Executive summary

Since 2007, the OECD Nuclear Energy Agency has been organising a series of workshops on Structural Materials for Innovative Nuclear Systems. The third meeting was held on 7-9 October 2013 in Idaho Falls (United States). The main objectives of this workshop are to stimulate an exchange of information on current materials R&D programmes for different innovative nuclear systems. The main topics of the workshop covered **fundamental studies, modelling and experiments** on innovative structural materials including cladding materials for the range of **advanced nuclear systems** such as thermal/fast systems, sub-critical systems, as well as fusion systems.

During the workshop, the following topics were discussed:

- Fundamental studies.
- Metallic materials.
- Ceramic materials.
- Novel materials pathways.
- Ion vs neutron irradiation.

Fundamental studies focused on the identification of mechanisms driving the response of materials under the conditions expected in innovative nuclear systems. These mechanisms may have acted at the atomic or higher scale with the application of multiscale approaches, together with related problems of scale-bridging or numerical methods, were of special interest. Moreover, irradiation experiments and subsequent characterisation of materials with analytical techniques were included in the session if aimed at better understanding the acting mechanisms or drawing physics-based correlations. **Metal alloys, ceramic and ceramic composites** included in- and out-of-core applications which took into account the scope of: data availability and gaps (considering also licensing issues); experimental and modelling needs for specific components or degradation modes; the link between R&D, standardisation and experimental protocols; coolant effects and mechanical properties. Code development and implementation plans were also discussed. Application of SiC composites to LWR systems was of interest as an advanced concept. **Novel materials pathways** considered routes to fabricate materials and components for innovative nuclear systems. The "**ions vs. neutron irradiation**"topic focused on specific irradiation comparisons including mechanical properties and microstructural effects caused by ion or neutron irradiation. Comparative irradiation studies on a common material were also welcome. *Fuel-cladding interaction was not covered in this edition of the workshop*.

The workshop received 74 abstracts, and was scheduled with 5 invited talks, 27 oral presentations and 2 poster sessions (42 posters) from 75 registered participants. However, it was necessary to reorganise the programme at extremely short notice to take into account the effects of the unexpected US government shutdown and the constraints this imposed on the workshop. In total, 38 participants from 12 countries and 2 international organisations attended, and the final number of presentations amounted to 51 (22 oral presentations and 29 posters).

The re-scheduled workshop opened with the welcome address by S. Cornet on behalf of the OECD Nuclear Energy Agency followed by technical sessions:

Session I: Overview on programmes and metal alloys.
Session II: Metal alloys.
Session III: Novel pathways.
Session IV: Ceramic composites, ions vs. neutrons and general.

Session I: Overview on programmes

International perspectives from several current programmes were presented: *Céline Cabet (CEA, France)* described the vision for sustainable nuclear energy that was defined in the European SET-plan, which envisaged a roadmap for SFR then LFR and GFR development in the longer term. Within Europe, the national R&D efforts are to be coordinated within the European Energy Research Alliance Joint Programme for Nuclear Materials (JPNM); the function of the new MatISSE project is to bring the EERA JPNM forwards to integration. The key work packages address: the development of a European R&D roadmap and strategic research agenda; irradiation hardening and creep in F/M alloys; ceramic matrix composites and MAX phase for refractories; ODS alloys; design, selection and qualification of materials for ESNII; and dissemination and communication. *Victor Inozemtsev (IAEA)* described the IAEA tools for programme implementation, which are co-ordinated research programmes (CRP) in addition to technical meetings (TM) and Expert Reviews. Recent examples of CRPs include fuel modelling; accelerator simulation and theoretical modelling of radiation effects (SMoRE); an ODS irradation effects benchmarking exercise; calculation of primary radiation damage, and also accident tolerant fuels and in-core structural materials for water-cooled reactors. *Lyndon Edwards (ANSTO, Australia)* gave an overview of the programmes on the Australian research reactor, which was designed for materials irradiation, isotopes and neutrons and is currently the most modern research reactor in the world. The key materials research themes are: radiation damage and multi-scale modelling to inform experiment design and surveillance programmes; advanced waste forms, such as synroc; PIE, with a focus on micromechanical testing, weld-modelling and synchrotron X-ray studies.

Session II: Metal alloys

Concetta Fazio (KIT, Germany) described the *GETMAT* project, whose objectives has been to procure and test ODS steels for clad and structural components and address their compatibility with environments, including irradiation effects, as well as to perform PIE on F/M steels and to expand understanding on Fe and Fe-Cr alloys. Key recommendations included the need for better understanding of fracture mechanisms to address low toughness (scatter and anisotropy) including a comparative study of ODS and F/M steels, and compatibility with liquid metal environments. *Pär Olsson (KTH, Sweden)* (for L. Malerba, *SCK•CEN, Belgium*) presented new data on nano-structure evolution and mechanical properties in neutron-irradiated Fe-Cr alloys, studied by SANS, APT, PAS and TEM after irradiations at ~300°C; a contribution to the hardening mechanisms was proposed from Cr segregation to dislocation loops. *Céline Cabet (CEA, France)* discussed 9Cr steels for SFR applications and the challenge for welded joints in the design code. These include creep and the influence of thermal ageing and fatigue on subsequent creep rates where new mechanistic models are needed for reliable prediction, particularly at low stress, and also corrosion in liquid sodium. *Concetta Fazio (KIT, Germany)* reviewed materials for Pb-cooled nuclear systems; corrosion mitigation requires control of oxygen in the coolant. Oxidation affects structural integrity and heat transfer; cracking of the oxide scale can also lead to creep rupture. Control of oxygen content at high temperatures may be difficult, but in this situation a coating of an Al-containing Fe-Cr alloy can improve oxidation resistance. *Jim Cole (INL, United States,* for Todd Allen) described the ATR user facility for neutron irradiations, which is open to all nations via a

peer reviewed proposal route and provides access to a range of PIE facilities. A US university lead proposer is generally needed (INL can act as a matchmaker), but not necessarily for rapid-turnaround projects that utilise archive materials or do not require extensive PIE. *Alberto Saez (CIEMAT, Spain)* reported SCC CERT testing at 400°C to 500°C of 316L stainless steel in SCWR environments, in which the composition profile of the double oxide layer was found to be affected by temperature; prior cold work increased SCC susceptibility. *Victor Ignatiev* (Kurchatov Institute, Russian Federation) described studies of Ni-Mo and Ni-W alloys for fuel circuit materials in MSR concepts that would use fluoride-based fuel salts at temperatures of 600-800°C; the key issues include irradiation embrittlement and fission products such as Tellurium, which is shown to cause SCC at 700°C. *Changhuie Jang (KAIST, Republic of Korea)* reported studies of the tensile and creep properties of Ni-based alloys (Alloy 617 and Haynes 230) in high temperature steam at 900°C; carbide redistribution with long-term increase strength but reduces ductility, while surface oxides act as crack initiation sites. *Joel Simpson (INL, United States)* described creep-fatigue degradation in Ni-alloy (Alloy 617) for VHTR applications, tested at 950°C, concluding that separation of creep and fatigue interactions in true creep-fatigue test is problematic. *Julian Benz (INL, United States)* presented work on fatigue and creep crack propagation in Alloy 617 for intermediate heat exchanger and steam generator applications. Crack growth rates, studied at 650°C to 800°C in He, are affected by oxide formation, carburisation and decarburisation, of which carburisation is most detrimental; impure He environments accelerate crack growth due to a lack of oxidation protection. *Dan Shepherd (NNL, United Kingdom)* reported a TRL (technology readiness level) assessment of cladding alloys for advanced nuclear fuels, with a focus on fuels for Gen III and Gen IV systems; the assessment may be used to target research. TRL levels were low for ceramics compared to metals, with cladding TRLs also lower than fuels, indicating that clad development may be a limiting factor.

Session III: Novel pathways

David Gandy (EPRI, United States) described developments in powder metallurgy and HIP, focused on the vision for structural and pressure retaining applications for which large castings and forgings are needed for nuclear as well as for fossil-fuel super critical water plant. Examples include 316L stainless steel and carbon steels, with developments towards approval for components that can be inside the RPV. It was noted that higher fabrication costs may be compensated lower lifetime costs due to better ability to inspect; the more homogeneous structure improves inspection compared to castings and forgings. Power processing also enhances chemistry control and provides an alternate supply route for large components. *Indrajit Charit (Idaho University, United States*) presented a study of spark plasma sintered (SPS) nano structured ferritic ODS steels, utilising lanthanides instead of Yttria for slower diffusion. SPS can be advantageous as oxide particles and nano-clusters form before grain growth can occur. *Akira Kohyama (Muroran Institute of Technology, Japan)* described development work to scale up production of SiC-SiC composites within the INSPIRE & SCARLET programmes, which have been influenced by the recent increased requirements for accident tolerance in Gen III reactors, replacing Zr alloys and establishing the technology basis for fuel assembly fabrication. Irradiation programmes at the Halden reactor are planned. The issues discussed included joining (brazing and treaded joints have been demonstrated) and confidence in gas tightness to address fission product release.

Session IV: Ceramic composites, ions vs neutrons and general

Pär Olsson (KTH, Sweden) described Kinetic MonteCarlo modelling studies of FeCrAl steels, in which there is an optimum composition range to obtain corrosion resistance without 475°C embrittlement with thermal aging due to the effects of Al on the spinodal decomposition rate and its segregation to the surface. *Ji-Yeon Park (KAIST, Republic of Korea)*

described SiC-SiC fibre composites for accident tolerant fuels, and also for VHTR control rod and GFR fuel clad applications, with a fabrication concept of monolithic SiC, composite inner layer and external monolithic SiC; data for mechanical strength tests, corrosion in LWR environments and joining were presented. *Pär Olsson (KTH, Sweden,* for Lorenzo Malerba, SCK-CEN, Belgium) presented atom probe tomography studies of Fe-12Cr in a comparative study of neutron and ion irradiation at 300°C: neutrons form clusters and alpha', but ions form only clusters; the sizes and composition of clusters also differ. The different response can be understood by the high flux of ion irradiation; it was concluded that it was important for ion-irradiations to be supported by underlying physics, and used to focussed experiments on aspects of irradiation damage, not as a direct substitute for neutrons.