SOTERIA

Safe long term operation of light water reactors through the improved understanding of radiation effects

[Public Website](#)
[Contact details](#)

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 **last issue of the SOTERIA newsletter** contains a summary of the activities carried out within the different work packages since April 2019, when the newsletter #6 was issued, highlighting the project achievements and main results. Short remarks on the latest project events are also included: the SOTERIA Final Workshop and the Final Consortium Meeting.*

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.

The SOTERIA project partners

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

During the last period of SOTERIA WP2, Deliverable D2.6 – "Set of guidelines on use of experiments carried out in WP2" was issued by CIEMAT in collaboration with FRAMATOME, HZDR, EDF and WOOD. This document compiles most of the microstructure and other experimental data produced within SOTERIA WP2. Some recommendations are included that mainly are focused on the future collection and storage of these data to be used for model validation or for predictive trend curves.

The work performed on neutron and ion irradiated austenitic stainless steel was compiled in Deliverable D2.4 – "Role of particular radiation defects in radiation hardening and swelling mechanisms" by CVR and CIEMAT. The examination by means of Transmission Electron Microscopy (TEM) of dedicated irradiated internals steels, in particular, type AISI-321 austenitic stainless steel is reported. The aim is to gain knowledge about the nature and the stability of irradiation-induced features. The results from TEM examination of neutron irradiated AISI-321 showed the presence of faulted Frank loops and small black dots, also cavities and some degree of radiation induced segregation to grain boundaries were detected. The ion irradiation conditions employed did not reach to emulate all the radiation induced features found after neutron irradiation, however, the population of faulted loops and the small black dot structure was reproduced.

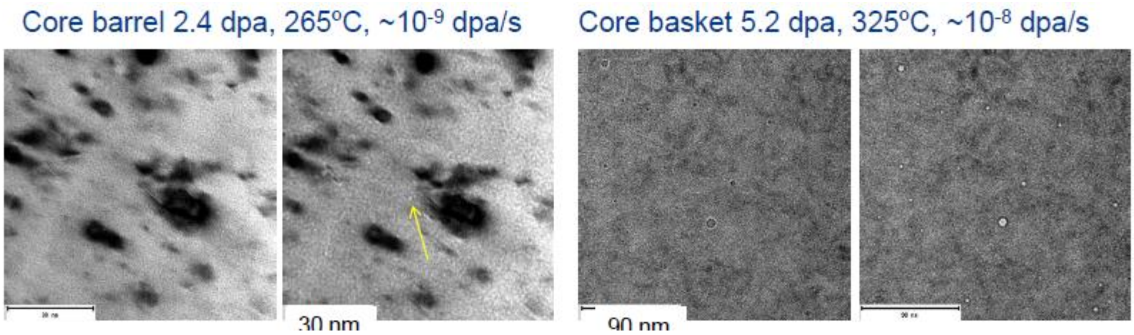

Figure 1 – TEM examination of neutron irradiated stainless steel (CIEMAT, CVR)

TEM in-situ annealing experiments were performed, both at CIEMAT and CVR facilities. The ion-irradiated materials were considered for this purpose. The aim was to assess the stability under annealing of the radiation induced features. Results indicate that during the annealing sequence, part of the faulted loop population disappears. This fact was observed by examination of the images taken while the experiment was in course and, quantitatively, resulted in a decrease of number density. The decrease in density was accompanied by a general growth, with a shift to larger sizes, i. e., smaller loops disappeared and medium-sized loops increased. However, the average size is not increasing as there is a general decrease in the population of larger loops, i. e., loops become larger, but their amount is reduced, resulting in a slight decrease of average size. The observed results are in agreement with those reported in literature, where the partial or even total disappearance of faulted Frank loops has been observed after ex-situ annealing.

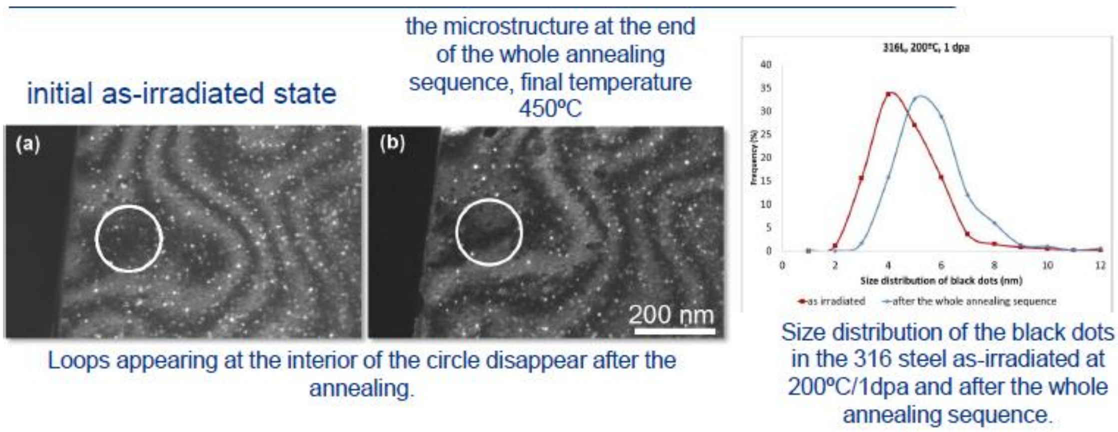

Figure 2 – In situ TEM post irradiation annealing of ion irradiated stainless steel (CIEMAT, CVR)

The role of grain boundary on the susceptibility of IASCC has been studied and reported in Deliverable D2.5 – Effect of nanostructural changes on intergranular cracking susceptibility by CEA and CIEMAT. Investigation of helium effect on degradation of grain boundaries was included. The material under study has been an austenitic stainless steel implanted with high energy He ions at CEMHTI. Interrupted SSRT tests have been performed and the near surface microstructure has been examined by means of FEG-SEM/EBSD. Results were described for implanted and non-implanted samples.

A new crack initiation model based on sub-grain plasticity mechanisms, analyzed by dislocation dynamics simulations was also summarized.

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

The assessment of uncertainties in RPV irradiation behaviour with respect to initial microstructure, material variability and other influencing factors was summarized in a dedicated deliverable with the objective to contribute to the definition of European best practice in dealing with scatter and uncertainty in data analysis and condition assessment for LTO including assessment and validation of embrittlement trend curves (ETCs). For this purpose, a specific review of the main results was performed to address quantifiable uncertainties and scatter effects from an end user perspective and to provide an added value for improved reliability of RPV irradiation surveillance data.

It was found that the primary initiation site is not characterized by a specific microstructural feature, such a precipitate or inclusion, at which brittle fracture would have initiated, whereas the existence of particles in initiation sited is considered as typical for weld metals.

In general, tensile properties of studied material do not show a significant scatter, whereas the fracture toughness tests can show larger scatter than expected that could be attributed to the presence of intergranular fracture areas and to a dependence on the chemical composition, respectively.

Further examinations of several RPV materials by hardness measurements, fracture toughness tests, and SEM, EBSD and TEM analyses highlight the effects of material inhomogeneities on the mechanical properties of RPV steels. The scatter of the impact and fracture property data can be explained by the different locations of the specimens. Regarding chemical analysis a non-negligible uncertainty in weight % was found for some chemical elements, such as C, P, S, Cu and Ni playing an important role in aging mechanisms of RPV steels.

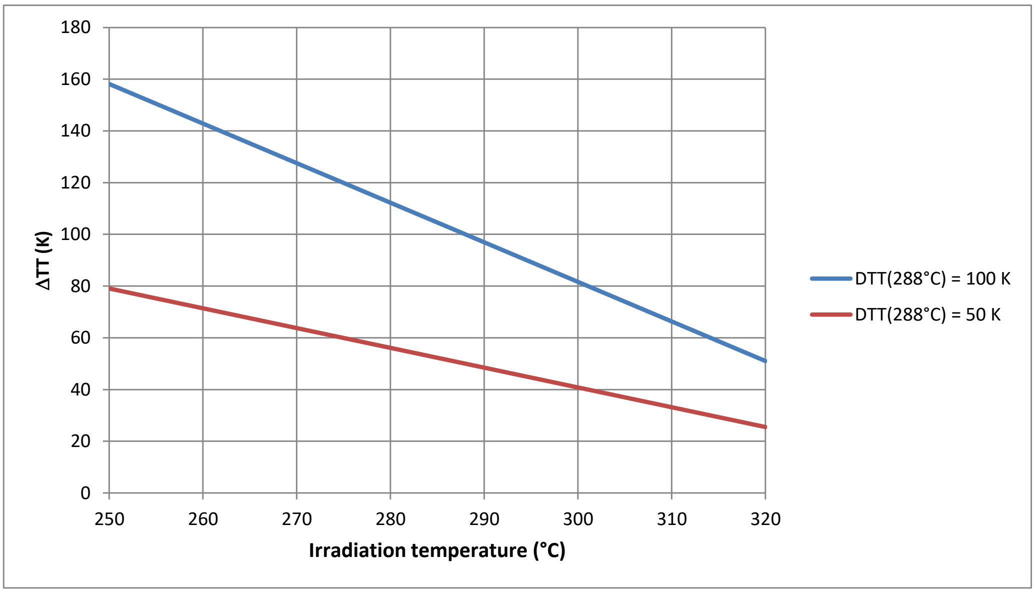

Figure 3 – Effect of irradiation temperature on transition temperature shift ΔTT

Engineering estimations for uncertainty quantification were elaborated as well. As an example, the uncertainty related to irradiation temperature can be assessed by an estimation of the deviation of the irradiation temperature of the surveillance specimens from the true temperature at relevant RPV wall position (Figure 3). This gives as a rough approximation for moderate irradiation embrittlement of RPV materials under LTO condition: 1 K increase in irradiation temperature results in 1 K lower irradiation-induced transition temperature shift. This confirms the relevance to consider the effect of irradiation temperature as an uncertainty factor in surveillance testing and assessment.

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

IASCC is a phenomenon whereby a material that would not usually be susceptible to SCC in a particular environment becomes so, due to changes to the material and/or environment by the presence of neutron irradiation. WP4 aims to understand environmental factors on IASCC susceptibility through a combination of sub-tasks focusing on key areas (irradiated microstructure, material properties (cold work, surface finish), environment (abnormal chemistry, hydrogen), irradiation SCC testing (neutron vs. proton) and helium effects. Below is a summary of the significant findings from the sun-tasks within WP4:

- **WP4.1 - Characterisation of irradiation effects (UoM, VTT, Framatome):** Comparison between 5 dpa proton and low dpa neutron shown some similarities such as nanoscale solute redistribution and segregation. Fine cavities were observed in the proton irradiated material, which is a surprising outcome as this usually occurs in high dpa neutron irradiated material.

- **WP4.2 - Cold work effects (Framatome, CEA):** Cr depletion is a detrimental factor, expected to arise from RIS has been implicated as a likely cause of IASCC. Cr depletion was explained at high temperature (550 C) by diffusion experiments but not at low temperature (400 C). This is usually due to other influencing factors than diffusion such as stress, oxidisation and dislocations.

  Oxidation in high temperature water with a load can lead to oxide layer rupture then strain localisation at grain boundaries occurs. Some pronounced oxidation was observed via post-SCC testing microscopy, in particular for heat treated material.

- **WP4.3 - Environmental effects (Ciemat, VTT):** Changes observed in the protective oxide layer caused by changes in the environment (B/Li ratio, hydrogen). One example is the presence of alpha prime martensite in high H environments.

  Cracking occurred more readily in neutron irradiated material exposed to a higher H environment.

- **WP4.4 - IASCC testing (UoM, Framatome, UoM, VTT) :** Two dpa levels (65 and 100 dpa) neutron irradiated material in the form of O-ring geometry were subjected to compression tests and cracking occurred for both levels at a load of 62-65% irradiation yield stress. Cracking occurred in the most tensile regions. Analysis of fracture surfaces is yet to be performed.

  IASCC testing of proton irradiated material was performed using four point bending but one utilising dynamic (slow strain rate) loading and the other static loading. Cracking was only observed in material subjected to slow strain rate loading. All data has been plotted on the IASCC applied stress / Irradiated yield stress vs dpa map.

- ***WP4.5 - He effects (PSI, CNRS, CEA):*** He-alone implantations with levels close to PWR conditions does not increase the susceptibility to inter-granular cracking.

  The He studies suggest there may be a synergy between He and displacement damage.

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

During the last period, final integration in the SOTERIA platform of Microstructure Informed Brittle Fracture (MIBF) model developed by CEA was completed allowing to compute the failure probability curve accounting precisely for the characteristic carbide distribution observed in reactor pressure vessel steels.

In addition, parametric capability has been added to the SOTERIA platform allowing to vary in an automatic manner parameters of pre-loaded studies and visualize variations of selected outputs. (See Figure 4). Such module could allow investigation of parameter sensitivity of multiscale models available in the platform.

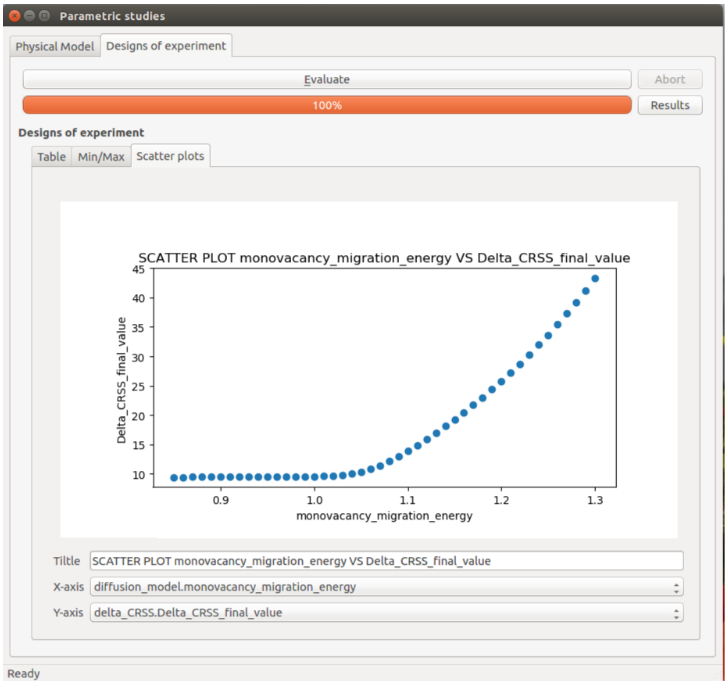

Figure 4 - Parametric module of the SOTERIA platform showing variation of the critically resolved shear stress versus migration energy of the monovacancy.

A cloud-based version of the SOTERIA platform has also been tested on EDF internal cloud using a Citrix receiver technology allowing access to the platform from different sites within the company network. A cloud-based version of the platform will considerably improve not only distant accessibility to the platform, which was End User group main concern, but also integration of new tools with significant library requirements, which were also identified as a clear barrier for the installation of the platform by first time users.

A final version of the platform will be released at end of August 2019 as milestone MS13.

SOTERIA EVENTS

SOTERIA Final Meeting
28-29 August 2019, Paris

SOTERIA held its final meeting, restricted to the project partners, on 28-29 August at CEA premises in Paris. The major achievements of the project were presented by the work package leaders and there was a special session to present end of project requirements and prepare the final reporting.

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

The SOTERIA Final Workshop, held on 25-27 June in Miraflores de la Sierra, Madrid, attracted 61 registered attendees.

Specially targeted to end-users, the workshop was organised next to the last end-users group meeting, which took place on 28 June, just after the workshop, to encourage end-users to attend both events.

Presentations made were an effort to convey the results of the last 4 years of work within the SOTERIA project. A poster session was also organised and some time was devoted to comment on future projects, with namely two project proposals particularly related to SOTERIA being presented: ENTENTE (E*uropean database for multiscale modelling of radiation damage*) and BOLTS (*Lifetime prediction of baffle-former bolt cracking*). All the presentations are available for download on the workshop website.

The workshop proved to be an efficient channel for networking and building collaborations based on the diverse technical background of the participants, who came from 25 organisations distributed in 15 different countries.

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

This project received funding from the Euratom research and training programme 2014-2018 under grant agreement no. 661913.

Editorial team: imarcelles@tecnatom.es | bertrand@arttic.eu | julien.vidal@edf.fr | christian.robertson@cea.fr