oxidized cracks formed by stress corrosion cracking in PWR. Is it due to combined effect of diffusion and stress? Cr tracer diffusion coefficient could be measured under creep test. Is it due to combined effect of diffusion and oxidation? Vacancies created in alloy by oxidation could accelerate the Cr diffusion. Consequently, oxidation tests with sample of various microstructures has been conducted in gas environments: two kinds of Cr depletion profiles are measured. Normal diffusion profiles: Cr depletion explained at 550 °C BUT NOT at 400 °C: at low temperature, other phenomenon occurs that could be due to a competition between annihilation and creation of vacancies. Abnormal diffusion profiles: Mass balance is not correct. How can we explain that phenomenon? Recrystallization. Stress effect.

Progress in the development, validation and integration of models to assess RPV and internals components under irradiation (WP5)

During the last period, final results on "experiment and modelling of swelling in internals", "application of space resolved long- and medium-term nanostructure evolution methods for RPV steels", "influence of cold working state on oxidation, local depletion and vacancy supersaturation for internals" and "effect of localised heterogeneities on cleavage fracture" have been reported.

- ***In D5.4 (Effect of localised heterogeneities on cleavage fracture)***, the aim of the study was to investigate effects of spatial heterogeneity of cleavage initiation particles in a local approach to cleavage fracture model and to verify whether such models are able to capture experimental outlying results. The conclusion of the work is that there is a large effect on the fractured toughness predicted by a local approach model when the variation in tensile properties is included in the finite element analysis. Furthermore, it may be possible to relate the specimen extraction location and results, potentially allowing the prediction of which specimens will have the lowest fracture toughness. This may offer a simple engineering approach to capture lower bound results as the variation in bulk tensile properties throughout a weld could be observed directly using hardness mapping.

- ***For D5.5 (Influence of cold working state on oxidation, local depletion and vacancy supersaturation for internals)***, modelling of the oxidation kinetics in the presence of substrate cold work was investigated: higher depletion depth and higher Cr content at the metal/oxide interface were observed for low cold-working. For the very specific investigated conditions, the results showed that the Kirkendall effect was widely predominant versus vacancy injection in case of rigid metal/oxide interface. Finally, considering homogeneous nucleation theory, the calculated supersaturation of vacancies was not sufficient for voids formation after 77 minutes of oxidation at 1000°C.

- ***In D5.6 (Application of space resolved long- and medium-term nanostructure evolution methods for RPV steels)***, improvements of both Atomic and Object Kinetic Monte Carlo approaches to describe microstructure evolution have been reported and summarized: improved treatment of chemical complexity has been achieved through neural network-based, cluster expansion-based and concentration dependant cohesive model, allowing to improve the prediction of the chemical composition of solute clusters. In addition, a complete and generic description of sink strength for 1D to 3D mobilities of defect clusters was established.

- ***In D5.7 (Experiment and modelling of swelling in internals)***, a microscopy analysis of highly irradiated austenitic stainless steels was performed and microstructural structure was fully resolved showing significant differences between ion and neutron irradiation. In addition, development of modelling tools was performed leading to significant advances in accounting for sink strength, elastic effects and spatial dependency on microstructure evolution of irradiated austenitic stainless steels.
- ***In D5.9 (Effect of Irradiation on Cavities Growth and Coalescence in Stainless Steels: Experiments and Modelling)***, a coupled experimental and theoretical study shone some light on the elementary mechanism leading to void growth and coalescence on irradiated austenitic stainless steel.

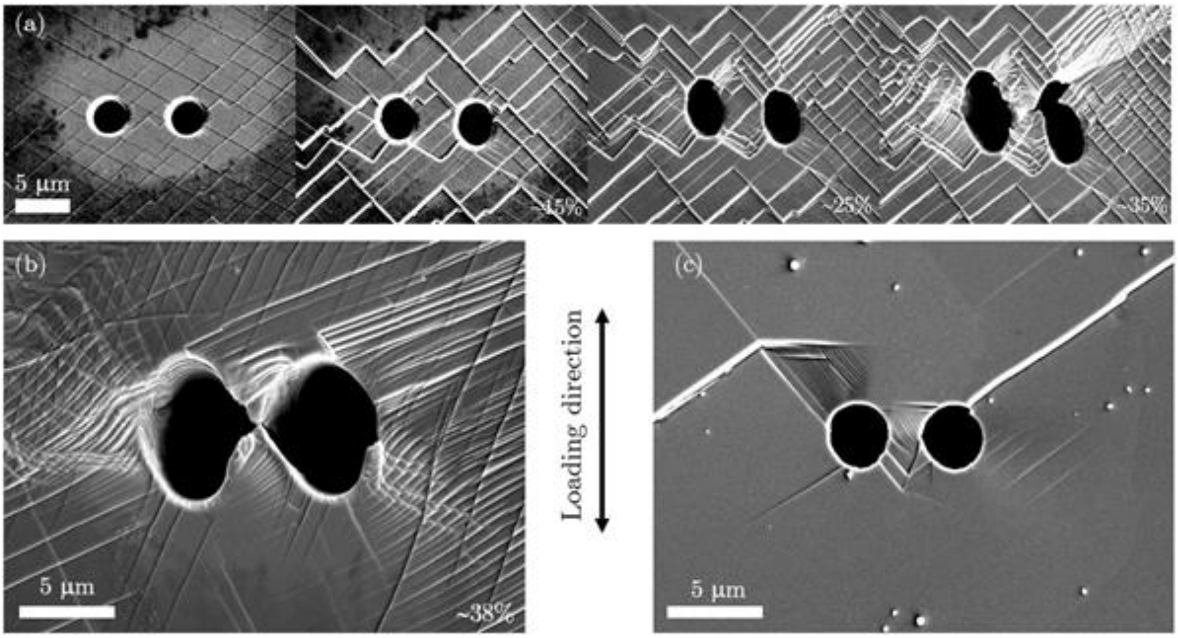

Figure 3 – Typical observations of voids coalescence in the material exhibiting dislocation channeling deformation mode.

It is inferred that the classical approach based on homogenization developed for porous material describing void growth and coalescence can thus be used as a first order approximation to describe ductile fracture of irradiated stainless steels. Dislocation channeling deformation mode affects only early stages of void growth whereas the coalescence mode, which involves large levels of plastic strain, is only weakly affected.

DISSEMINATION ACTIVITIES

REGISTER NOW!

SOTERIA Final Workshop

25-27 June 2019, Miraflores de la Sierra (Madrid)

SOTERIA will soon hold its final workshop during which the results obtained during the research work of the past 4 years will be presented.

The objective of the workshop will be to disseminate the project final results among the nuclear research and industrial communities, and particularly end-users, as well as to identify future research needs. The workshop will serve as a forum for regulators, user groups, experts and industry, to exchange information and experiences on the issue of radiation effects on nuclear power plant components.

Technical Programme

The technical programme will include oral presentations, 2 demonstration sessions with the SOTERIA modelling platform and a poster session.

RPV – Microstructure
Flux effect on RPV materials
Mechanisms of formation of nano-features in RPV
RPV – Uncertainties in determination of RPV fracture toughness
Effect of materials heterogeneities on mechanical properties at initial state
Effect of materials heterogeneities on microstructure and mechanical properties at irradiated state
Effects of additional uncertainties and handling and mitigation of uncertainties
INTERNALS – Microstructure
Flux effect on internals
Dose-dependent nano-features and their effect on intergranular cracking susceptibility
INTERNALS – Environmental effects on IASCC susceptibility of internals
Irradiation effects on microstructural evolution
Effects of the environment on the oxide properties
Effects of He on IASCC susceptibility

Multiscale Modelling Tools
Nanofeature models due to irradiation for RPV and Internals
Prediction of dose-dependent fracture response evolutions based on material microstructure
Fracture models for RPV and for the IASCC of Internals
Demonstration of the modelling platform

- **Please visit our website for additional information and online registration.**

SOTERIA End-User Group Meeting
28 June 2019, Madrid

The last end-user group meeting will be held on 28 June 2019 at Tecnatom, Madrid. The aim of the meeting is to present the latest developments of the SOTERIA platform and exchange with end-users about their needs and industrial application cases. A tour of Tecnatom facilities will be also organized.

- **In case you are interested in attending this meeting, please contact Julien Vidal** (julien.vidal@edf.fr).

SOTERIA at NUGENIA Forum 2019
13-15 March 2019, Paris

The NUGENIA Forum 2019 was held on 13-15 March 2019 at Cité Universitaire, in Paris, with the theme *Innovation for a safe, efficient and low-carbon nuclear energy production*. Among more than 260 participants, several SOTERIA members were present and seized the opportunity to showcase the project. In the picture, Julien Vidal (EDF) is presenting a poster with the highlights of SOTERIA.

Since project launch, SOTERIA has established a strong relationship with NUGENIA. The first SOTERIA end-user group meeting was held during the NUGENIA Forum 2017 in Marseille and the project mid-term workshop was held in conjunction with the Forum in April 2018. NUGENIA members are periodically invited to SOTERIA annual meetings and workshops and there is one official NUGENIA representative who is member of the project Technical Review Committee. In addition, SOTERIA events, like the forthcoming final workshop, are advertised at the NUGENIA site.

The SOTERIA consortium includes the following organisations:

COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES – CEA
WOOD GROUP (previously AMEC FOSTER WHEELER NUCLEAR UK LIMITED)
AREVA NP SAS
FRAMATOME GMBH (previously AREVA GMBH)
ARTTIC
CENTRO DE INVESTIGACIONES ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS - CIEMAT
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE - CNRS
CENTRUM VYZKUMU REZ S.R.O.
ELECTRICITE DE FRANCE - EDF
HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF EV - HZDR
INSTITUT DE RADIOPROTECTION ET DE SURETE NUCLEAIRE - IRSN
JOINT RESEARCH CENTRE- EUROPEAN COMMISSION - JRC
INSTITUT JOZEF STEFAN - IJS
KUNGLIGA TEKNISKA HOEGSKOLAN - KTH
PAUL SCHERRER INSTITUT - PSI
PHIMECA ENGINEERING
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE FONDATION D'UTILITE PUBLIQUE – SCK-CEN
TECNATOM S.A.
UJV REZ, A.S.
THE UNIVERSITY OF MANCHESTER - UoM
UNIVERSITAT POLITECNICA DE CATALUNYA - UPC
VATTENFALL AB
ECOLE NATIONALE SUPERIEURE D'ARTS ET METIERS
TEKNOLOGIAN TUTKIMUSKESKUS VTT OY - VTT

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